Scheduling Air Traffic Controllers at the Remote Tower Center

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Abstract—Remote Tower Service (RTS) is one of the techno-logical 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" at the Remote Tower Center (RTC), which means that he/she can handle two or more airports from one Remote Tower Module (controller working position).

In this paper, we present an optimization framework designed for automation of staff planning at the RTC. We highlight the problems experienced with real airport flight schedules, and present optimal shift assignments for five Swedish airports that were chosen for remote operation.

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

I. INTRODUCTION

Constructing rosters for air traffic controllers (ATCOs) is a complex problem, which becomes even more challenging in the context of Remote Tower. An effective method to produce real-world rosters requires the ability to model shifts and breaks, distribute the varying workload between several working positions, rotate staff through all the tasks for which they are qualified to maintain several endorsements, fulfill the requirement to train staff whilst continuing normal operations, and re-roster due to unexpected events.

In the civilian air traffic control (ATC) very strict and legally binding regulations outline ATCO's working conditions [8]. These regulations do not take seasonal traffic variations into account [11], resulting in overstaffing during lower-traffic months and staff shortages during peaks. Maximizing the efficiency of human resources (HR) is of particular importance because labour accounts for up to 85% of air traffic service (ATS) costs [25].

Remote Towers Services are one of several technological and operational solutions that the SESAR Joint Undertaking delivers to the ATM community for deployment. RTS was proposed as a cure for staff demand imbalances, from which most small airports (30-120 movements a day) suffer. The

RTS concept implementation splits the cost of ATS provision and staff management between several airports. Further, it should be noted that the difference in terms of investment is significant when comparing installation of sensors to the construction of a new tower.

It is extremely challenging to construct even a feasible roster, with so many possible permutations of controllers and their required endorsements at the RTC. Automation of the rostering process would have a positive effect on the flight safety (because all operational constraints–like breaks–would be enforced), and help to keep track of controller qualifications and individual preferences.

In this work, we present a generic optimization framework designed as a flexible tool for future RTC staff planning. In particular, we identified several issues related to staff scheduling when multiple airports are operated from a single center. The main question is: How to automate scheduling of controllers at the RTC?

We feed the model with real flight data samples for five Swedish airports planned for remote operation and output various solutions for staff scheduling at these airports, comparing different possible objectives. Additionally, we show how potential conflicts in airport schedules can be avoided.

The model under development was discussed with operational experts at LFV (Luftfartsverket, the Swedish ANSP) to provide a picture on staffing constraints as close as possible to reality. We demonstrate that RTS increases HR efficiency, thereby providing significant cost savings. The model easily incorporates individual controllers' preferences and airport specifics, and it helps to predict the required number of endorsements per controller, making it a handy support tool for future staff planning. The designed techniques and tools will be applied to other sets of airports being considered for remote operation.

A. Roadmap

In Section I-B we review related work. We present a general mathematical model for assigning controllers to remote airports at RTC in Section II. In Section III we verify the proposed model using real data from the five Swedish airports planned for remote operation; we also compare and discuss the resulting scheduling solutions. Section IV concludes the paper and outlines future work directions.

B. Related work

RTC aims at providing ATS for multiple airports by air traffic controllers located remotely as defined in [19]. Researches studied various aspects of the RTS concept. Möhlenbrink et al. [16] and Papenfuss et al. [22] considered usability aspects within the novel remote control environment. Wittbrodt et al. [26] stress the role of radio communication in the context of a remote airport traffic control center. In a safety assessment of the Remotely Operated Tower (ROT) concept, Meyer et al. [15] suggest functional hazard analyses and pinpoint the issue of getting reliable probability values for the models. Oehme and Schulz-Rueckert [20] propose a sensor-based solution for aerodrome control that removes the dependency on visibility conditions and tower location. In [10], [18], [17], [14] and [21] 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 RTC 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 [9] and references therein. Assigning airport traffic to Remote Tower Modules (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.

The effective rostering of Air Traffic Controllers is a complex and under-researched area of the personnel scheduling literature. ATC rostering inherits some features from the related staff scheduling problems, such as e.g. nurse scheduling [4], university course timetabling [5], multi-skilled staff planning [12].

ATCO rostering differs from the related scheduling problems, as schedule requirements are much stricter. Only few attempts to solve the ATCO scheduling problem are described in the literature. An overview of early works on ATC shift scheduling is presented in [3], which in addition presents the European regulations and policies connected to ATCO work organization.

The methods for effective staff rostering vary significantly. The survey [6] covers Linear Programming, Tabu Search, Simulated Annealing, Constraint Programming, Case-Based Reasoning, and some more.

Stojadinović [24] proposed to solve the ATC shift scheduling by using various exact methods: CSP, SAT, Partial MaxSAT, SMT, ILP and PB. The results indicate that SAT-related approaches outperform other methods for the problem described.

Conniss et al. [7] proposed an effective greedy heuristics to solve the ATCO scheduling problem. Their problem description is close to the one we formulate in our current work, but naturally lacks constraints related to the Remote Tower Operation. Our solution will be based on a MILP (mixed-integer linear program).

II. REMOTE TOWER AIR TRAFFIC CONTROLLER SHIFT SCHEDULING PROBLEM

We create a single-day roster which assigns a qualified controller to each position at the RTC, respecting constraints on the duration of controllers' shifts and breaks, and the necessity to hold the corresponding endorsements.

The input to our problem is a one-day airport flight schedules, and the output is the optimal assignments of controllers to the RTC airports per hour, which takes into account constraints on the operation possibilities.

We formulate our problem as a MILP, which in general is NP-hard to solve. However, smaller instances of the problem can be solved using commercial off-the-shelf optimization software, as we demonstrate in Section III. Our MILP is based on the strong formulation for min/max on/off sequences as presented by Pochet and Wolsey [23] (cp. Lidén et al. [13]).

A. Input

We are given a set of airports with their opening hours and the scheduled arriving and departing flights. We quantify the total traffic by the number of *movements* (both arriving and departing flights) which occur during a certain time period.

B. Constraints

Table I summarizes the notation used in this section.

