

A Step Towards Remote Tower Center Deployment: Optimizing Staff Schedules

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Abstract—Remote Tower Service (RTSs) is one of the technological and operational solutions delivered for deployment by the Single European Sky ATM Research (SESAR) Programme. This new concept fundamentally changes how operators provide Air Traffic Services, as it becomes possible to control several airports from a single remote center. In such settings an air traffic controller works at a so-called “multiple position” in the remote center, that is, he/she handles two or more airports from one Remote Tower Module (RTM), i.e. the controller working position.

In this paper, we present an optimization framework for the traffic management at five Swedish airports that were chosen for remote operation using a Remote Tower Center designed to serve a number of airports. We highlight the problems experienced with real airport schedules, and present optimal assignments of the airports to the RTMs. We consider both scheduled traffic and special (non-scheduled) traffic at these five airports.

Keywords—Air Traffic Management, Remote Control Tower, Optimal Personnel Scheduling, Integer Programming

I. INTRODUCTION

Remote Towers Services (RTSs) are one of several technological and operational solutions that the SESAR Programme is delivering to the ATM community for deployment. Over the last years, the Swedish ANSP Luftfartsverket (LFV) has been working on the deployment of the RTS concept as an alternative to traditional Air Traffic Service (ATS). The control centre from which LFV provides remote air navigation services for Örnköldsvik Airport since April 2015 is called Remote Tower Centre (RTC). Two additional Swedish airports, Sundsvall-Midlanda and Linköping SAAB, will be connected during spring 2017.

In 2015 and 2016 LFV and a Swedish airports operator conducted a joint feasibility study to analyze the impact of the transition from traditional tower ATS to RTS for five additional appointed airports in Sweden. The study confirmed that RTS is technically and operationally feasible, the level of risk is manageable, and that it is deemed financially advantageous to use RTS for these airports. In particular, the study identified several issues related to staff scheduling when multiple airports

are operated from a single center. The main question is: How to distribute the workload from several airports over several controller working positions?

In this paper we present a general optimization framework designed as a flexible tool for future staff planning. The model under development was discussed with operational experts during a workshop in Sundsvall RTC to provide a picture on staffing constraints as close as possible to reality. We consider how the traffic (either with or without non-scheduled flights) can be distributed over a number of working positions. In addition, we suggest a way to resolve potential conflicts in schedules – both within a single airport and between airports, and analyse how special airport traffic may influence our solutions. We evaluate the residual capacity of the system to calculate its ability to manage unpredictable workload variations.

A. Related work

RTC aims at providing the ATS for multiple airports by air traffic controllers (ATCOs) located remotely as defined in [9]. Researches studied various aspects of the RTS concept. Möhlenbrink et al. [6] and Papenfuss et al. [11] considered usability aspects within the novel remote control environment. Wittbrodt et al. [12] stress the role of radio communication in the context of a remote airport traffic control center. In a safety assessment of the ROT concept, Meyer et al. [5] suggest functional hazard analyses and pinpoint the issue of getting reliable probability values for the models. Oehme and Schulz-Rueckert [10] propose a sensor-based solution for aerodrome control that removes the dependency on visibility conditions and tower location. In [8] and [7] Möhlenbrink et al. consider various aspects of work organization in a remote center. They propose several methods to control two airports from a single center. Using simulations they studied how the monitoring performance may influence the system design and behavioral strategies, and suggested several ideas on the design of novel ATC-workplaces.

Distributing the total traffic load between controller positions is the subject in the sectorization research – a well studied area in ATM; see e.g., the survey [4] and references thereof. Assigning airport traffic to Remote Tower Modules

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(RTMs) was considered in [2]. That model did not take into account the possibility to switch assignments during the day or load balancing. Based on the model proposed in [2], we create an optimization framework with multiple objectives and additional constraints, and demonstrate how it enables personnel planning at RTCs on real data.

B. Roadmap

In Section I-A we review related work. We present a general mathematical model for assigning airports' scheduled traffic to the Remote Tower Center modules in Section II. In Section III we verify the proposed model using real data from the five Swedish airports planned for remote operation. We propose various solutions for staff scheduling at these airports, comparing different possible objectives. We present how potential conflicts in schedules for a module can be avoided—both within a single airport and between airports. Moreover, we estimate the residual capacity of the system. Section IV concludes the paper and outlines our future work.

II. MODELLING

We develop a mathematical model using integer programming: it takes one-day airport data schedules as an input and outputs the optimal assignment of airports to remote tower modules (RTMs) per hour, taking into account constraints on the operation possibilities.

Our model is a mixed-integer program (MIP), which in general is NP-hard to solve. In particular, it is a Bin-Packing problem variant [3], again an NP-hard problem. However, smaller instances of the problem can be solved using commercial off-the-shelf optimization software, as we demonstrate in Section III.

Table I summarizes the notations used in this section.

A. Input

We are given a set of airports with their opening hours and the scheduled arriving and departing flights. We quantify the total amount of traffic by the number of movements which occur during a certain time period. *Movements* include scheduled and non-scheduled (military, school, charter flights, hospital helicopters, etc.) airport arrivals and departures.

