

# Integrating Weather Impact in RTC Staff Scheduling

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**Abstract**—Weather affects the work of air traffic controllers, however, for staff scheduling in Remote Tower Centers (RTCs) it has not been taken into account. In this paper, we study the impact of different weather phenomena on air traffic controller (ATCO) taskload through structured interviews with ATCOs, and deduce taskload-driven impact factors and thresholds for the intensity of different weather phenomena at different Swedish airports above which a weather phenomena influences an ATCO’s work significantly. Using probabilistic weather modeling, we compute the probability of the occurrence of any of these impactful weather phenomena at an airport. We extend our prior Mixed Integer Programming (MIP) model to account for impactful weather occurrences and yield a distribution for the necessary number of ATCOs for RTC staff scheduling.

We present experimental results for five Swedish airports (which are either already operated remotely or considered for future remote operation). We show that taking impactful weather into account increases the number of necessary controllers, compared to planning for “optimal” conditions.

**Keywords**—ATCO workload, weather, RTC staff scheduling

## I. INTRODUCTION

Weather conditions have a high impact on the performance of the air traffic management (ATM) system (see, e.g., [1]). Within SESAR, new models for weather forecasts and their integration in planning problems, e.g., in trajectory planning, have been developed in several projects (e.g., [2]–[4]). Weather also effects the work of air traffic controllers (ATCOs), for example, through increased communication need with ground traffic and pilots, through increased out-of-the-window observation, and through changes to the arrival and departure routes. Weather disturbances have a noticeable influence on ATCOs working in a conventional tower, and they may have even higher impact on ATCOs working in a Remote Tower Center (RTC), in particular, if a single ATCO monitors more than a single aerodrome at a time (possibly with different weather conditions)—the so-called “multiple” setup promising to have the most significant impact on cost-effectiveness. In this paper, we aim to study this impact of weather and integrate it into optimization of ATCO work at RTCs, in particular, into an automated staff scheduling—revealing another important application area for weather models for aviation.

For staff planning at RTCs, the ATCO–airport assignment needs to ensure that no ATCO is confronted with traffic-inherent situations from the (multiple) airport(s) that constitute an unacceptable workload. Workload is a subjective concept—it “represents the cost incurred by a human operator to

achieve a particular level of performance” [5]—and cannot be measured directly. Additionally, it is an accumulated metric of different stressors, that is, we will not be able to find a single factor driving it. One of the main stressors though is uncertainty—and weather is a major source of uncertainty for the ATCOs: weather forecast and planned procedures in case of occurrence of a weather phenomenon exist, however, the exact time of occurrence, and the duration and intensity at the location of the airport are hard to predict, and additional ATCO tasks appear.

We have observed the influence of a severe occurrence of a weather phenomenon on ATCO workload in our field study at Bromma airport, Sweden, in [6]. With 4, 5, 9 and 27 movements during four hours, the average workload rating (self-assessed by the ATCOs using the adapted Cooper-Harper Scale from [7]) was higher in the first three hours, during which regular snow sweeping with a convoy of 10-14 vehicles occurred, than in the final hour with peak traffic.

However, no good measures or classifications for weather impact on ATCOs and their workload exist—while other impact factors have been studied, e.g., flight events for en-route traffic [8] and complexity factors without weather for multiple remote control [9]. This yields a couple of research questions: How do different weather phenomena impact ATCO workload (at different airports)? How to quantify the resulting weather-induced capacity reductions? And how can we integrate this impact in RTC staff scheduling?

To fill the research gap on classification of weather impact at different airports, we interviewed experienced ATCOs working at five (small) Swedish airports on measurement, incidence, classification and resulting additional ATCO tasks for various weather phenomena (snow, low visibility, precipitation, wind, and convective weather). In particular, we are interested in thresholds for significantly increased taskload induced by the weather phenomena. We concentrate on taskload (rather than workload), which measures the objective demand of a task rather than the subjective stress experienced during that task.