We integrate the following safety and efficiency requirements for RTC personnel operation as constraints to our model:

(a) Maximum number of airports assigned to one controller
(b) Maximum number of movements per controller
(c) Maximum number of controllers per airport
(d) Potential conflicts in schedules are to be avoided
(e) Upper and lower bound on controller shift length
(f) Maximum total time "in position" (i.e. the time when an ATCO is assigned to control some airport)
(g) Maximum continuous time "in position" without break
(h) Endorsements (ATCOs are assigned only to those airports, for which they hold endorsements. Special qualifications are needed, which differ from airport to airport and each controller has to undergo the corresponding training in order to obtain the endorsement for each specific airport.)

TABLE I
NOTATION

Notation	Parameter	Notation	Variable
A	set of airports	q_i	binary, $= 1$ if controller i is used during some period
A^+	set of airports for breaks	$y_{i,k}$	binary, $= 1$ if controller i is at work during period k
C	set of controllers	$v_{i,k}$	binary, $= 1$ if controller i starts his shift at period k
P	set of time periods	$period_{i,j,k}$	binary, $= 1$ if controller i is assigned to airport j during period k
p	number of time periods	$mov_{i,j,k}$	number of movs handled by controller i at airport j during period k
z	max number of consecutive periods controller is in position	$active_{i,j}$	binary, $= 1$ if controller i is assigned to airport j
$mMov$	max number of movs per controller per period	$W_{i,k}$	number of consecutive periods including k controller i is at work
mA	max number of airports per controller per period	$s_{i,j,k}$	binary, $= 0$ if $period_{i,j,k} = period_{i,j,k+1}$
mCA	max number of controllers per airport per period		
$Amov_{j,k}$	number of movs at airport j during period k		
$op_{j,k}$	$= 1$ if airport j is open during period k, $= 0$ otherwise		
$l_{i,j}$	$= 1$ if controller i holds endorsement to control airport j		
HA	set of airports which have conflicts in schedules		
$H_{j,jj}$	set of periods when airport j has conflicts with airport jj		
DUB	upper bound on number of periods controller is in position		
DLB	lower bound on number of periods controller is in position		
TUB	upper bound on the length of controller shift		
TLB	lower bound on the length of controller shift		

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

$$\sum_{j \in A \cup A^+} period_{i,j,k} \leq y_{i,k} \cdot mA \qquad \forall i \in C, \forall k \in P \qquad (2)$$

$$mov_{i,j,k} \leq period_{i,j,k} \cdot mMov \qquad \forall i \in C, \forall j \in A, \forall k \in P \qquad (3)$$

$$\sum_{i \in C} mov_{i,j,k} = Amov_{j,k} \qquad \forall j \in A, \forall k \in P \qquad (4)$$

$$\sum_{i \in C} period_{i,j,k} \geq op_{j,k} \qquad \forall j \in A, \forall k \in P \qquad (5)$$

$$\sum_{i \in C} period_{i,j,k} \leq mCA \qquad \forall j \in A, \forall k \in P \qquad (6)$$

$$period_{i,j,k} + period_{i,jj,k} \leq 1 \qquad \forall i \in C, \forall j, jj \in HA, \forall k \in H_{j,jj} : j \neq jj \qquad (7)$$

$$\sum_{k \in P} period_{i,j,k} = 0 \qquad \forall i \in C, \forall j \in A \cup A^+ : l_{i,j} = 0 \qquad (8)$$

$$v_{i,k} \geq y_{i,k} - y_{i,(k-1)\,(\mathrm{mod}\,p)} \qquad \forall i \in C, \forall k \in P \qquad (9)$$

$$v_{i,k} \leq y_{i,k} \qquad \forall i \in C, \forall k \in P \qquad (10)$$

$$\sum_{kk=k+1-TLB}^{k} v_{i,kk\,(\mathrm{mod}\,p)} \leq y_{i,k} \qquad \forall i \in C, \forall k \in P \qquad (11)$$

$$\sum_{kk=k+1-TUB}^{k} v_{i,kk\,(\mathrm{mod}\,p)} \geq y_{i,k} \qquad \forall i \in C, \forall k \in P \qquad (12)$$

$$\sum_{k \in P} v_{i,k} \leq q_i \qquad \forall i \in C \qquad (13)$$

$$\sum_{k \in P} (y_{i,k} - period_{i,j,k}) \leq DUB \qquad \forall i \in C, j \in A^+ : l_{i,j} = 1 \qquad (14)$$

$$\sum_{k \in P} (y_{i,k} - period_{i,j,k}) \geq DLB \qquad \forall i \in C, j \in A^+ : l_{i,j} = 1 \qquad (15)$$

$$period_{i,j,k} + period_{i,jj,k} \leq 1 \qquad \forall i \in C, \forall j \in A, \forall jj \in A^+, \forall k \in P : l_{i,j} = l_{i,jj} = 1 \qquad (16)$$

$$y_{i,k} \leq \sum_{\substack{j \in A: \\ l_{i,j}=1}} period_{i,j,k} + \sum_{\substack{jj \in A^+: \\ l_{i,jj}=1}} period_{i,jj,k} \qquad \forall i \in C, \forall k \in P \qquad (17)$$

$$W_{i,k} = \sum_{kk=k}^{k+z-1} \left(y_{i,kk\,(\mathrm{mod}\,p)} - period_{i,j,kk\,(\mathrm{mod}\,p)} \right) \quad \forall i \in C, \forall j \in A^+ : l_{i,j}=1, \forall k \in P \qquad (18)$$

$$period_{i,j,(k+z)\,(\mathrm{mod}\,p)} \geq (1/z) \cdot W_{i,k} - (z-1)/z \qquad \forall i \in C, \forall j \in A^+ : l_{i,j}=1, \forall k \in P \qquad (19)$$

Equations (1), (2) and (3) represent the restrictions on the total number of movements and the number of airports per controller per time period, respectively. Constraints (4) and (5) guarantee that all scheduled traffic is handled and all opening hours at all airports are covered. One or two controllers can be assigned to manage an airport for a given period, which is assured by equation (6). Constraint (7) makes sure that potential conflicts in airport schedules are avoided. Constraint (8) guarantees that only qualified controllers are assigned to the corresponding airports. The remaining constraints implement the operational controller shift requirements[1] (i.e., a maximum total time at work, bounds on the time "in position", and a maximum continuous time without break).

