

A Step Towards Remote Tower Center Deployment: Optimizing Staff Schedules

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Remote Tower Service is one of the technological and operational solutions delivered for deployment by the Single European Sky Air Traffic Management Research Program. 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, 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 Remote Tower Modules. We consider both scheduled traffic and special (non-scheduled) traffic at these five airports.

Nomenclature

A	=	set of airports
R	=	set of RTMs
P	=	set of time periods
p	=	number of time periods
$mMov$	=	max number of movements per RTM per period
mA	=	max number of airports per RTM
$Amov_{j,k}$	=	number of movements at airport j during period k

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- $op_{j,k}$ = binary variable, equals 1 if airport j is open during period k , 0 otherwise
 $RTM_{i,k}$ = binary variable, equals 1 if RTM i is used during period k , 0 otherwise
 $period_{i,j,k}$ = binary variable, equals 1 if airport j is assigned to RTM i during period k , 0 otherwise
 $mov_{i,j,k}$ = number of movements handled by RTM i at airport j during period k
 $switch_{i,j,k}$ = binary variable, equals 0 if $period_{i,j,k} = period_{i,j,k+1}$, 1 otherwise
 $d_{l,m,k}$ = difference between the workloads in modules l and m in period k

I. Introduction

Remote Towers Service (RTS) is one of several technological and operational solutions that the European Sky Air Traffic Management Research (SESAR) Program is delivering to the Air Traffic Management (ATM) community for deployment. Over the last years, the Swedish Air Navigation Service Provider 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, connected in 2017.

In 2015 and 2016 LFV and a Swedish airport 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. Moreover, the study identified several issues related to staff scheduling when multiple airports are operated from a single center. The main question was: 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

An RTC aims at providing ATS for multiple airports by air traffic controllers (ATCOs) located remotely as defined in [1]. Researchers have studied various aspects of the RTS concept. Möhlenbrink et al. [2] and Papenfuss et al. [3] considered usability aspects within the novel remote control environment. Wittbrodt et al. [4] stress the role of radio communication in the context of a remote airport traffic control center. In a safety assessment of the RTS 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 [6] propose a sensor-based solution for aerodrome control that removes the dependency on visibility conditions and tower location. In [7], [8], [9], [10] and [11] various aspects of work organization and human performance issues related to the remote operation are considered. The authors 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 ATS-workplaces.

Distributing the total traffic load between controller positions is the subject of sectorization research—a well studied area in ATM; see e.g., the survey [12] and references therein. Assigning airport traffic to Remote Tower Modules (RTMs) was first considered in [13]. Based on the model proposed in [13], in this work we create an optimization framework with multiple objectives, including load balancing and minimizing the switching between the assignments, and additional constraints, and demonstrate how it enables personnel planning at RTCs on real airport data. Here we output and analyse the detailed airport-to-module daily assignments for different objectives, and study the trade-offs between them. While the authors of [13] estimated the number of RTMs required to serve all 29 active airports in Sweden, in this work we focus on the real data for the five airports actually planned for remote operation in Sweden. An alternative problem of assigning controllers to RTMs, taking into account the requirements for the actual controller shifts was considered in [14]. The same RTM can be used by several controllers during the day, and can be assigned to different airports, different scheduling problems are to be considered for optimizing resources at RTC. While this current work focuses on optimization of equipment utilization, the later work [14] dealt with optimization of the human resources and their working conditions.

B. Roadmap

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 summarizes the results of this work and concludes the paper.

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 RTMs per hour, taking into account constraints on the operation possibilities.

Our model is a mixed-integer program (MIP), that is, we have both integer and real variables, which in general is

NP-hard to solve. In particular, it is a Bin-Packing problem variant [15], 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.

A. Input

We are given a set of airports A 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* may include scheduled and non-scheduled (military, school, charter flights, hospital helicopters, etc.) airport arrivals and departures.