We then aim to integrate the identified influence of weather on the ATCOs in our prior model for RTC staff scheduling [10]. Previously, we limited the number of movements per hour that a single ATCO may handle, and suggested to resolve conflicts in terms of simultaneous movements at two airports within a 5-minute-interval ([10], [11]). However, we know that ATCO workload is not a monotone, linear function of the

number of movements: it might stay more or less constant with an increasing number of movements under normal conditions, but will rise suddenly in case of unexpected events. Here, we identify occurrence of a certain strength of a weather phenomenon as an unexpected event, which needs to be taken into account: a conflict between airports appears not only because of simultaneous movements, but when an impactful weather event at one airport demands the full attention of an ATCO (for increased communication duration and frequency with ground and pilots etc.), it should be monitored in single mode (and would be in conflict with all other airports when in multiple mode). For this paper, we assume that all five weather events are independent (but may occur simultaneously).

This work contributes to a safety assessment for multiple mode by showing that we can account for weather-induced increased taskload in staff scheduling to ensure that ATCOs do not face situations that compromise safety. Unions and regulation bodies have emphasized such a safety assessment as a requirement for implementation.

In the remainder of this section, we review related work. In Section II we outline our procedure for integrating weather impact in RTC staff scheduling and present its details in Sections III (ATCO interviews and deduction of taskload-driven impact factors), IV (probabilistic weather modeling of the different weather phenomena, and resulting distribution of the necessary number of ATCOs for RTC rostering), and V (integration of weather-related constraint into our previous optimization model). We present experimental results for five Swedish airports in Section VI and conclude in Section VII.

**RTC Staff Scheduling.** The RTC concept aims to provide air traffic service simultaneously to multiple airports with ATCOs at a remote location, see [12]. A variety of aspects of this concept has been studied: Möhlenbrink et al. [13] and Papenfuss et al. [14] considered usability aspects within the novel remote control environment. Meyer et al. [15] provided a safety assessment of the RTC concept, where they suggest functional hazard analyses and pinpoint the issue of getting reliable probability values for the models. Oehme and Schulz-Rueckert [16] suggested sensor-based solutions that alleviate the dependency on visibility conditions and tower location. In addition, [17], [18], [19], [20] and [21] studied work organization and human performance issues in the context of remote towers. The authors proposed several methods to control two airports from a single RTC and investigated how the monitoring performance may influence the system design and behavioral strategies, in particular, they presented results on the design of the novel RTC workplaces.

For references on RTC staff scheduling, we refer to [10] and the references therein.

**Probabilistic Weather Modeling.** Quantification of the impact of different weather phenomena on airport operation is reflected in many recent research activities. The problem of analysing and quantifying the effects of meteorological uncertainty in Trajectory Based Operations was considered in [22], [23]. The authors considered two types of meteorological uncertainty: wind uncertainty and convective zones.

New probabilistic radar-based nowcasting methods to support ATM challenged by winter weather were proposed in [24], [25]. Impact of deep convection and thunderstorms is also subject to ongoing research, e.g., Steiner et al. [26], [27] and Song et al. [28] investigated its implication both on en-route flow management and for terminal area applications. Klein et al. [29] used a high-level airport model to quantify the impact of weather forecast uncertainty on delay costs. Recent works [30], [31], [32] confirmed the relevance and emphasized the importance of studying the weather impact on airport operation. To the best of our knowledge, there were no published attempts to quantify the effect of different weather phenomena on controllers taskload or workload.

## II. STRATEGY OUTLINE FOR INTEGRATING WEATHER IMPACT IN RTC STAFF SCHEDULING

To achieve our goal to integrate weather impact in RTC staff scheduling, we implement the following steps:

- (1) Identify impactful weather phenomena for each considered airport, see Section III.
- (2) Define threshold values for the impactful weather phenomena from (1), see Subsection IV-A.
- (3) Choose exemplary historical dates at which all considered weather phenomena are present. (Other dates can be used as well, but in this work we aim to highlight the extent of possible weather influence.)
- (4) Calculate probabilities for the weather phenomena exceeding the threshold values from (2), see Subsection IV-B.
- (5) Calculate probability for any impactful weather phenomenon occurrence for each hour of the exemplary dates, see Subsection IV-B.
- (6) Obtain flight movements for all airports for chosen dates.
- (7) Calculate a distribution of the necessary number of ATCOs for RTC staffing, see Subsection IV-C.