B. Constraints

There are restrictions on the number of airports and the total number of movements which can be assigned to one module per time period. These restrictions are reflected in the following basic constraints in our model:

$$\sum_{j \in A} mov_{i,j,k} \leq mMov \quad \forall i \in R, \forall k \in P \quad (1)$$

$$\sum_{j \in A} period_{i,j,k} \leq RTM_{i,k} \cdot mA \quad \forall i \in R, \forall k \in P \quad (2)$$

$$\sum_{i \in R} period_{i,j,k} \leq 1 \quad \forall j \in A, \forall k \in P \quad (3)$$

$$mov_{i,j,k} \leq period_{i,j,k} \cdot mMov \quad \forall i \in R, \forall j \in A, \forall k \in P \quad (4)$$

$$\sum_{i \in R} mov_{i,j,k} = Amov_{j,k} \quad \forall j \in A, \forall k \in P \quad (5)$$

$$\sum_{i \in R} period_{i,j,k} \geq op_{j,k} \quad \forall j \in A, \forall k \in P \quad (6)$$

Equations (1) and (2) represent the restrictions on the total number of movements in each module per time period and the number of airports per module per time period, respectively. Constraint (3) ensures that each airport is assigned to only one RTM during each time period. Equations (4) and (5) guarantee that all scheduled traffic is handled. Moreover, all opening hours at all airports are to be covered, which is enforced by the constraint (6).

C. Objectives

Targeting a flexible optimization framework, adjustable to the needs of future RTC staff planning, we propose several alternative objective functions for our model.

1) Minimize the number of RTMs: :

To guarantee that the remote tower center facilities are used with maximum efficiency, we may target to assign the given airports to as few RTMs as possible:

$$\min \sum_{i \in R} \sum_{k \in P} RTM_{i,k} \quad (7)$$

2) *Balance workload between modules:* The scheduling may need to target equal workload distribution between the modules in order to equalize controllers shifts. We introduce the variables $d_{l,m,k}$ that denote the difference in workload between the modules l and m during period k . Obviously, we are only interested in the absolute value of this difference, thus, we introduce the following two inequalities that assign this absolute value to the variable $d_{l,m,k}$:

$$d_{l,m,k} \geq \sum_{j \in A} mov_{l,j,k} - \sum_{j \in A} mov_{m,j,k} \quad \forall l, m \in R, \forall k \in P \quad (8)$$

$$d_{l,m,k} \geq \sum_{j \in A} mov_{m,j,k} - \sum_{j \in A} mov_{l,j,k} \quad \forall l, m \in R, \forall k \in P \quad (9)$$

When we want to minimize the workload imbalances in the staff schedule, we use the following objective function:

$$\min \sum_{k \in P} d_{l,m,k} \quad \forall l, m \in R : l \neq m \quad (10)$$

TABLE I
NOTATIONS

| Notation | Parameter | Notation | Variable |
|--------------|--|------------------|---|
| A | set of airports | $op_{j,k}$ | = 1 if airport j is open during period k , = 0 otherwise |
| R | set of RTMs | M_k | number of modules in use during period k |
| P | set of time periods | $RTM_{i,k}$ | = 1 if RTM i is used during period k , = 0 otherwise |
| p | number of time periods | $period_{i,j,k}$ | = 1 if airport j is assigned to RTM i during period k , = 0 otherwise |
| $mMov$ | max number of movements per RTM per period | $mov_{i,j,k}$ | number of movements handled by RTM i at airport j during period k |
| mA | max number of airports per RTM | $switch_{i,j,k}$ | = 0 if $period_{i,j,k} = period_{i,j,k+1}$, = 1 otherwise |
| $Amov_{j,k}$ | number of movements at airport j during period k | $dl_{m,k}$ | difference between the workloads in modules l and m in period k |

3) *Minimize assignment switches*: Our model allows schedules where airport-to-module assignments can switch every time period. Such switches result in frequent changes in the controllers' working environment, which induces handovers and additional workload. Consequently, the objective for scheduling might be to minimize assignment switches.

To this end, we introduce the variable $switch_{i,j,k}$, which equals 0 when the assignment of airport j to the module i is the same during the periods k and $k+1$, and equals 1 otherwise. In addition we use an auxiliary variable $s_{i,j,k}$, with $s_{i,j,k} = period_{i,j,k+1} - period_{i,j,k}$, and add Equations (11) and (12) to define $switch_{i,j,k}$:

$$switch_{i,j,k} \geq s_{i,j,k} \quad \forall i \in R, \forall j \in A, \forall k \in P \quad (11)$$

$$switch_{i,j,k} \geq -s_{i,j,k} \quad \forall i \in R, \forall j \in A, \forall k \in P \quad (12)$$

The corresponding objective function is:

$$\min \sum_{i \in R} \sum_{j \in A} \sum_{k=1}^{p-1} switch_{i,j,k} \quad (13)$$

III. EXPERIMENTAL STUDY

In this section, we analyse and compare the schedules for the different objectives introduced in Section II-C.

A. Data

We analyzed traffic data of five Swedish airports for 2 weeks in September 2016. These include airport opening hours and the times for arrival and departure of flights. In addition we use the description of airport specifics, covering non-scheduled traffic patterns and other special airport features from the Chief of Operations.

Airports' properties can be shortly described as follows. *Airport 1* (AP1) - small airport with low traffic, few scheduled flights per hour, non-regular helicopter traffic, sometimes special testing activities. *Airport 2* (AP2) - low to medium-sized airport, multiple scheduled flights per hour, regular special traffic flights. *Airport 3* (AP3) - small regional airport with regular scheduled flights, optional helicopter and general aviation flights. *Airport 4* (AP4) - small airport with significant seasonal variations and occasional significant military activities, general aviation. *Airport 5* (AP5) - small airport with low scheduled traffic, non-regular helicopter flights.

B. Assumptions and limitations

The following constraints are included into the model to reflect the safety and efficiency requirements for RTC personnel operation.