B. Constraints

Let $mov_{i,j,k}$ be the number of movements handled by RTM i at airport j during period k , $Amov_{j,k}$ the total number of movements at airport j during period k , R the set of RTMs, and P the set of time periods. We introduce a binary variable $period_{i,j,k}$, which equals 1 if airport j is assigned to RTM i during period k , and 0 otherwise; and a binary variable $op_{j,k}$, which equals 1 if airport j is open during period k , and 0 otherwise. If $mMov$ is the maximum number of movements per RTM per period and mA the maximum number of airports per RTM, then the restrictions on the number of airports and the total number of movements which can be assigned to one module per time period, 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 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:

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

Minimizing the number of modules in use we are targeting lower costs for equipment, maintenance and human resources.

2. Balance Workload between Modules

The scheduling may need to target equal workload distribution between the modules in order to equalize controllers shifts. The goal is to guarantee an as fair as possible distribution of the total amount of work between the controllers, which facilitates ATCO interchangeability and, additionally, will foster employee satisfaction. We introduce variables $d_{l,m,k}$ as the difference in assigned flight movements, i.e. workload, between the modules l and m during period k . Here, we use only flight movements as an approximate measure for controller workload, which provides an indication of the relative demands for controllers, but does ignore the other factors that determine the mental workload for a controller.

Obviously, we are only interested in the absolute value of $d_{l,m,k}$, thus, we introduce the following two inequalities that assign this absolute value to the variable:

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

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

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

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

3. Minimize Assignment Switches

Our model allows schedules in which airport-to-module assignments can switch every time period. Such switches result in frequent changes in the controllers' working environment, which induce handovers and additional workload. Whenever controllers switch from one airport to another, the transfer of responsibility requires a formal handover procedure to ensure that the incoming controller is aware of all necessary information: the location and intentions of all aircraft receiving a service, the local weather conditions, unusual deviations from normal procedures, temporary airspace restrictions, and any other information deemed necessary for safe operations. This prevents controllers from switching tasks instantaneously and places additional pressure onto the staff supervisor's 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 two 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.

Airport 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) - Small 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.

(a) *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.

(b) *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. The assumption places an 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. This limitation is quite conservative and made preliminary. Further studies will address the realistic limitations on the controller workload.

(c) *Potential conflicts:* We aim to detect and avoid potential conflict situations. Here, we consider a *conflict* as more than 3 movements that are scheduled during a 5-minute period in a single module. This definition of the conflict is preliminary and subject to further discussions with operational specialists.

(d) *Zero handover time:* The model does not take into account the time required for actual switching between the assignments. We plan to account for handover time in future work.

(e) *Only scheduled traffic:* In this model we assume there are no other movements but scheduled arrivals and departures at the airports in consideration. The influence of non-scheduled flights and special traffic is analyzed in Section III.G.

(f) *Single-manned RTM:* We study work of a single controller in the RTM and do not consider other events that may take away attention/capacity of the ATCO.

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 assign 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 (scheduled flights only) 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 [16] 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 number of traffic movements at the five input airports. For that purpose 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. Here we disregard the constraint (1), apply the first optimization objective (7), feed the flight data collected during the busiest day in September 2016 into the model, and solve the problem. The resulting assignment 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 shows how much traffic (in the number of movements) is assigned to each of the two modules per hour, which clearly illustrates how the workload is distributed between the two modules.

Airports\Hours	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	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.

We conclude that two modules are sufficient to manage all the traffic at the given five airports for the considered day. Figure 2 visualizes module occupancy per hour and helps to identify the quiet and rush hours at the RTC. During quiet hours one module is sufficient to handle all the movements, and 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). Even 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 a single RTM. For that