In some constraints indices are computed modulo p: instead of considering the current day as a single unit, we create a loop, such that the periods in the end of the day connect to the periods in the beginning of the day.

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 controllers at the RTC: To guarantee that the remote tower center facilities are used with maximum efficiency, we may aim to assign the minimum number of controllers to control the given airports. This yields a lower bound on the number of controllers at the RTC that are sufficient to manage the total airport traffic. To minimize the number of controllers we use the following objective function:

$$\min \sum_{i \in C} q_i \qquad (20)$$

2) Minimize the average number of controllers per airport: Before a controller obtains the endorsement that qualifies him to be assigned to a specific airport, he needs to pass a long

training. We may aim to minimize the average number of controllers per airport, which at the same time minimizes the number of endorsements that controllers need to be trained for. The corresponding objective is:

$$\min \sum_{i \in C} \sum_{j \in A} active_{i,j} \qquad (21)$$

Variable $active_{i,j}$ equals 1 when controller i is ever assigned to airport j, and is 0 otherwise. The following additional constraint guarantees proper assignment of the corresponding values to that variable:

$$active_{i,j} \geq \frac{1}{p} \sum_{k \in P} period_{i,j,k} \; \forall i \in C, \forall j \in A, \forall k \in P \quad (22)$$

3) Minimize assignment switches: Our model allows schedules where controller-to-airport assignments can switch every time period. Such switches result in frequent changes in the controllers' working environment, and lead to 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.

We define the binary variable $s_{i,j,k}$ and add the following constraints $\forall i \in C, \forall j \in A, \forall k \in P$:

$$s_{i,j,k} \geq period_{i,j,k+1\,(\mathrm{mod}\,p)} - period_{i,j,k} \qquad (23)$$
$$s_{i,j,k} \geq period_{i,j,k} - period_{i,j,k+1\,(\mathrm{mod}\,p)} \qquad (24)$$

The corresponding objective function is:

$$\min \sum_{i \in C} \sum_{j \in A} \sum_{k \in P} s_{i,j,k} \qquad (25)$$

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[1] We add one artificial "break" airport per controller to our formulation: the set A^+. Using the on/off sequences presented by Pochet and Wolsey [23] we consider the breaks as part of the working day, and controllers are assigned to airports in A^+ during their breaks. No opening hours at these airports need to be covered, for each of the airports in A^+ exactly one controller holds an endorsement, and after z continuous hours of work at "real" airports, the ATCO must be assigned to an airport in A^+.

	1	2	3	4	5	6	7	8	9	10	11	12	2016
AP1	281	310	313	233	240	204	240	304	237	259	288	282	3302
AP2	2284	2348	2433	2518	2767	2469	2148	2435	2776	2793	2468	2189	30626
AP3	1398	1524	1581	1621	1682	1465	1011	1387	1832	1892	1785	1667	19485
AP4	658	702	775	870	992	988	1671	1014	1008	955	826	735	11557
AP5	702	841	874	758	729	646	419	612	790	762	743	716	8882
RTC	5323	5725	5976	6000	6410	5772	5489	5752	6643	6661	6110	5589	73852

Fig. 1. Scheduled airport traffic statistics per month for the year 2016. Green cells highlight the total RTC traffic during the months with low traffic, while the red cells – the high traffic months.
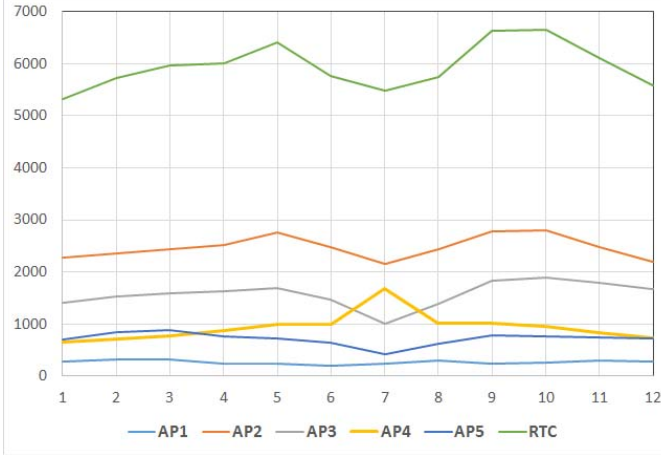

Fig. 2. Scheduled traffic statistics for the year 2016.

Conflict count	AP1	AP2	AP3	AP4	AP5
AP1		1058	621	366	339
AP2	1058		6473	3400	3021
AP3	621	6473		2603	2517
AP4	366	3400	2603		1449
AP5	339	3021	2517	1449	

Fig. 3. The number of potential conflicts in schedules for each airport pair during the year 2016.

Conflict days	AP1	AP2	AP3	AP4	AP5
AP1		341	316	278	285
AP2	341		366	363	365
AP3	316	366		362	362
AP4	278	363	362		359
AP5	285	365	362	359	

Fig. 4. The number of days when potential conflicts in schedules occur.

III. EXPERIMENTAL STUDY

In this section, we present and analyze the resulting controller shift schedules for different input parameters and the objectives introduced in Section II-C.

A. Data

The general properties of the five Swedish airports in consideration 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 (usually open 24/7, with exceptions).
- *Airport 3* (AP3). Small regional airport with regular scheduled flights (usually open 24/7, with exceptions).
- *Airport 4* (AP4). Small airport with significant seasonal variations.
- *Airport 5* (AP5). Small airport with low scheduled traffic, non-regular helicopter flights.

We analyzed traffic data at these airports for the whole year of 2016. The major input are aircraft movements at each airport, which we received from the Demand Data Repository (DDR) hosted by EUROCONTROL.