- Maximum number of airports controlled from one RTM*: The default value of the maximum number of airports assigned to one remote tower module is set to 2 (considered to be the most practical). For a feasibility study we relaxed this assumption and allowed more airports to be controlled from a single RTM. From the experts we learned that there may be problems with visual representation and switching between the views when more than three airports are assigned to one module. But theoretically it is possible to control even more airports from one RTM.
- Maximum number of movements per module*: The maximum number of movements which can be assigned to one RTM during one hour is set to 10. This conservative assumption places the upper bound on the total number of movements which can be handled by one controller in one module that represents a manageable workload for the ATCO.
- Potential conflicts*: We aim to detect and avoid potential conflict situation. Here, we consider a *conflict* as more than 3 movements that are scheduled during a 5-minute period in a single module.

Sometimes input data violates the initial assumption *b*). For example, one day at AP2, 13 movements are scheduled during a one hour period. We define such a situation as a *self-conflict*, and consider assigning this airport to a separate module in single operation. Without loss of generality, for modeling purposes we simply replace this number with 10 movements to make the problem initially feasible.

In the remainder of this section, we present optimal assignments of the five airports to the remote tower modules under several optimality criteria. We also compare to schedules which include non-scheduled traffic, and analyse how special airport traffic may influence our solutions.

We use the AMPL modeling language [1] and CPLEX 12.6 to model and solve the MIP.

C. Minimizing the number of RTMs

1) *Lower bound*: First, we estimate the theoretical lower bound on the number of modules necessary to handle the total amount of traffic at the 5 input airports. For that purpose

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
|-----|---|---|---|---|---|---|---|---|----|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| AP1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| AP2 | 1 | 2 | 1 | 1 | 2 | 1 | 3 | 9 | 10 | 6 | 4 | 3 | 3 | 5 | 2 | 0 | 5 | 6 | 5 | 7 | 2 | 6 | 4 | 1 |
| AP3 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 2 | 1 | 6 | 3 | 1 | 5 | 2 | 0 | 3 | 6 | 3 | 4 | 4 | 4 | 2 | 2 | 1 |
| AP4 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 2 | 4 | 3 | 2 | 1 | 2 | 2 | 1 | 0 | 3 | 1 | 3 | 1 | 0 | 3 | 1 | 0 |
| AP5 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 2 | 0 | 4 | 1 | 0 | 3 | 0 | 0 | 1 | 3 | 1 | 2 | 2 | 1 | 2 | 1 | 0 |

Fig. 1. Airports-to-RTMs assignment without an upper bound on the number of airports per RTM (Schema 1). The table entries give the number of movements per airport. Blue and red correspond to module 1 and 2, respectively.

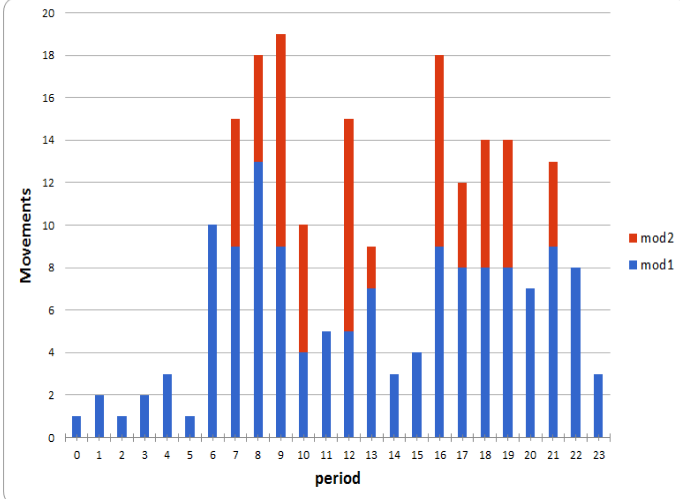


Fig. 2. Workload distribution between two active RTMs (Schema 1). Blue and red correspond to module 1 and 2, respectively.

we ignore the initial assumption (*a*) from Section III-B by allowing more than two airports to be assigned to one module in the same time period. The resulting schema (Schema1) is presented in Figures 1 and 2. Figure 1 gives the assignment of airports to RTMs per hour with the number of movements in the table cells. The cells colored in blue and red correspond to the module 1 and 2, respectively. These colors are also used in the chart in Figure 2. It illustrates how much traffic (number of movements) is assigned to each of the two modules.

We conclude that two modules are sufficient to manage all the traffic at the given five airports for the considered day. During quiet hours up to four airports are assigned to one module (e.g., during hour 6: four airports are assigned to one module, with a total of 10 movements). During rush hours (e.g., during hours 9, 12, 16) all scheduled traffic can be handled with two modules.

2) *Assignment of at most two airports to an RTM:* After verifying that—in theory—two modules are enough to handle all scheduled traffic in the current situation, we reintroduce the initial assumption (*a*) from Section III-B: at most two airports can be assigned to one RTM. The resulting assignment of airports to modules is shown in Figure 3 as Schema 2 and illustrated in Figure 4.

The overall traffic load is now distributed between the three active modules, and the total workload per module is reduced in comparison to Schema 1. For example, during hour 6, the total of 10 movements is distributed so that 4 movements (1 at

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
|-----|---|---|---|---|---|---|---|---|----|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| AP1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| AP2 | 1 | 2 | 1 | 1 | 2 | 1 | 3 | 9 | 10 | 6 | 4 | 3 | 3 | 5 | 2 | 0 | 5 | 6 | 5 | 7 | 2 | 6 | 4 | 1 |
| AP3 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 2 | 1 | 6 | 3 | 1 | 5 | 2 | 0 | 3 | 6 | 3 | 4 | 4 | 4 | 2 | 2 | 1 |
| AP4 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 2 | 4 | 3 | 2 | 1 | 2 | 2 | 1 | 0 | 3 | 1 | 3 | 1 | 0 | 3 | 1 | 0 |
| AP5 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 2 | 0 | 4 | 1 | 0 | 3 | 0 | 0 | 1 | 3 | 1 | 2 | 2 | 1 | 2 | 1 | 0 |

Fig. 3. Airports-to-RTMs assignments with an upper bound of 2 on the number of airports per RTM (Schema 2). Table entries give the number of movements per airport. Blue, red, and yellow correspond to module 1, 2, and 3, respectively.