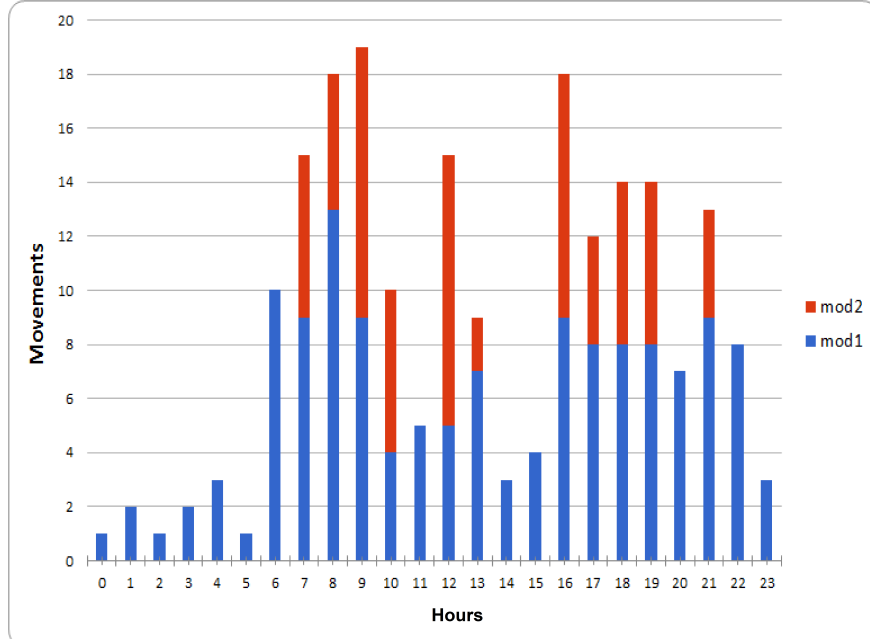


Fig. 2 Workload distribution between two active RTMs (Schema 1). Blue and red correspond to module 1 and 2, respectively.

we enforce the constraint (1), setting the value of $mMov$ to 2, and again apply the first optimization objective (7) to the model. The resulting assignment of airports to modules is shown in Figure 3 as Schema 2 and illustrated in Figure 4.

Airports\Hours	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.

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 four movements (one at AP1 and three at AP2) are assigned to module 1 and six movements (three at AP4 and three 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

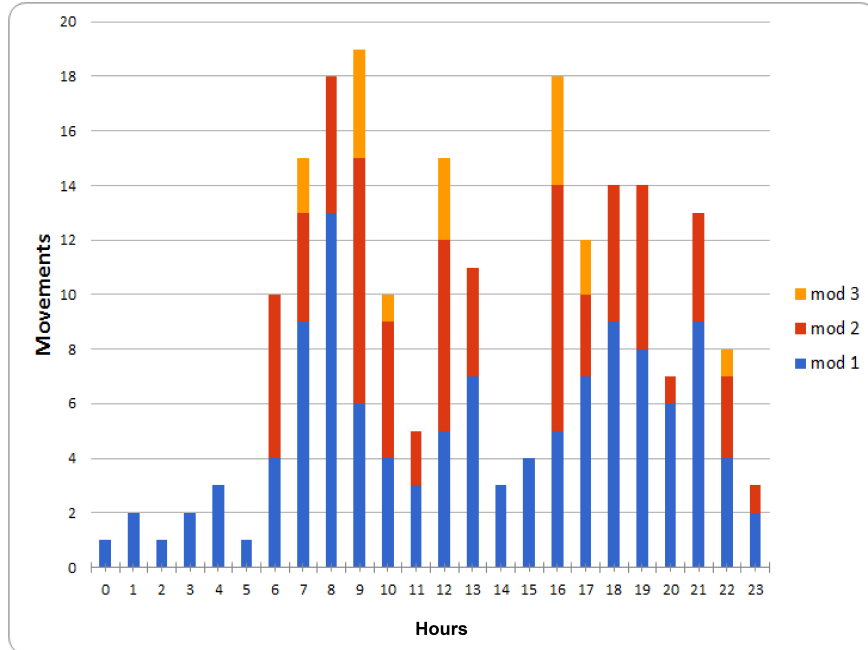


Fig. 4 Workload distribution between three active RTMs (Schema 2). Blue, red, and yellow correspond to module 1, 2, and 3, respectively.

a period only two airports have movements: one with nine and one with three movements. 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 a post-processing stage (here we implement it within the model).