1) Seasonal variations in traffic intensity: Figure 1 shows the scheduled traffic given by the number of movements at the five airports for each month of the year 2016, and summarizes the total amount of traffic to be controlled from the RTC. Figure 2 illustrates the seasonal variations of the traffic for the five airports and their cumulative flight traffic at the RTC (shown in green). The difference between the maximum and the minimum cumulative traffic during the year is significantly smaller at the RTC (20%) than the 50-60% at individual small airports. Note that larger seasonal traffic variations result in a larger mismatch between demand and supply for controllers.

Additionally, we noticed that for several airports the traffic patterns are in fact complementary (e.g., AP4 and AP5), which makes these pairs potential candidates for multiple operation in one Remote Tower Module.

The cumulative high seasons (the periods with high traffic intensity, highlighted in red in Figure 1) are May and October; the cumulative low seasons (the periods with low traffic intensity, highlighted in green in Figure 1) are January and July. For our initial model validation we choose the busiest day of October (October 19, we refer to it as the day with highest traffic) and the day with the lowest traffic in July (July 23rd). Using these extreme data samples we demonstrate how the outcomes of the model depend on the cumulative traffic intensity.

2) Potential conflicts in schedules: To detect potential conflicts, we merged airport data schedules in pairs. We define a *conflict* as two movements at two different airports that are scheduled within a 5-minute period. Figure 3 shows the number of conflicts in the schedules for all airport pairs for the year 2016, while Figure 4 illustrates the number of days during which these conflicts occur.

We can observe that the number of conflicts is very high, and they occur almost every day for most airport pairs. We should take into account these conflicts when we pair airports to be controlled simultaneously within one module. Later in this section we discuss how we solve the assignment problem avoiding the potential conflicts in airport flight schedules.

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 assigned to one controller*: The default value of the maximum number of airports assigned to a controller is set to 2. From the experts we learned that there may be problems with visual representation, communication, and switching between the views when more than two airports are controlled by the same person within one remote tower module. But theoretically it is possible to control even more airports from one module.

(b) *Maximum number of movements per controller*: The maximum number of movements one controller handles at the remote tower during one hour is set to 10. This conservative assumption represents a manageable workload for the ATCO.

(c) *Maximum number of controllers per airport*: In this work we assume each airport is handled by one ATCO during each period of time. But in principle, for safety reasons it may be needed to assign two controllers to control one airport. Our model provides such a possibility.

(d) *Potential conflicts*: We have identified multiple potential conflicts for all airport pairs. Recall that we defined a *conflict* as two movements at two different airports that are scheduled within a 5-minute period, and place a limitation, which prevents the two airports from being assigned to the same controller during the whole hour during which the potential conflict was detected.

(e) *Length of controller shift*: The total time a controller spends at work should be between 4 and 10 hours.

(f) *Time "in position"*: The time when controller is assigned to control an airport, is denoted as time "in position". It should not exceed 8 hours per day. For one of the experiments we reduced this number to 6. We do not consider bounds on the minimum time "in position", but we plan to add such constraints later into weekly rosters. A minimum number of hours at a specific airport reflects the requirement for maintaining ratings (i.e., familiarity with each particular airport the controller holds endorsement for).

(g) *Maximum continuous time without break*: Controllers should not work "in position" for longer than 4 hours without break. In one of the experiments we reduced this value to 3.

(h) *Endorsements*: ATCOs are assigned only to those airports for which they hold endorsements.

(i) *Period*: The length of the time period is one hour.

C. Metrics

To enable comparison between the output schedules we introduce the following metrics:

- *Total number of ATCOs*: measures the total number of controllers assigned during the day in order to handle all the traffic at RTC.
- *Average number of ATCOs per airport*: we count the number of controllers assigned to each particular airport during the day and calculate the average over the given number of airports.
- *Average time at work*: we count the total time controllers spend at work (including breaks) and take the average over the number of controllers.
- *Average time "in position"*: for each controller we count the time each controller works "in position" and calculate the average over the number of controllers.
- *Average number of endorsements per ATCO*: for each controller we count the number of airports he/she is assigned to during the day and calculate the average over the number of controllers.
- *Coefficient of performance (COP)*: for each controller we calculate the ratio of the time "in position" over the total time at work, and take the average over the number of controllers. This metric may be interpreted as an indicator of the controller's work intensity, and at the same time represents the quality of the resulting controller shift, as it shows the percentage of the time a controller is actually "in position" during his shift.

D. Results

In the remainder of this section, we present optimal controller shift assignments for the five airports at the RTC.

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

1) Minimizing the total number of controllers at RTC: First, we estimate the theoretical lower bound on the number of controllers necessary to handle the total amount of traffic at the five input airports during the day with the minimum number of movements (the day with the lowest traffic in 2016, July 23). Figure 5 shows the assignment of controllers to remote airports per hour with the number of movements in the table cells. We use five different colors to represent different controllers working at the RTC during the day. These colors are also used in the chart in Figure 6, which illustrates the actual controller shifts; the table below the chart gives the corresponding statistics for Schema 1.

Each controller is monitoring one or two airports during his shift with at most 10 total movements per hour. Sometimes the controllers are assigned to airports where 0 movements are scheduled for the given period, which reflects the requirement to cover all airport open hours.

Next, we estimate the theoretical lower bound on the number of controllers for the day with the maximum number of movements (the day with highest traffic in 2016, October 19). Figure 7 shows the output assignment (Schema 2) for that day. Figure 8 illustrates the actual controller shifts and the corresponding statistics for Schema 2.

Obviously, the resulting assignments are not optimal w.r.t. training costs. The schemas have unreasonably high values for

23-Jul-16	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	0	1	1	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0
AP2	0	0	1	1	3	3	3	1	2	5	5	2	2	4	5	2	1	3	3	1	2	4	2	0
AP3	0	0	0	0	0	0	3	0	0	1	2	1	1	0	0	0	1	0	0	0	0	0	0	0
AP4	0	0	0	0	0	0	4	3	3	3	3	1	4	1	0	4	3	0	0	1	0	0	0	0
AP5	0	0	0	0	0	0	1	0	2	1	2	2	2	0	0	0	0	0	0	0	0	0	0	0

Fig. 5. Controllers-to-airports assignment for the minimum total number of controllers (objective 1) during the day with lowest traffic (Schema 1). The table entries give the number of movements per airport. Different colors represent different controllers.