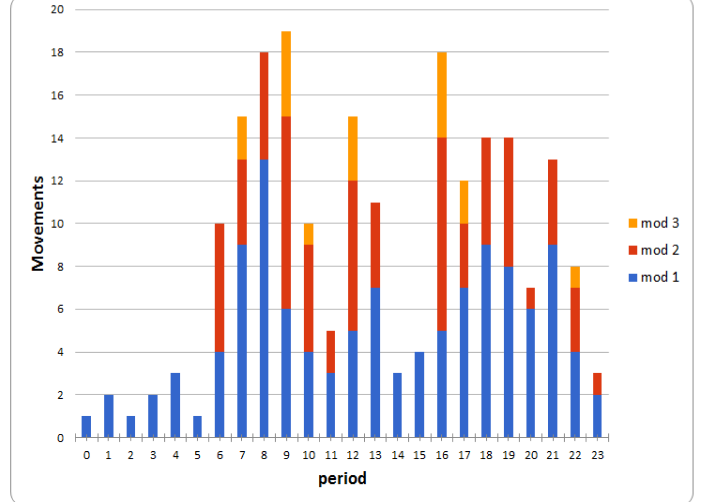


Fig. 4. Workload distribution between three active RTMs (Schema 2). Blue, red, and yellow correspond to module 1, 2, and 3, respectively.

AP1 and 3 at AP2) are assigned to module 1 and 6 movements (3 at AP4 and 3 at AP5) are assigned to module 2. During rush hours (e.g., hours 7, 8), the traffic at AP2 is so heavy that it is automatically assigned to a separate module in single operation.

D. Balancing the load

The resulting workload in our schemes is not balanced between the modules—neither per hour, nor in the larger scope (during the whole day). Often, it is not possible to obtain a perfectly balanced schedule. For example, if during a period only two airports have movements: one has 9, the other 3. In that case, given the constraints on the maximum number of movements per module, one ATCO will have to monitor 9 movements, and another 3, as we cannot split movements from a single airport. Nevertheless, we would like to distribute the load between the working ATCOs as evenly as possible: we want to minimize the imbalance under the given constraints. The balancing condition can be implemented either within the model, or later during post-processing stage.

Using the objective function (10) with the corresponding additional constraints (Equations (8) and (9)) to the basic model we obtain the optimal assignment as illustrated in Figure 5 and Figure 6, and denoted as Schema 3.

As it is clearly seen from the chart in Figure 6, the resulting workload is now better balanced between the modules. Comparing it to Schema 2 we conclude that the fairness was

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
|-----|---|---|---|---|---|---|---|---|----|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| AP1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| AP2 | 1 | 2 | 1 | 1 | 2 | 1 | 3 | 9 | 10 | 6 | 4 | 3 | 3 | 5 | 2 | 0 | 5 | 6 | 5 | 7 | 2 | 6 | 4 | 1 |
| AP3 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 2 | 1 | 6 | 3 | 1 | 5 | 2 | 0 | 3 | 6 | 3 | 4 | 4 | 4 | 2 | 2 | 1 |
| AP4 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 2 | 4 | 3 | 2 | 1 | 2 | 2 | 1 | 0 | 3 | 1 | 3 | 1 | 0 | 3 | 1 | 0 |
| AP5 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 2 | 0 | 4 | 1 | 0 | 3 | 0 | 0 | 1 | 3 | 1 | 2 | 2 | 1 | 2 | 1 | 0 |

Fig. 5. Airports-to-RTMs assignment for three active modules with the optimal balance (Schema 3). Blue, red, and yellow correspond to module 1, 2, and 3, respectively.

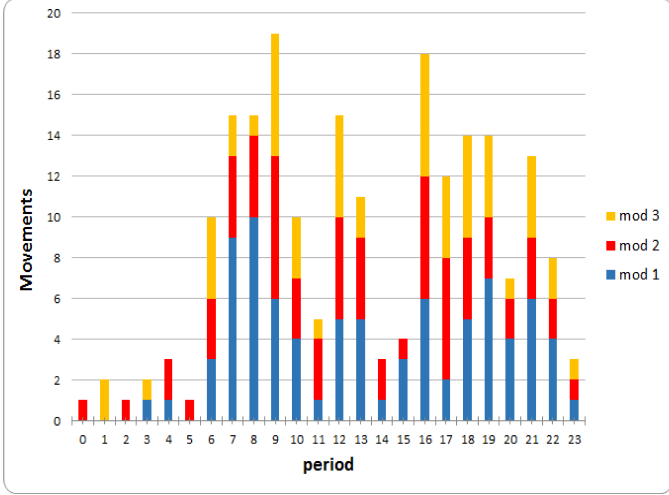


Fig. 6. Workload distribution between three active modules with optimal balance (Schema 3). Blue, red, and yellow correspond to module 1, 2, and 3, respectively.

achieved at the expense of the increased number of modules in use (e.g., during hours 2, 3, and 4 two modules are in use in Schema 3 instead of 1 in Schema 2.) This example demonstrates a clear trade-off between the two objectives. A smart combination of them should be used in order to achieve reasonable assignments.