Using objective function (10) with the basic model and the additional constraints (Equations (8) and (9)) 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 achieved at the expense of an increased number of modules

Airports\Hours	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	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.

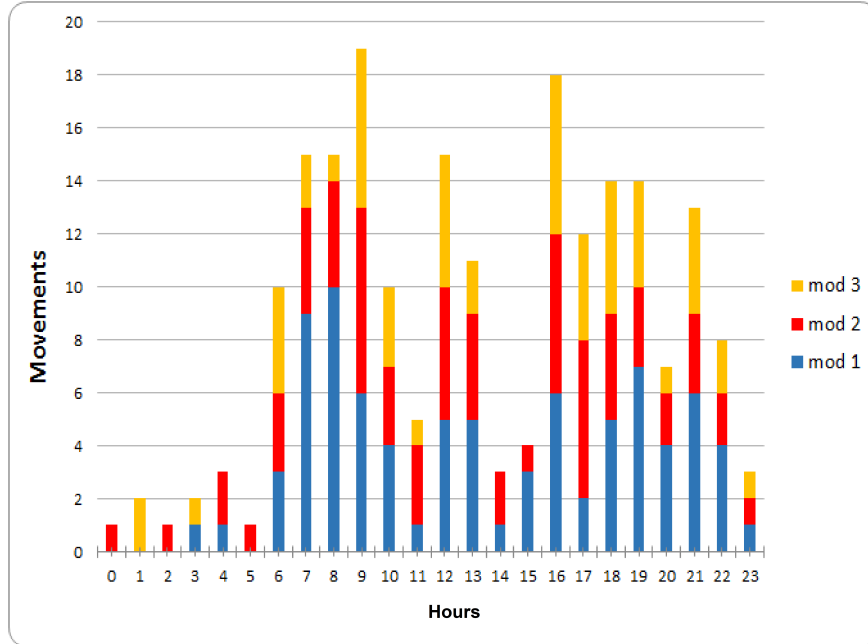


Fig. 6 Workload distribution between three active modules with optimal balance (Schema 3). Blue, red, and yellow correspond to module 1, 2, and 3, respectively.

in use (e.g., during hours 2, 3, and 4 two modules are in use in Schema 3 instead of a single module in Schema 2). This example demonstrates a clear trade-off between the two objectives. Which objective will be given a priority is a subject of discussions with operational specialists at the RTC. On the one hand, adding a new module requires involvement of more human resources, both controllers and technicians, to serve the equipment, and will increase the operational costs. On the other hand, fair distribution of workload between the controllers, especially during the rush hours, may be of interest for human resource management and professional unions. The final decision is on the final implementers.

In addition, 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. Again, the priorities over the objectives

are to be determined by operational specialists and management. Our optimization framework provides a flexible tool for their decision making. A linear combination of several objectives may be applied to our model in order to produce sub-optimal but operationally valuable solutions. Again, the values of the corresponding weights for the objectives are to be advised by the operational specialists. In particular, if combinations of the objective functions are of operational interest, we suggest to study Pareto-optimal solutions.

F. Post-processing: Avoiding Potential Conflicts

According to the definition given in Section III.B, there is a *conflict* in the schedules when more than 3 simultaneous movements scheduled at a single module occur within a 5-minute period.

First, 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

Airports\Hours	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.