19-Oct-16	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	2	0	0	2	1	0	0	2	0	0	0	0	0	0	0	0	1	0	0	0
AP2	1	1	2	3	4	9	10	7	5	3	2	5	7	4	5	10	8	7	6	8	8	2	0	2
AP3	1	0	2	1	6	5	2	6	4	3	5	4	2	5	6	4	6	8	6	4	3	1	2	2
AP4	0	0	0	0	2	3	3	3	2	1	2	3	2	2	2	4	3	3	0	2	0	0	0	0
AP5	0	0	0	0	3	2	0	4	3	1	2	1	0	2	4	3	2	2	1	2	0	1	0	0

Fig. 7. Controllers-to-airports assignment for the minimum total number of controllers (objective 1) during the day with highest traffic (Schema 2).The table entries give the number of movements per airport. Different colors represent different controllers.

Total #. of ATCOs	Av. # of ATCOs per airport	Av. # endorsements per ATCO	Av. time in position	Av. time at work	COP
5	4	4	7	9.4	0.74

Fig. 6. Top: Controllers shifts (for Schema 1) for each of the five controllers assigned to work at the RTC during the lowest traffic day. The rectangular boundaries indicate the complete shift, while the colored cells indicate the hours "in position" for each controller. Bottom: Statistics for Schema 1.

Total #. of ATCOs	Av. # of ATCOs per airport	Av. # endorsements per ATCO	Av. time in position	Av. time at work	COP
8	7.2	4.5	7.88	9.88	0.8

Fig. 8. Top: Controller shifts (for Schema 2) for each of the eight controllers assigned to work at the RTC during the highest traffic day. The rectangular boundaries indicate the complete shift, while the colored cells indicate the hours "in position" for each controller. Bottom: Statistics for Schema 2.

the average number of controllers per airport (4 for Schema 1 and 7.2 for Schema 2), and the corresponding average number of endorsements per controller (4 for Schema 1 and 4.5 for Schema 2). Next we show how to reduce these values while keeping the same (minimum) number of controllers.

2) Minimizing the average number of controllers per airport: Based on the lower bound on the total number of controllers, we aim to optimize the average number of controllers per airport for the given day. We fix the number of available controllers at the lower bound, and apply the second objective (Equation (21)) with the same set of constraints. Figures 9 and 11 illustrate the controllers-to-airport assignments for the day with the lowest traffic and the highest traffic, respectively. Figure 10 and Figure 12 show the actual controller shifts and the corresponding statistics for July 23 and October 19, respectively.

3) Minimizing assignment switches: When we consider the schedules obtained so far, we observe many switches. For example, in Schema 3 (Figure 9) controller 5 (orange) is assigned to AP2 during period 9, followed by controller 3 (yellow) assigned to AP2 during periods 10 and 11, and controller 2 (green) assigned to AP2 during hour 12, and by controller 4 (light blue) assigned to AP2 during period 13. Such frequent switches should be avoided as they may cause safety issues during handovers with overlaid traffic complications as discussed in Section II-C3.

Using objective function 3 (Equation (25)) with the corresponding additional constraints (23) and (24), we obtain a solution with minimum number of switches as illustrated in Figures 13 and 14 (Schema 5) for the day with the highest traffic (we no longer restrict the number of available controllers to be at the lower bound, and no longer minimize the average number of controllers per airport).

In Schema 5 each controller is assigned to the same airport(s) for several consecutive time periods. According to constraint (19) controllers can not stay "in position" for longer than z consecutive hours. Indeed, in the current setup, after at most four consecutive hours "in position" each controller takes a scheduled break.

For example, in Schema 5 (Figure 13) controller 1 (red) is assigned to AP2 for three consecutive hours (from 2 to 4), and in addition he is monitoring AP1 from 3 to 4. After he has worked for three hours, he is taking a break during hour 5. Controller 5 (orange) takes his position at AP2 in hour 5, while AP1 is temporarily closed during that hour. After controller 1's break, he cannot get back to his position at AP2, as this would result in an assignment switch for controller 5. Thus, controller 5 keeps the position at AP2, while controller 1 is assigned to AP3 for the hours 6-9. Moreover, controller 1 returns to AP1 (also for the hours 6-9). Hence, minimizing the number of assignment switches here enforces controller 1 to be assigned to AP3 in addition to AP1 and AP2, as his return to AP2 would increase the number of switches for some other controller. That is, the objective of few assignment switches increases the number of required endorsements per controller. Indeed, if we compare the statistics for Schema 5 and Schema 4, we observe that—even though the total number of controllers remains the same (eight)—the average number of ATCOs per airport increases noticeably, as does the average number of endorsements per ATCO. Consequently, the schedule of Schema 5 (with objective function (25)) is suboptimal w.r.t. objective function (21), the number of controllers per airport.

This demonstrates a clear trade-off between the two objectives of minimizing the assignment switches (25), and minimizing the number of controllers per airport (21). A

23-Jul-16	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	0	1	1	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0
AP2	0	0	1	1	3	3	3	1	2	5	2	2	4	5	2	1	3	3	1	2	4	2	0	0
AP3	0	0	0	0	0	0	3	0	0	1	2	1	1	0	0	0	1	0	0	0	0	0	0	0
AP4	0	0	0	0	0	0	4	3	3	3	3	1	4	1	0	4	3	0	0	1	0	0	0	0
AP5	0	0	0	0	0	0	1	0	2	1	2	2	2	0	0	0	0	0	0	0	0	0	0	0

Fig. 9. Controllers-to-airports assignment for the minimum average number of controllers per airport (objective 2) during the day with the lowest traffic (Schema 3). The table entries give the number of movements per airport. Different colors represent different controllers.