Moreover, we observe that load balancing increases the number of assignment switches, these also contribute to the workload, and must be integrated in a trade-off between the objectives.

E. Minimizing the number of switches

Consider the example schedule in Figure 5: AP3 is assigned first to module 3 during hour 3, then switches to module 1 for hour 4 and then to module 2 after a break. Such frequent switches should be avoided as they may cause safety issues during handovers with overlaid traffic complications and difficulties with individual controller scheduling and rating.

Using objective function (13) with the corresponding additional constraints (Equations (11) and (12)), we obtain the solution with a minimum number of switches as illustrated in Figures 7 and 8 (Schema 4).

We yield an optimal schedule without any switches for the day in consideration. That is, each airport was assigned to the same module throughout the entire day. However, the resulting schedule lacks load balancing and is sub-optimal in the number of active modules, which confirms the trade-offs outlined above.

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
|-----|---|---|---|---|---|---|---|---|----|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| AP1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| AP2 | 1 | 2 | 1 | 1 | 2 | 1 | 3 | 9 | 10 | 6 | 4 | 3 | 3 | 5 | 2 | 0 | 5 | 6 | 5 | 7 | 2 | 6 | 4 | 1 |
| AP3 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 2 | 1 | 6 | 3 | 1 | 5 | 2 | 0 | 3 | 6 | 3 | 4 | 4 | 4 | 2 | 2 | 1 |
| AP4 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 2 | 4 | 3 | 2 | 1 | 2 | 2 | 1 | 0 | 3 | 1 | 3 | 1 | 0 | 3 | 1 | 0 |
| AP5 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 2 | 0 | 4 | 1 | 0 | 3 | 0 | 0 | 1 | 3 | 1 | 2 | 2 | 1 | 2 | 1 | 0 |

Fig. 7. Airports-to-RTM assignment for three active modules with minimum number of switches (Schema 4). Blue, red, and yellow correspond to module 1, 2, and 3, respectively.

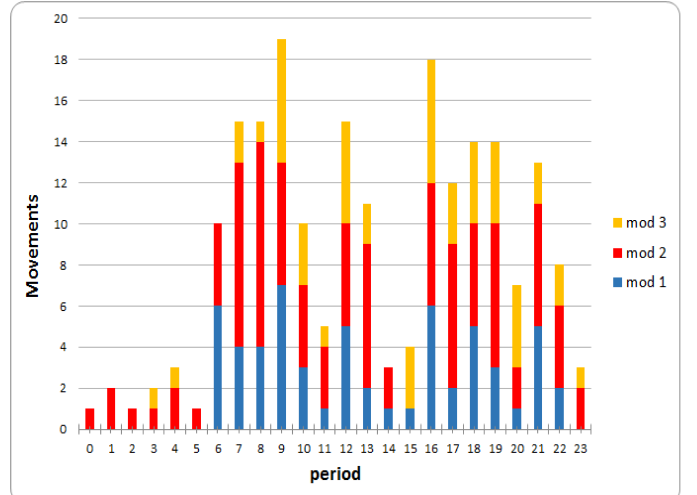


Fig. 8. Workload distribution between three active modules with minimum number of switches (Schema 4). Blue, red, and yellow correspond to module 1, 2, and 3, respectively.

In future work, we plan to extend the model, such that it keeps assignments for some fixed period (e.g, airports must be assigned to modules for at least two or three hours—the minimum time for holding an assignment advised by experts), taking into account the requirements for the actual controller shifts.

F. Post-processing: Avoiding potential conflicts

As discussed in Section III-B, we define a *conflict* in the schedules as more than 3 simultaneous movements scheduled at a single module within a 5-minute period.

For each pair of airports we detect the conflict hours by merging their corresponding schedules. We want to avoid assigning 2 airports into one module during the periods when there are potential conflicts in the resulting schedules.

Moreover, if more than 3 movements are scheduled at the same airport during a 5-minute period, we define it as a *self-conflict*. We aim to assign this airport to a separate module in single operation during the conflict period.

Figure 9 illustrates both a self-conflict at AP2 at 21:15 and a potential conflict between AP2 and AP4 schedules at the same time. In the solution output by our model (see Figure 10), AP2 was assigned to a separate module (module 2). Thus, we do not need to perform any re-assignment during hour 21.

However, re-assignment is clearly needed during hours 8, 9 and 17, see Figure 10. One way of resolving the conflicts is given in Figure 10, bottom, which was obtained by slightly

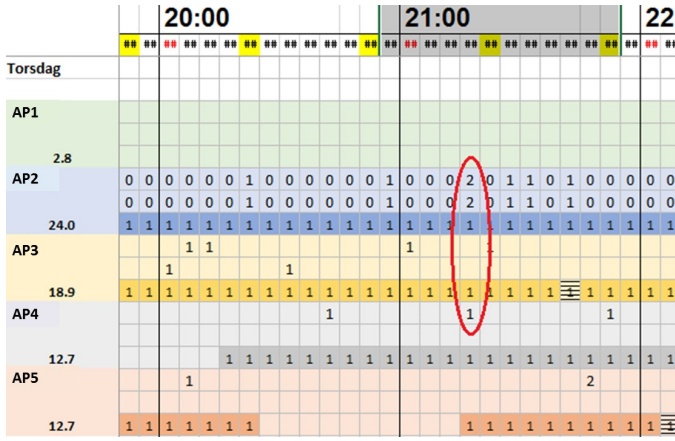


Fig. 9. Detection and avoidance of potential conflicts in schedules.