## III. WEATHER IMPACT

Our goal is to study the impact of weather on ATCOs and their workload. However, no measures or classifications for this exist. Hence, we performed structured interviews with three Swedish ATCOs working at five Swedish airports (considered for or in remote operation). We present the airports and ATCOs in Subsections III-A and III-B, respectively. In Subsection III-C, we present the interviews and, in Subsection III-D, we present our results on the impact of different weather phenomena at these five airports on ATCOs.

### A. Airports

The general properties of the five Swedish airports (APs) in consideration can be shortly described as follows:

- *AP1.* Small AP with low traffic, few scheduled flights per hour. Inland location north of the Arctic Circle and AP2-5, continental subarctic climate (Köppen climate classification Dfc, see [33]).
- *AP2.* Small regional AP with regular scheduled flights (usually open 24/7). Coastal location, Dfc, north of AP3-5.

- AP3. Small regional AP with regular scheduled flights. Coastal location, Dfc, north of AP5.
- AP4. Small regional AP with regular scheduled flights. Coastal location, Dfc, north of AP3 and AP5.
- AP5. Low to medium-sized AP, multiple scheduled flights per hour (usually open 24/7). Coastal location in the South of Sweden, Marine West Coast Climate.

### B. ATCOs

We selected ATCOs with experience in working in a remote tower and/or with significant operational experience (as not all five airports are currently operated remotely); this way we ensured they are familiar with all weather phenomena at the selected airports. One ATCO answered the interview questions for AP1-AP3; one for AP3, AP4; and one for AP5.

We interviewed two male and one female ATCO with an average age, average experience as ATCO and at the considered towers of 46.7 years, 17.7 years, and 13 years, respectively. Two ATCOs have worked remotely. However, our goal is to map the additional weather-induced tasks at the five airports, hence, experience of working remotely is not important (as several of the airports are only considered for future remote operation, but currently not operated remotely).

### C. Structured Interviews

The structured interviews were performed based on a questionnaire (see [34]). Each ATCO was interviewed separately via Zoom; each interview lasted 2-3 hours (each ATCO was interviewed on one airport, and we asked them to fill in the questionnaire for other airports).

We started with background information on ATCO and airport (traffic density, seasonal variations), then we moved to weather-related questions. This included questions relating to all weather phenomena: sources for weather information, person in charge for and frequency of weather updates, and influence of weather on staffing decisions when operating the airport from a conventional tower.

Thereafter, we treated different weather phenomena separately: snow, low visibility, precipitation (excluding snow), wind (strong low-level and surface winds), and convective weather. For each weather phenomenon we asked about its metric and usual values of this metric, and which additional ATCO or manager tasks appear in case of occurrence of that weather phenomenon. Finally, we queried the occurrence of additional ATCO tasks in case of a minor, moderate or severe occurrence of the weather phenomenon (we derived the list of possible additional tasks associated with different weather phenomena from the hazard assessment cards suggested by EUROCONTROL [35]). Examples for the additional tasks are:

- Anticipation and condition detection
- Visual observation
- Runway closing for inspection and re-opening
- Change of departure/arrival runway
- Clearing arrivals to holding areas
- Increased coordination with the ground traffic

TABLE I. PROSE TO NUMERICAL VALUES

Prose formulation	Numerical value
no	0
rarely, not too much	0.25
sometimes, maybe, can happen, several times	0.5
often, increased, more likely, higher	0.75
yes	1
much more; yes, significantly	1.25

- Provision of information on alternate aerodromes conditions and availability

We completed the questions for each weather phenomenon asking for possible ATCO tasks to add to our list.

### D. Interview Results on Weather Impact

The ATCOs answered our queries on the occurrence of additional ATCO tasks in case of a minor, moderate or severe strength of the weather phenomena (the tables in Sections 4-8 of [34]) in prose. We transfer these answers to numerical values according to Table I. Taking the average of these values for all additional ATCO tasks associated with a weather phenomenon (and for AP3 over two ATCOs' answers), we obtain average taskload-driven impact factors of minor, moderate and severe occurrences of all weather phenomena. For easy visual differentiation of the airports, we transfer the numerical average taskload-driven impact factors to a heat value, and present the resulting impact-heat tables for snow, low visibility, precipitation, strong winds and convective activity in Fig. 1(a), (b), (c), (d) and (e), respectively.