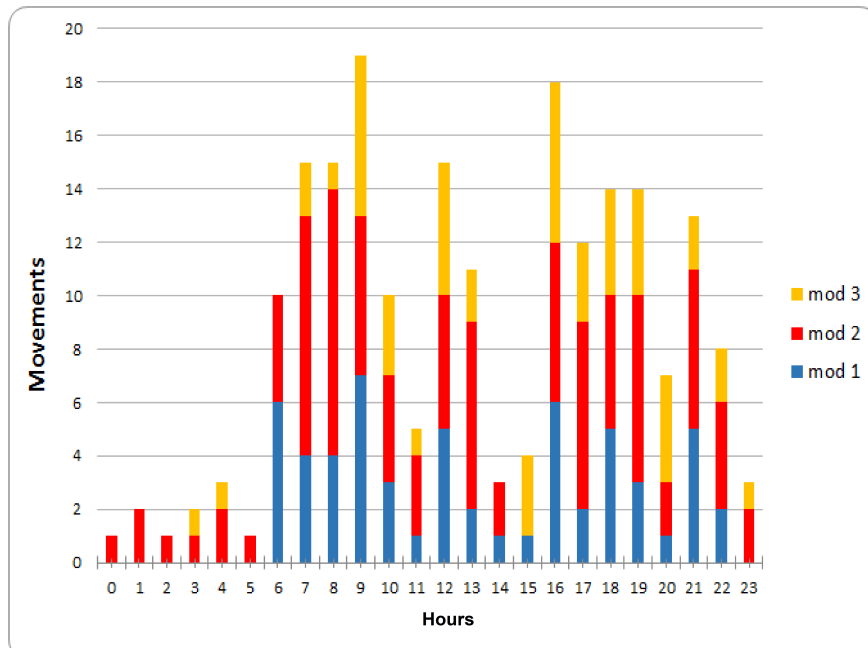


Fig. 8 Workload distribution between three active modules with minimum number of switches (Schema 4). Blue, red, and yellow correspond to module 1, 2, and 3, respectively.

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.

For example, Figure 9 illustrates both a self-conflict at AP2 detected at 21:15 and a conflict between AP2 and AP4 schedules at the same time. In the figure each of the five airports is marked by a different color. For each airport, the first two rows contain airport movements (1 when there is a movement within the five minute interval, 0 otherwise), the third row (filled with darker colors) shows airport opening hours (1 when airport is open, 0, otherwise), and the cells representing the conflict are circled with red. In one of the solutions output by our model (see Figure 10, middle table), AP2 was initially assigned to a separate module (module 2). Thus, in this case we do not need to perform any re-assignment during hour 21. However, re-assignment is clearly needed during hours 8, 9 and 17 (where the corresponding movements at AP2 are highlighted with bold red). For example, during hour 8 a self-conflict was detected at AP2 (Figure 10, top), and according to the assignment output from our model, this airport is scheduled together with AP5, which results in an infeasible assignment during this hour.

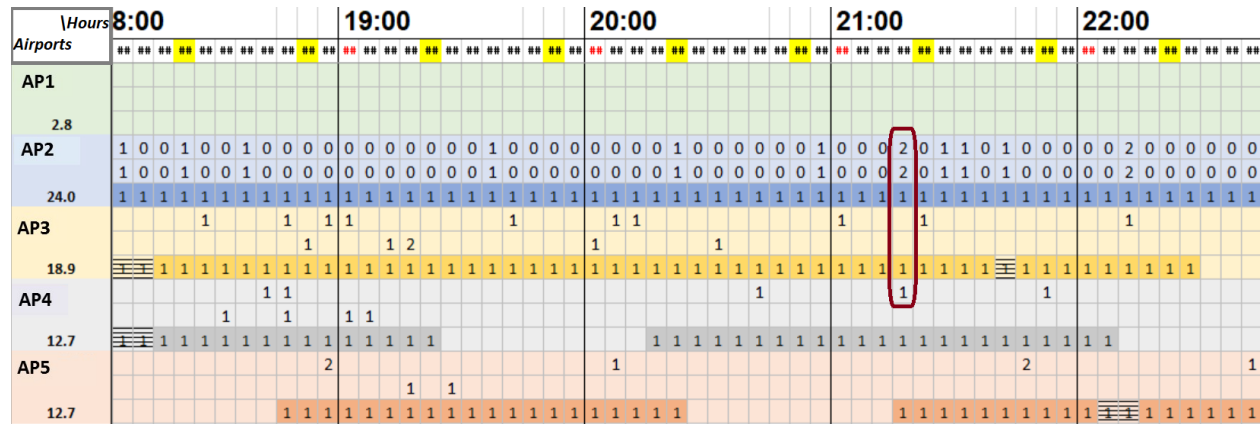


Fig. 9 Detection and avoidance of conflicts in airport schedules.