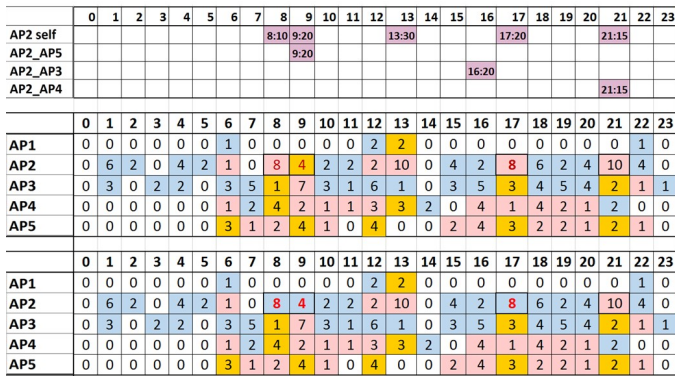


Fig. 10. Re-assignment during post-processing for resolving potential conflicts in the schedules. In the first table the times of the conflicts are specified in the purple cells. The second and the third table represents the schedule before and after post-processing.

modifying the schedules during the conflict hours only, making sure that the initial assumptions are preserved.

In future work, we will consider early detection of potential conflict. We believe it may be incorporated into the model, and airport incompatibility or self-conflicts may be excluded by modeling them as initial constraints.

G. Analysis and management of non-scheduled traffic

We studied the information about the airports specifics connected to the management of non-scheduled traffic, which includes military service (FM), hospital helicopters (HKP), school trainings (Skol), charters (Special) and other unscheduled traffic. A description of the airports non-scheduled traffic was retrieved from the Chief of Operations of the considered airports. We summarize the amount per day of such extra traffic in Table II.

Note, that the data in column 3 of the table describes the maximum amount of special traffic during the normal day of airport operation, while the worst-case numbers presented in column 4 cover all the possible situations involving special traffic per site (which include even potential control zone crossings).

TABLE II
APPROXIMATE AMOUNT OF NON-SCHEDULED TRAFFIC AT THE AIRPORTS PER DAY.

| Airport | Type of traffic | Normal operation | Worst case |
|---------|-----------------|------------------|------------|
| AP1 | FM | 3 | 10 |
| | HKP | 5 | 17 |
| | Skol | 1 | 3 |
| | Special | 2 | 5 |
| | Other | 1 | 5 |
| AP2 | FM | 1 | 3 |
| | HKP | 1 | 4 |
| | Skol | 5 | 20 |
| | Special | 14 | 60 |
| | Other | 2 | 10 |
| AP3 | HKP | 4 | 12 |
| | Skol | 2 | 8 |
| | Special | 4 | 10 |
| | Other | 4 | 4 |
| AP4 | FM | 6 | 125 |
| | HKP | 7 | 21 |
| | Skol | 4 | 10 |
| | Special | 2 | 10 |
| AP5 | FM | 8 | 20 |
| | HKP | 8 | 20 |
| | Skol | 3 | 8 |
| | Special | 4 | 12 |

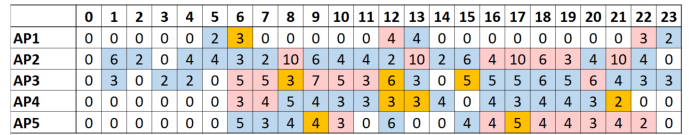


Fig. 11. Airports-to-RTM assignment for airports in normal operation with extra traffic (Mode 2). Blue, red, and yellow correspond to module 1, 2, and 3, respectively.

In order to evaluate the influence of extra traffic load on our scheduling solutions we compare the performance of the system in the following operational modes:

1. With regular scheduled traffic only;
2. With moderate amount of additional traffic (normal operation);
3. With extra large amount of additional traffic (theoretical worst-case scenario).

1) *Mode 1. Scheduled traffic only:* All schemes discussed (Schemes 1, 2, 3, and 4) were developed for scheduled traffic only, that is, without considering additional traffic.

2) *Mode 2. Normal operation with some additional traffic:* In this subsection, we want to highlight how the schedules change when additional traffic is introduced. We distribute the estimated amount of extra traffic (corresponding to the third column in Table II) evenly among the opening hours of each airport, add it to the scheduled data making sure the number of movements per hour does not exceed the maximum of 10.

We feed the data into the model with the objective function minimizing the number of RTMs in use. The resulting schedule is presented in Figures 11 and 12 (right).

We observe that even with this moderate additional traffic three active modules are still sufficient to handle all airports. During quiet hours, the assignment is similar to the one for operation with scheduled traffic only. During rush hours,

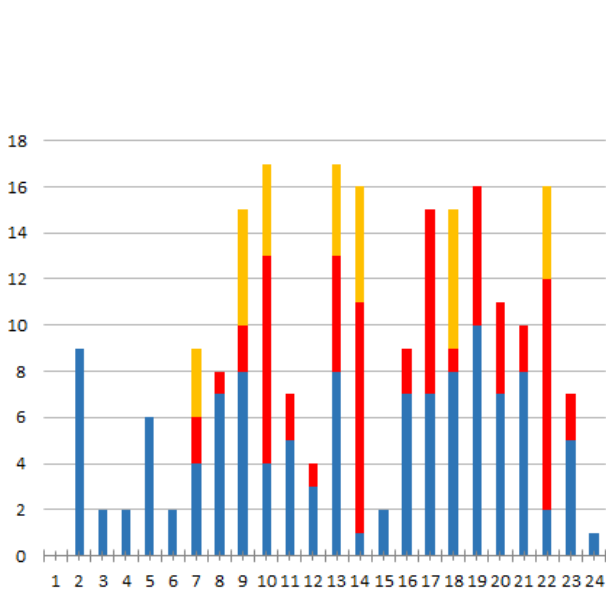


Fig. 12. Workload distribution for scheduled traffic (Mode 1) vs. workload with moderate amount of extra traffic (Mode 2). Blue, red, and yellow correspond to module 1, 2, and 3, respectively.