We can clearly see that the ubiquitous weather phenomenon snow has highest impact on the northern airports AP1 and AP2, and has hardly any influence on AP5, located in the South, where it occurs rarely. Remember that we consider taskload (not workload). Hence, even while ATCOs working at AP1 and AP2 are used to the occurrence of snow, this still yields additional tasks and, thus, an increased taskload. A particularly high impact of severe low visibility can be observed at AP2: a coastal airport in the North of Sweden. Convective weather has a particularly high impact on AP5 already for light convective activity.

These average taskload-driven impact factors allow us to differentiate the impact that different intensities of the weather phenomena have on the five airports. However, as a next step, we aim to integrate the varying impact into the staff scheduling for an RTC with AP1-AP5 in remote control. Hence, we need to decide what constitutes a threshold over which a weather phenomenon influences ATCO's work at an airport significantly. Taking Table I into account, in the remainder of this paper we will use a value of 0.5 as a cutoff for the taskload-driven impact factor; the rationale is that an impact that happens at least sometimes is strong enough to necessitate integration in planning. This value may be changed depending on the operator's estimate of what constitutes a strong enough impact to be accounted for. In Table II, we summarize the strength of a weather phenomenon at each airport that has an average taskload-driven impact factor of at least 0.5, and

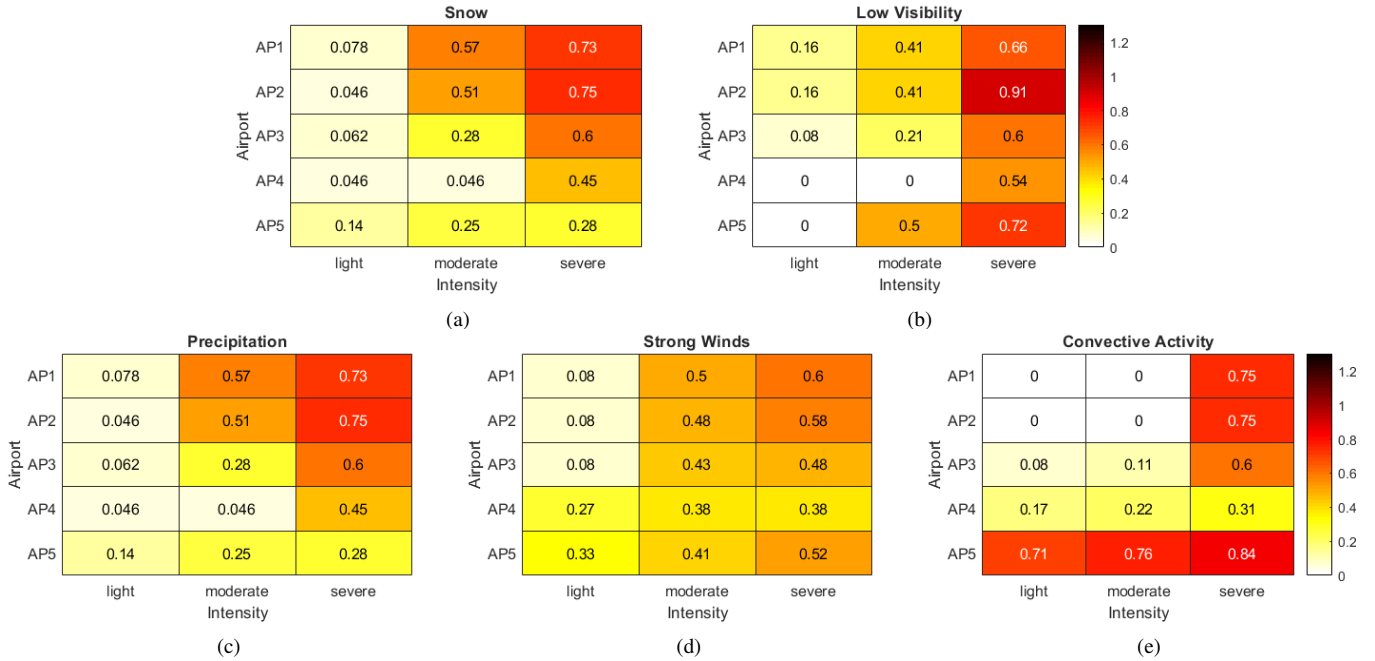


Figure 1. Impact-heat tables for (a) snow, (b) low visibility, (c) precipitation, (d) strong winds, and (e) convective activity.

which, hence, is considered strong enough that it must be accounted for in staff planning.

TABLE II. WEATHER INTENSITY FOR AVERAGE TASKLOAD-DRIVEN IMPACT FACTORS  $\geq 0.5$

	Snow	Low Visibility	Precipitation	Strong Winds	Convective Activity
AP1	moderate	severe	moderate	moderate	severe
AP2	moderate	severe	moderate	severe	severe
AP3	severe	severe	severe	-	severe
AP4	-	severe	-	-	-
AP5	-	moderate	-	severe	light

#### IV. PROBABILISTIC WEATHER MODELING

In this section, we describe the steps from Section II that relate to probabilistic weather modeling, that is, to the deduction of probabilities for the occurrence of any of the weather phenomena with taskload-driven impact factor exceeding our threshold. And next, we integrate these probabilities in our model for RTC staff scheduling.