One way of resolving the conflicts is given in Figure 10, bottom, which was obtained by modifying the schedules slightly during only the conflict hours, making sure that the initial assumptions are preserved. When the resolution of the conflict is not feasible with the number of modules calculated in the output, an additional module has to be introduced during the post processing phase.

Our optimization framework is highly flexible, and can integrate various sets of constraints and airports. We have run a similar model for 29 Swedish airports and 9 remote tower modules [13]. We were able to handle this in reasonable computational time. The conflict avoidance may be incorporated into the model by treating the conflicts as hard constraints. We have opted for post-processing of the conflicts, as forbidding conflicting airports to be assigned to the same module will likely result in a sharp increase of the number of modules. In fact, in [17] we showed that minor adjustments to the initial flight schedules may provide significant staff savings at an RTC.

Airports\Hours	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
AP2 self									8:10	9:20				13:30				17:20				21:15		
AP2_AP5										9:20														
AP2_AP3																	16:20							
AP2_AP4																						21:15		

Airports\Hours	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	0	0	0	0	0	0	1	0
AP2	0	6	2	0	4	2	1	0	8	4	2	2	2	10	0	4	2	8	6	2	4	10	4	0
AP3	0	3	0	2	2	0	3	5	1	7	3	1	6	1	0	3	5	3	4	5	4	2	1	1
AP4	0	0	0	0	0	0	1	2	4	2	1	1	3	3	2	0	4	1	4	2	1	2	0	0
AP5	0	0	0	0	0	0	3	1	2	4	1	0	4	0	0	2	4	3	2	2	1	2	1	0

Airports\Hours	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	0	0	0	0	0	0	1	0
AP2	0	6	2	0	4	2	1	0	8	4	2	2	2	10	0	4	2	8	6	2	4	10	4	0
AP3	0	3	0	2	2	0	3	5	1	7	3	1	6	1	0	3	5	3	4	5	4	2	1	1
AP4	0	0	0	0	0	0	1	2	4	2	1	1	3	3	2	0	4	1	4	2	1	2	0	0
AP5	0	0	0	0	0	0	3	1	2	4	1	0	4	0	0	2	4	3	2	2	1	2	1	0

Fig. 10 Re-assignment during post-processing for resolving 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 represent the schedule before and after post-processing (bold red font highlights the movements at the airports which were re-assigned to other modules).

G. Analysis and Management of Non-Scheduled Traffic

In this Subsection, we study 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 airport non-scheduled traffic was retrieved from the Chief of Operations of the considered airports. We summarize the number of such extra traffic per day in Table 1.

The data for normal operation in the table represents the average number of special traffic movements during an average day of airport operation, while the worst case numbers account for all possible situations involving special traffic per site (which include even potential control zone crossings).

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 number of additional traffic movements (normal operation)
- (3) With extra large number of additional traffic movements (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.

Table 1 Approximate number of non-scheduled traffic movements at the airports per day in Mode 2 (normal operation) and Mode 3 (worst case)

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

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 number of extra traffic movements (Table 1) evenly among the opening hours of each airport, add it to the scheduled data while 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 (equation 7). The resulting schedule is presented in Figures 11 and 12 right.

Airports\Hours	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	2	3	0	0	0	0	0	4	4	0	0	0	0	0	0	0	0	3	2
AP2	0	6	2	0	4	4	3	2	10	6	4	4	2	10	2	6	4	10	6	3	4	10	4	0
AP3	0	3	0	2	2	0	5	5	3	7	5	3	6	3	0	5	5	5	6	5	6	4	3	3
AP4	0	0	0	0	0	0	3	4	5	4	3	3	3	3	4	0	4	3	4	4	3	2	0	0
AP5	0	0	0	0	0	0	5	3	4	4	3	0	6	0	0	4	4	5	4	4	3	4	2	0

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

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, 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.