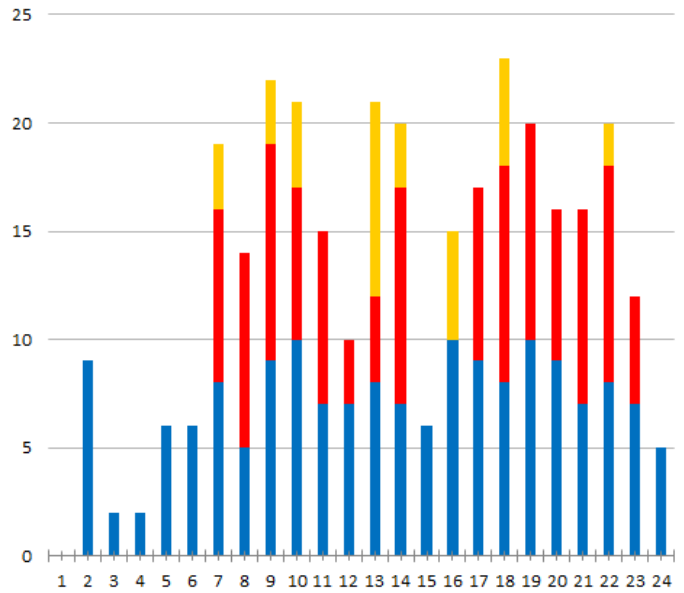
the total number of movements increases significantly (in comparison to the scheduled traffic only), but the assignment still resembles the schedule without extra traffic.

Comparing the workload distribution between the three active modules (Figure 12) we conclude that the extra load is added to all modules in relatively fair proportions, and the overall system is still far from being overloaded.

3) *Mode 3. Worst-case scenario:* We repeat the procedure for Mode 2 for the maximum amount of special traffic (the worst-case, corresponding to the fourth column in Table 4).

In this case, the estimated amount of extra traffic for AP4 exceeds the limits of the system: we are restricted to a maximum of 10 movements per hour. That is, under the 15 regular opening hours at AP4 at most 150 aircraft movements can be handled. Already the total number of additional movements of 166 exceeds this upper bound. Without relaxing the initial assumption we cannot add these 166 movements to the regular schedule of AP4. Consequently, for modeling purposes, we reduced the number of extra movements to 117 (150 minus the 33 movements in Mode 1). We do so, having in mind that this additional traffic was overestimated in the first place. Obviously, we now have 10 movements per hour in AP4, which in practice should have the airport assigned to a separate module in single operation. Our model confirms this conclusion. The optimal solution is presented in Figures 13 and 14 (right).

We observe that in the worst-case scenario we have to utilize as many as four active modules during rush hours (i.e., 33% of the time), while the rest of the day we can still handle the traffic with 3 modules. We believe the results confirm RTC efficiency, even in the absolutely worst-case scenario, which is unlikely to occur.



| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | |
|-----|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| AP1 | 0 | 0 | 0 | 0 | 0 | 6 | 10 | 0 | 0 | 0 | 0 | 0 | 5 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 10 |
| AP2 | 6 | 8 | 8 | 6 | 8 | 6 | 7 | 6 | 8 | 8 | 8 | 8 | 8 | 10 | 6 | 9 | 7 | 8 | 9 | 6 | 6 | 10 | 8 | 6 | 6 |
| AP3 | 0 | 4 | 0 | 4 | 2 | 0 | 3 | 5 | 5 | 7 | 6 | 5 | 6 | 6 | 0 | 6 | 5 | 6 | 6 | 5 | 6 | 3 | 3 | 3 | 3 |
| AP4 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 0 | 10 | 10 | 10 | 10 | 10 | 10 | 0 | 0 | 0 |
| AP5 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 5 | 6 | 8 | 6 | 0 | 8 | 0 | 0 | 6 | 7 | 7 | 6 | 6 | 7 | 7 | 6 | 0 | 0 |

Fig. 13. Airports-to-RTM assignment for airports with maximum amount of extra traffic, worst-case (Mode 3). Blue, red, and yellow correspond to module 1, 2, and 3, respectively.

The total workload in the worst case is significantly higher than the one without extra traffic (Figure 14), which forces the modules to operate in full capacity most of the time. For safety and security reasons it is desirable to avoid overloading the system and to leave some buffer for unpredictable situations. In future work, we suggest to separate special traffic of high priority from extra traffic of low priority. Then, traffic of high priority should be treated as extra load, which may happen at any time during the day, and contribute to the resilience of the system, while traffic of low priority can occupy free slots in the schedules. Again, it is desirable to include some buffer that covers a possible increase in workload. We plan to use more accurate data statistics when studying the assignment of special traffic for more realistic planning.

H. Residual capacity of the system

In order to guarantee the possibility to add extra traffic and to keep some safety buffer in the resulting schemes, we estimate the residual capacity of the initial airport schedules.

Figure 15 gives an example of calculating residual capacity of a schedule: Given the initial airport schedules and the limitation on the number of movements per hour, we simply subtract the number of scheduled movements per airport per hour (for open hours only) from the upper bound (=10).