##### A. Numerical Thresholds for Impactful Weather Phenomena

We use various sources to obtain numerical values for the different weather phenomena of light, moderate and severe intensity for the different airports: airport-specific threshold values obtained from the ATCO interviews, general threshold values derived from literature, and threshold values obtained from historical weather data. Depending on which strength of a weather phenomenon is identified as impactful at an airport we are interested in thresholds for different intensities of the weather phenomena. Here, we focus on the thresholds for the weather phenomena strengths from Table II.

For wind, we have airport-specific thresholds from the interviews available for all airports: The ATCO working at

AP1-AP3 defined moderate wind as 15 – 25 knots for all three airports, hence, our threshold for moderate wind at AP1 is 15 knots, and our threshold for severe wind at AP2 is 25 knots. The ATCO working at AP5 defined light wind to be more than 15 knots, moderate wind to be 25 – 35 knots and severe wind to be above 35 knots, hence, our threshold for AP5 is 35 knots.

For convective weather and limited visibility, we use the work by Taszarek et al. [36], who define threshold values for hazard types of different weather phenomena. We use these thresholds for severe weather occurrence as follows: for convective weather they define a Convective Available Potential Energy (CAPE) of at least 150 J/kg and convective precipitation (cp) of at least 0.25 mm/h; for limited visibility, they give the threshold by a ceiling height (cbh) of less than 200 ft AGL and a low-level cloud cover (lcc) of 100%. From these values we deduce the thresholds for moderate low visibility as  $cbh \leq 500$  ft AGL and  $lcc \geq 0.9$ , and for light convective activity as  $CAPE \geq 50$  J/kg and  $cp \geq 0.1$  mm/h.

Finally, for snow and precipitation, we considered historical weather data and studied the patterns typical for Sweden, and deduced thresholds of 1mm and 2mm per hour for moderate and severe occurrences, respectively. Altogether, this yields Table III.

##### B. Probability of Weather Metrics Exceeding the Thresholds

Ensemble Prediction Systems (EPSs) are an approach to weather forecasting that characterizes and quantifies the uncertainty inherent to the prediction [26]. We obtain the ensembles from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 database, provided via the C3S Data Store in form of NetCDF files [37]. The data consists of