19-Oct-16	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	2	0	0	2	1	0	0	2	0	0	0	0	0	0	0	0	1	0	0	0
AP2	1	1	2	3	4	9	10	7	5	3	2	5	7	4	5	10	8	7	6	8	8	2	0	0
AP3	1	0	2	1	6	5	2	6	4	3	5	4	2	5	6	4	6	8	6	4	3	1	2	2
AP4	0	0	0	0	2	3	3	3	2	1	2	3	2	2	2	4	3	3	0	2	0	0	0	0
AP5	0	0	0	0	3	2	0	4	3	1	2	1	0	2	4	3	2	1	2	0	1	0	0	

Fig. 11. Controllers-to-airports assignment for the minimum average number of controllers per airport (objective 2) during the day with the highest traffic (Schema 4). The table entries give the number of movements per airport. Different colors represent different controllers.

shifts	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1																								
2																								
3																								
4																								
5																								

Total #. of ATCOs	Av. # of ATCOs per airport	Av. # endorsements per ATCO	Av. time in position	Av. time at work	COP
5	2.4	2.4	6	9.2	0.65

Fig. 10. Top: Controller shifts (for Schema 3) for each of the five controllers assigned to work at the RTC during the day with the lowest traffic. The rectangular boundaries indicate the complete shift, while the colored cells indicate the hours "in position" for each controller. Bottom: Statistics for Schema 3.

shifts	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1																								
2																								
3																								
4																								
5																								
6																								
7																								
8																								

Total #. of ATCOs	Av. # of ATCOs per airport	Av. # endorsements per ATCO	Av. time in position	Av. time at work	COP
8	3.4	2.13	7.5	9.38	0.8

Fig. 12. Top: Controller shifts (for Schema 4) for each of the eight controllers assigned to work at the RTC during the day with the highest traffic. The rectangular boundaries indicate the complete shift, while the colored cells indicate the hours "in position" for each controller. Bottom: Statistics for Schema 4.

smart combination of them should be used in order to achieve reasonable assignments, which is subject of further discussions with operational experts, in particular, about the weighting of the two goals.

4) Alternative set of shift parameters: When we analyzed the different schemes w.r.t. the COP, we observed that its value is high for assignments with a minimum number of switches (e.g., in Schema 5 we have COP= 0.84). This—according to the COP definition—indicates that, on average, controllers are "in position" for 84% of their shift time. Operational experts argue that one should not expect ATCOs to demonstrate such high efficiency; they claim that a reasonable value for the COP lies between 0.4 and 0.7. The exact numbers are not known, and they vary from airport to airport: the controller performance is influenced by the complexity of the airport organization, and the time "in position" without breaks depends on the airport traffic intensity.

A look at our shift parameters with a maximum shift length of 10 hours and a maximum time "in position" of 8 hours indicates that if we would employ all working ATCOs to these limits, we would obtain a COP of 0.8. The even higher value of 0.84 in Schema 5 stems from various controllers working—feasible—9-hour shifts with 8 hours "in position". This suggests that we need to alter the shift parameters in order to obtain an average COP in the range provided by the operational experts. In general, we have two options to adjust the model's parameters: we could either extend the maximal shift length (for example, to 12 hours), or we could reduce the time "in position" (for example, to 6 hours) . Considering the effects of these two options, the former would put more work strain on the ATCOs, while the latter, with every single ATCO contributing fewer hours "in position", would come at the cost of using more controllers. Here, we provide an example of the latter strategy. We choose the following alternative

set of shift parameters: we reduce the upper bound on the time "in position" from 8 to 6, and the upper bound on the continuous time without breaks from 4 to 3. The resulting optimal assignment for the same day of the highest traffic load is presented in Figures 15 and 16.

According to the new assignment schema, two extra controllers are needed in order to compensate for the reduced intensity of the controller shifts with the corresponding COP= 0.67 (< 0.7).

5) Avoiding potential conflicts in airport schedules: In case of a conflict, we place a limitation that prevents the two airports from being assigned to the same controller at the whole hour during which the potential conflict occurs. These hours with conflicts are marked in dark blue in the table cells of Figure 18, top.

The schedule shown in Figure 17, Schema 7, gives an assignment in which airports in conflict are assigned to separate ATCOs. During the conflict hours more controllers are obviously scheduled because the airports with the potential conflicts are to be controlled by separate controllers. For example, according to Schema 6 (Figure 15), during hour 14 two controllers are assigned to the four open airports, while Schema 7 assigns four controllers to the same four airports during for the same hour 14. The resulting statistics (Figure 18, bottom) show a noticeable increase in the lower bound on the total number of controllers (from eight necessary controllers without conflict avoidance (Schema 4) to 10 necessary controllers with conflict avoidance). Moreover, for Schema 8 we have a COP of 0.81. If we want to reduce the controller workload according to the operational experts' suggestion using new shift parameters as discussed above, the number of controllers needed at the RTC would increase

19-Oct-16	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	2	0	0	2	1	0	0	2	0	0	0	0	0	0	0	0	1	0	0	0
AP2	1	1	2	3	4	9	10	7	5	3	2	5	7	4	5	10	8	7	6	8	8	2	0	2
AP3	1	0	2	1	6	5	2	6	4	3	5	4	2	5	6	4	6	8	6	4	3	1	2	2
AP4	0	0	0	0	2	3	3	3	2	1	2	3	2	2	2	4	3	3	0	2	0	0	0	0
AP5	0	0	0	0	3	2	0	4	3	1	2	1	0	2	4	3	2	2	1	2	0	1	0	0

Fig. 13. Controllers-to-airports assignment with the minimum number of switches (objective 3) for the highest traffic day (Schema 5). The table entries give the number of movements per airport. Different colors represent different controllers.

19-Oct-16	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	2	0	0	2	1	0	0	2	0	0	0	0	0	0	0	0	1	0	0	0
AP2	1	1	2	3	4	9	10	7	5	3	2	5	7	4	5	10	8	7	6	8	8	2	0	2
AP3	1	0	2	1	6	5	2	6	4	3	5	4	2	5	6	4	6	8	6	4	3	1	2	2
AP4	0	0	0	0	2	3	3	3	2	1	2	3	2	2	2	4	3	3	0	2	0	0	0	0
AP5	0	0	0	0	3	2	0	4	3	1	2	1	0	2	4	3	2	2	1	2	0	1	0	0

Fig. 15. Controllers-to-airports assignment with minimum number of switches (objective 3) for the highest traffic day (Schema 6). Maximum time without break = 3, maximum time "in position" = 6. The table entries give the number of movements per airport. Different colors represent different controllers.