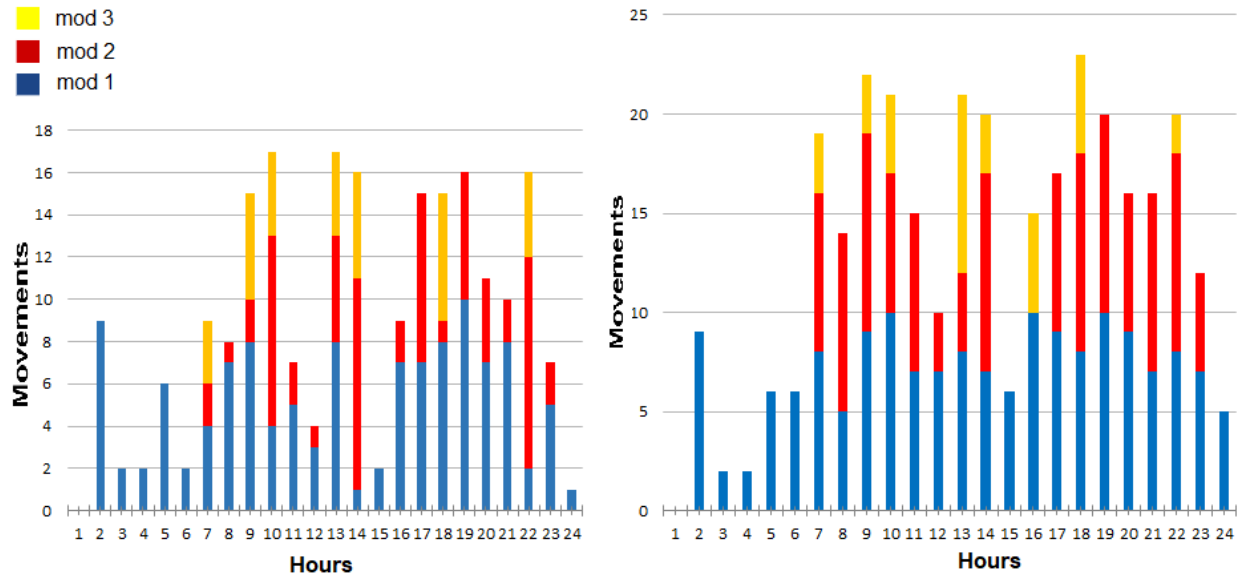


Fig. 12 Workload distribution for scheduled traffic (mode 1) vs. workload with some additional traffic movements (mode 2). Blue, red, and yellow correspond to module 1, 2, and 3, respectively.

3. Mode (3)—Worst-Case Scenario

We repeat the procedure for Mode 2 for the maximum number of special traffic movements (the worst case, Table 1).

In this case, the estimated number of extra traffic movements 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 assumption. The optimal solution is presented in Figures 13 and 14 right.

Airports\Hours	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	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
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
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
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

Fig. 13 Airports-to-RTM assignment for airports with maximum number of extra traffic movements, worst case (mode 3). Blue, red, yellow and green correspond to module 1, 2, 3 and 4, respectively.