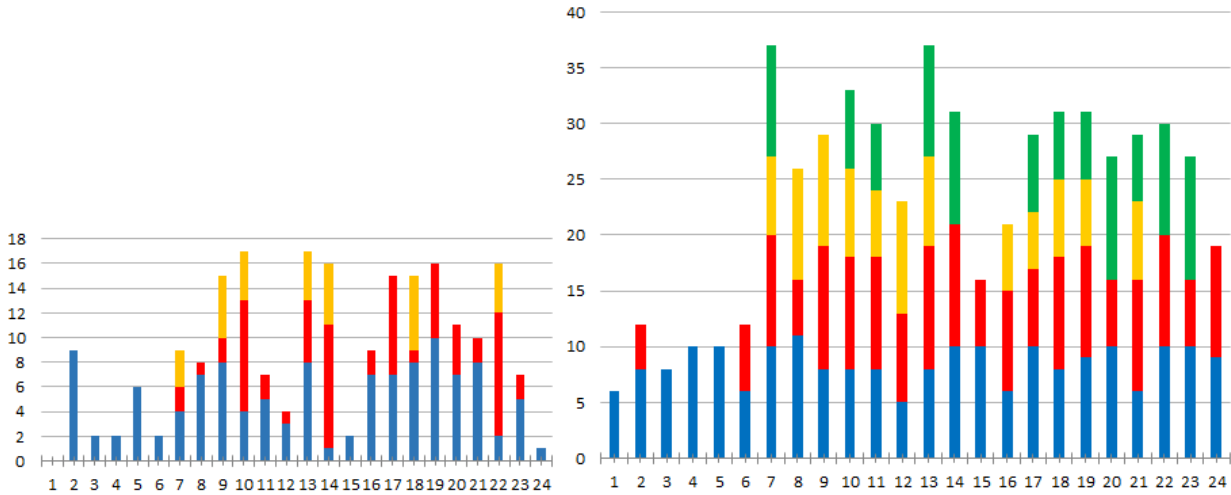


Fig. 14. Workload distribution for scheduled traffic (Mode 1) vs. workload with maximum amount of extra traffic, worst-case (Mode 3). Blue, red, and yellow correspond to module 1, 2, and 3, respectively.

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | sum |
|-----|----|---|---|----|---|----|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|-----|
| AP1 | | | | | | 10 | 9 | | | | | | 8 | 8 | | | | | | | | | 9 | 10 | 54 |
| AP2 | 10 | 4 | 8 | 10 | 6 | 8 | 9 | 2 | 6 | 8 | 8 | 8 | 0 | 6 | 8 | 2 | 4 | 8 | 6 | 0 | 6 | 10 | 6 | 10 | 137 |
| AP3 | 10 | 7 | | 8 | 8 | | 7 | 5 | 9 | 3 | 7 | 9 | 4 | 9 | | 7 | 5 | 7 | 6 | 5 | 6 | 8 | 9 | 9 | 148 |
| AP4 | | | | | | | 9 | 8 | 6 | 8 | 9 | 9 | 7 | 7 | 8 | | 6 | 9 | 6 | 8 | 9 | 8 | | | 117 |
| AP5 | | | | | | | 7 | 9 | 8 | 6 | 9 | | 6 | | | 8 | 6 | 7 | 8 | 8 | 9 | 8 | 9 | | 108 |

Fig. 15. Residual capacity of the schedule for the busiest day of the example week.

TABLE III
RESIDUAL CAPACITY OF THE SYSTEM VS. EXTRA TRAFFIC AMOUNT IN MODE 2 AND MODE 3 PER DAY.

| Airport | Residual | MODE 2 (normal) | MODE 3 (worst-case) |
|---------|----------|-----------------|---------------------|
| AP1 | 54 | 12 | 40 |
| AP2 | 137 | 23 | 97 |
| AP3 | 148 | 24 | 34 |
| AP4 | 117 | 19 | 166 |
| AP5 | 108 | 23 | 60 |

The resulting table shows residual number of movements in the schedule per hour. Summing up the movements for each airport for the whole day, we obtain the estimation of the residual capacity of our daily schedules. Note that we again find the 117 movements for AP4 as discussed in Section III-G3. Similarly, we can evaluate the residual capacity of the output schemes per module, by subtracting the number of movements assigned to each module per hour from the upper bound. By summing up the results for the whole day, we can estimate the utilization of the proposed schema.

The residual amount of traffic per airport is summarized in the second column of Table III and compared with the estimated amount of special traffic in normal operation and the worst-case load in columns three and four. We conclude that even with the conservative assumption of a maximum of 10 movements per hour, the given airport schedules can accommodate even the worst-case amount of extra traffic. The only outlier is AP4, where the amount of military traffic may significantly deviate from the normal. We may need to discuss special measures to prevent the respective system from overloading. As we learned from the experts, the worst-case operation numbers are significantly overestimated and are subject to further discussions.

IV. CONCLUSION AND FUTURE WORK

In this work we presented an optimization framework for staff planning at the remote tower center. The proposed solutions are subject to a constant reality check and create a base for further discussions. The studies identified several issues related to staff scheduling when multiple airports are operated from a single center.

The model under development was discussed with operational experts during a workshop in Sundsvall RTC to provide a picture on staffing constraints as close as possible to reality. Their expertise helped us to adjust optimization goals and outline the steps for a more detailed model to develop a deeper insight into management needs of remotely controlled airports.

The results of this work help to evaluate efficiency of the RTC concept in general and give intuition for further deployment. Furthermore, the designed techniques and tools will be applied to other sets of airports being considered for remote operation.

In future studies, we target a more detailed data analysis for better airport clustering. This will include data for an entire year and reflect seasonal changes. We will study airports specifics more carefully, and propose different ways of managing the total amount of airport traffic in realistic

operational scenarios. The optimization goals will be shifted towards creating actual staff working schedules, reflecting unit endorsements and other individual limitations and operational requirements.

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