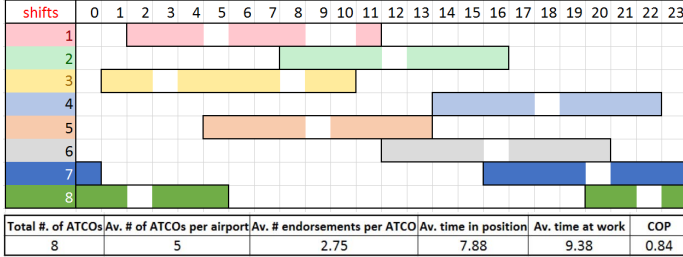| Total #. of ATCOs	Av. # of ATCOs per airport	Av. # endorsements per ATCO	Av. time in position	Av. time at work	COP
8	5	2.75	7.88	9.38	0.84

Fig. 14. Controller shifts (for Schema 5) for each of the eight controllers assigned to work at the RTC during the day with the highest traffic. The rectangular boundaries indicate the complete shift, while the colored cells indicate the hours "in position" for each controller. Bottom: Statistics for Schema 5.

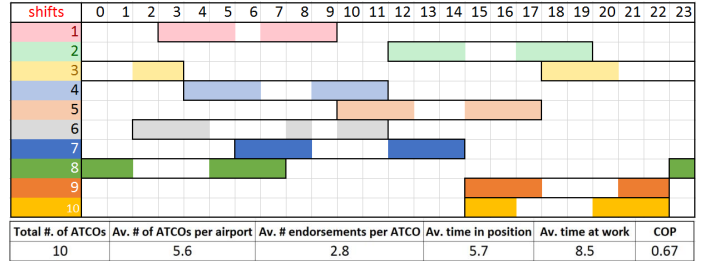| Total #. of ATCOs	Av. # of ATCOs per airport	Av. # endorsements per ATCO	Av. time in position	Av. time at work	COP
10	5.6	2.8	5.7	8.5	0.67

Fig. 16. Controller shifts (for Schema 6) for each of the 10 controllers assigned to work at the RTC during the day with highest traffic. The rectangular boundaries indicate the complete shift, while the colored cells indicate the hours "in position" for each controller. Bottom: Statistics for Schema 6.

further.

One way to circumnavigate the need for more staff at the RTC could be to ask airlines for slight adjustments to their schedules, by which they would contribute to cost savings. While finding an optimal distribution of the slots to 5-minute intervals is hard, local adjustments, that is, moving certain movements to adjacent intervals, may lead to a decreased RTC staff demand.

An important note for this discussion on integrating conflicts is that our definition of a conflict may be too conservative and too precautionary. The discussions with operational experts on this topic will continue.

But it is clear that the potential conflicts can not be disregarded, and will definitely be reflected in the resulting staff planning solutions.

E. Remote Tower Efficiency

The number of controllers required in the staff schedules reflects the seasonal variations in air traffic movements, as outlined in Subsection III-A1. Here, we assess the efficiency of RTCs in terms of their ability to solve this staff imbalance problem.

As a first step, we compare the number of controllers that are necessary to manage the traffic at each of the five airports individually for minimum and maximum traffic. That is, we consider the two days that we focus on in this paper: the day with the lowest and highest traffic volume (July 23 and October 19, respectively). The airports AP2 and AP3 are operated 24/7 all year round, and as a result, the variations in the number of controllers necessary for operation are insignificant (variation of 15-20%). In contrast, for the other three airports (AP1, AP4 and AP5), we observe a noticeable variation in the necessary number of controllers – about 50%. Our experimental results show that at the RTC the difference between the staff demand between July 23 and October 19 is 37.5%. This confirms that the RTC suffers less from staff imbalances, even when we consider only lower bounds.

For operation, staffing does not use the number of controllers that are at least necessary to manage the traffic volume only. A buffer is added to account for weekends, vacation, sick leave, maternity and paternity leave, control of non-regular special traffic (hospital helicopters, schools, charters, military), bad weather conditions, and possible technical problems. Today, the five airports we consider in this paper keep a buffer of about 33-45%. (The computation used in operation sets the lower bound equal to 55-67%, and the number of controllers with buffer is equal to the value of 100% (that is, [number of controllers used = (number of controllers necessary $\cdot 100)/x$, with $55 \leq x \leq 67$]). Significant HR savings can be achieved because the corresponding buffer is shared between the remotely operated airports at RTC.

For example, for the day with the highest traffic volume, October 19, our framework yields 17 controllers as the minimum number of controllers that are needed when the traffic is managed in regular towers individually. Thus, after accounting for the buffer at each airport separately, all airports together need to employ 26-34 controllers. If we add the buffer to the lower bound for the RTC, instead of to the lower bounds for each of the airports separately, the potential savings are significant. Adding the maximum buffer of 45% to the lower bound of 8, our model outputs that 15 controllers should be employed at the RTC at that day. This immediately provides staff savings of 42-55%.

19-Oct-16	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	2	0	0	2	1	0	0	2	0	0	0	0	0	0	0	0	0	1	0	0
AP2	1	1	2	3	4	9	10	7	5	3	2	5	7	4	5	10	8	7	6	8	2	0	2	
AP3	1	0	2	1	6	5	2	6	4	3	5	4	2	5	6	4	6	8	6	4	3	1	2	2
AP4	0	0	0	0	2	3	3	3	2	1	2	3	2	2	2	4	3	0	2	0	0	0	0	0
AP5	0	0	0	0	3	2	0	4	3	1	2	1	0	2	4	3	2	2	1	2	0	1	0	0

Fig. 17. Controllers-to-airports assignment with the minimum average number of controllers per airport (objective 2) and conflict avoidance during the day with the highest traffic (Schema 7). The table entries give the number of movements per airport. Different colors represent different controllers.

Total #. of ATCOs	Av. # of ATCOs per airport	Av. # endorsements per ATCO	Av. time in position	Av. time at work	COP
10	3.4	1.7	7.9	9.8	0.81

Fig. 18. Top: Potential conflicts in airport schedules for each pair of airports for the day with the highest traffic. Table cells colored in dark blue represent the hours during which the corresponding two airports (from the first column) are in conflict, and should not be assigned to the same controller. Bottom: Statistics for Schema 7.