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

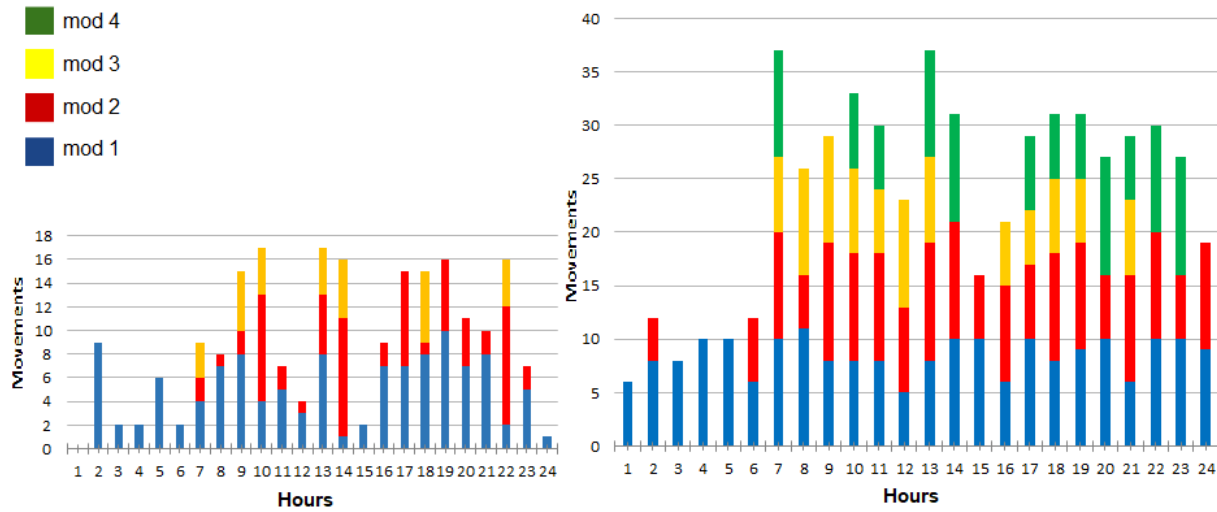


Fig. 14 Workload distribution for scheduled traffic (mode 1) vs. workload with maximum number of extra traffic movements, worst case (mode 3). Blue, red, yellow and green correspond to module 1, 2, 3 and 4, respectively.

efficiency, even in the absolutely worst-case scenario, which is unlikely to occur.

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 unforeseen 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.

In future work, 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.

In Figure 15, we give 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).

The resulting table shows residual capacity for the 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. We again find the 117 movements for AP4 as discussed in Section III.G.3. Similarly, we can evaluate the residual

Airports\Hours	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	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.

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 number of traffic movements per airport are summarized in the second column of Table 2 and compared with the estimated number of special traffic movements 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 number of extra traffic movements. The only outlier is AP4, where the number of military traffic movements may significantly deviate from the normal. We may need to discuss special measures to prevent the respective system from overloading. For example, during the days when military activities are planned, this airport is to be always assigned to a separate RTM in order to provide the service comparable to the one provided by a traditional tower previously operated at this airport. As we learned from the experts, the worst-case operation numbers are significantly overestimated and are subject to further discussions. Accurate predictions of the total expected traffic during the day will help to tune the value for the upper bound on the number of movements manageable within one module. Additionally, experts explained that different types of special traffic require unequal levels of controllers attention, and may result in incomparable workload. An objective assessment of controller workload is crucial in order to produce fair assignment schedules. As the state of the art methods of evaluating tower controller workload can be seen as imprecise or subjective, in future work we plan to design a complete and descriptive quantification method, which will help us to evaluate the total controller load more accurately and produce fairer assignment schemes.

Table 2 Residual capacity of the system vs. extra traffic movements 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

IV. Conclusions

In this work we presented an optimization framework for staff planning at the Remote Tower Center. We formulated the airport-to-module assignment problem as a MIP and implemented several constraints reflecting the requirements of safe operation, as well as three conflicting optimization objectives: minimizing the number of utilized RTMs, balancing the load between the modules, and minimizing assignment switches. We used the AMPL modeling language and CPLEX solver to solve the MIP. We presented the optimal solutions for five Swedish airports considered for remote operation w.r.t. the three objectives, and analyzed the resulting assignments. In addition, we suggested a way to resolve potential conflicts in schedules—both within a single airport and between airports, and analysed how special airport traffic may influence our solutions. We evaluated the residual capacity of the system to calculate its ability to manage unpredictable workload variations.

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