IV. CONCLUSION AND FUTURE WORK

In this work we presented an optimization framework for efficient air traffic controller shift scheduling at the remote tower center. We were able to confirm assumed staff savings with the RTC concept. The proposed solutions are subject to a constant reality check and create a base for further discussions. With our study we identified several issues related to staff scheduling when multiple airports are operated from a single center.

In future studies we aim to incorporate special airport traffic and ground traffic into the definition of controller workload. These traffic types influence the workload different than aircraft movements and significantly depend on the weather conditions. Moreover, we plan to assess the resilience of the scheduling solutions to the variations in the actual time of flight arrivals/departures. The corresponding statistics on the delays and early arrivals are not properly documented, which makes this work quite challenging for automation.

We plan to extend our work towards weekly rosters and include staff buffers to cover vacations and sicknesses. We will also supplement the model with constraints reflecting individual controller preferences and airport specifics, finally transforming it into a handy support tool for future staff planning.

Acknowledgment

REFERENCES

[1] AMPL. Optimization LLC. http://ampl.com/, accessed 2017/05/29.

[2] T. Andersson Granberg, P. Axelsson, J. Petersson, T. Polishchuk, V. Polishchuk, and C. Schmidt. Configuration and Planning of the Remote Tower Modules in a Remote Tower Center. In *ICRAT*, June, 2016.

[3] M. Arnvig, B. Beermann, B. Koper, M. Maziul, U. Mellett, C. Niesing, and J. Vogt. Managing shiftwork in European ATM: Literature review. Eutropean Organisation for the safety of air navigation, 2006.

[4] E. K. Burke, P. De Causmaecker, G. V. Berghe, and H. Van Landeghem. The state of the art of nurse rostering. *J. of Scheduling*, 7(6):441–499, Nov. 2004.

[5] M. Chiarandini, M. Birattari, K. Socha, and O. Rossi-Doria. An effective hybrid algorithm for university course timetabling. *J. of Scheduling*, 9(5):403–432, 2006.

[6] R. Conniss. A survey on constructing rosters for air traffic controllers. In *INCoS 2015, Taipei, Taiwan, Sept. 2-4, 2015*, pages 467–471, 2015.

[7] R. Conniss, T. Curtis, and S. Petrovic. Scheduling air traffic controllers. In *PATAT*, 2014.

[8] L. Delgado, A. Cook, and S. Christobal. Controller time and delay costs - a trade-off analysis. In *Fifth SESAR Innovation Days*, 2015.

[9] P. Flener and J. Pearson. Automatic airspace sectorisation: A survey. *CoRR*, abs/1311.0653, 2013.

[10] M. Friedrich, S. Pichelmann, A. Papenfuss, and J. Jakobi. The evaluation of remote tower visual assistance system in preparation of two design concepts. In *HCI International 2017, Vancouver, Canada.*, 2017.

[11] A. Grebensek and T. Magister. Effect of seasonal traffic variability on the performance of air navigation service providers. *Journal of Air Transport Management*, 25:22–25, December 2012.

[12] H. Li and K. Womer. Scheduling Projects with Multi-skilled Personnel by a Hybrid MILP/CP Benders Decomposition Algorithm. *J. of Scheduling*, 12(3):281–298, June 2009.

[13] T. Lidén, H. Waterer, and T. Kalinowski. Resource considerations for integrated planning of railway traffic and maintenance windows. In *RailLille2017 - 7th International Conference on Railway Operations Modelling and Analysis, At Lille, France*, 2017.

[14] P. Manske and S. Schier. Visual Scanning in an Air Traffic Control Tower—A Simulation Study. *Proc. Manufacturing, Elsevier.*, 3:3274–3279, 2015.

[15] L. Meyer, M. Vogel, and H. Fricke. Functional hazard analysis of virtual control towers. In *IFAC HMS 2010*, pages 146–151.

[16] C. Möhlenbrink, M. Friedrich, A. Papenfuss, M. Rudolph, M. Schmidt, F. Morlang, and N. Furstenau. High-fidelity human-in-the-loop simulations as one step towards remote control of regional airports: A preliminary study. In *ICRAT*, 2010.

[17] C. Möhlenbrink and A. Papenfuss. ATC-monitoring when one controller operates two airports research for remote tower centres. *Proceedings of the Human Factors and Ergonomic Society annual meeting*, 55(1):76–80, 2011.

[18] C. Möhlenbrink, A. Papenfuss, and J. Jakobi. The role of workload for work organization in a remote tower control center. *Air Traffic Control Quarterly*, 20(1):5, 2012.

[19] NORACON. OSED for remote provision of ATS to aerodromes, including functional specification. Brussels: SESAR Joint Undertaking, 2013.

[20] A. Oehme and D. Schulz-Rueckert. Distant air traffic control for regional airports. In *IFAC HMS 2010*.

[21] A. Papenfuss and M. Friedrich. Head up only—a design concept to enable multiple remote tower operations. In *DASC*, 2016.

[22] A. Papenfuss, M. Friedrich, C. Möhlenbrink, M. Rudolph, S. Schier, M. Schmidt, and N. Fürstenau. Assessing operational validity of remote tower control in high-fidelity tower simulation. In *IFAC HMS 2010*, pages 117–122.

[23] Y. Pochet and L. A. Wolsey. *Production Planning by Mixed Integer Programming*. Springer-Verlag New York, Secaucus, NJ, USA, 2006.

[24] M. Stojadinović. *Air Traffic Controller Shift Scheduling by Reduction to CSP, SAT and SAT-Related Problems*, pages 886–902. Springer International Publishing, Cham, 2014.

[25] G. A. Tobaruela. *A Framework to assess the ability of automation to deliver capacity targets in European airspace*. PhD thesis, Imperial College, London, March 2015.

[26] N. Wittbrodt, A. Gross, and M. Thüring. Challenges for the communication environment and communication concept for remote airport traffic control centres. In *IFAC HMS 2010*, pages 129–134.