TABLE III. WEATHER PHENOMENA THRESHOLDS FOR AVERAGE TASKLOAD-DRIVEN IMPACT FACTORS  $\geq 0.5$ 

	Snow	Low Visibility	Precipitation	Strong Winds	Convective Activity
AP1	$\geq 1\text{mm/h}$	$\text{cbh} \leq 200\text{ft AGL, lcc} = 1$	$\geq 1\text{mm/h}$	$\geq 15$ knots	$\text{CAPE} \geq 150\text{J/kg, cp} \geq 0.25\text{mm/h}$
AP2	$\geq 1\text{mm/h}$	$\text{cbh} \leq 200\text{ft AGL, lcc} = 1$	$\geq 1\text{mm/h}$	$\geq 25$ knots	$\text{CAPE} \geq 150\text{J/kg, cp} \geq 0.25\text{mm/h}$
AP3	$\geq 2\text{mm/h}$	$\text{cbh} \leq 200\text{ft AGL, lcc} = 1$	$\geq 2\text{mm/h}$	-	$\text{CAPE} \geq 150\text{J/kg, cp} \geq 0.25\text{mm/h}$
AP4	-	$\text{cbh} \leq 200\text{ft AGL, lcc} = 1$	-	-	-
AP5	-	$\text{cbh} \leq 500\text{ft AGL, lcc} \geq 0.9$	-	$\geq 35$ knots	$\text{CAPE} \geq 50\text{J/kg, cp} \geq 0.1\text{mm/h}$

10 ensemble members and has temporal granularity of three hours.

Let  $A$  be the set of airports in consideration (AP1-5),  $E$  be the set of weather events (snow, low visibility, precipitation, strong winds and convective activity), and  $h$  a three-hour period of the prognosis. Each ensemble member specifies whether each of the weather events  $E$  occurs during  $h$  in each airport  $a \in A$ . Let  $W_{i,j}^{h,a} = 1$  when in the ensemble member  $j$  the weather metric corresponding to the event  $i \in E$  is exceeding the threshold according to Table III; otherwise,  $W_{i,j}^{h,a} = 0$ . Let  $n$  be the number of ensemble members. Then the probability of the weather event  $i$  to impact airport  $a$  during  $h$  is calculated as  $p_i^{h,a} = \sum_{j=1}^n W_{i,j}^{h,a} / n$ . Because of the three-hour granularity, we calculate  $p_i^{h,a}$  for  $h = 0, 3, \dots, 21$  and propagate the probabilities to the nearest hours back and forth.

Based on the calculated probabilities  $p_i^{h,a}$  of observing each impactful weather phenomenon, we derive the probability that *any* of these weather phenomena can be observed. For this paper, we assume that all five weather events are independent (but may occur simultaneously). In future work, we plan to study the interdependencies of the weather phenomena and include them in the computation of this joint probability.

Let  $I^{h,a}$  be the indicator of the event that an impactful weather occurs during hour  $h$  at airport  $a$ . Under our assumption of independence

$$P(I^{h,a} = 1) = 1 - \prod_{i \in E} (1 - p_i^{h,a}) \quad (1)$$

### C. Distribution of Necessary Number of ATCOs

We consider a time period  $T$  consisting of the hours during which we have to schedule the ATCOs to control our set  $A$  of the airports. For each hour  $h \in T$  and each airport  $a \in A$  let  $X_{h,a} = 1$  if some impactful event occurs at airport  $a$  during hour  $h$ , and let  $X_{h,a} = 0$  otherwise. The  $|T| \times |A|$  binary matrix  $X$  fully describes how the weather situation evolves during  $T$  in all our airports; we therefore call a  $|T| \times |A|$  binary matrix  $X$  a *scenario*. For each of the  $2^{|T||A|}$  possible scenarios we run our ATCO scheduling MIP (described in Section V) and determine the minimum number of controllers necessary to cover all our airports during time period  $T$ .

Since we assume that the impactful events at different airports and different hours are independent, the probability of any scenario  $X$  can be calculated as the product of the probabilities of its entries:  $P(X) = \prod_{h \in T} \prod_{a \in A} P\{I^{h,a} = X_{h,a}\}$ . These probabilities are transformed into the distribution of necessary ATCOs: the probability that at least  $k$  ATCOs are needed is equal to the sum of the probabilities of the scenarios in which at least  $k$  were needed.

## V. OPTIMAL RTC STAFF SCHEDULING

Our MIP for RTC staff scheduling is based on our prior work [10], we recapitulate the MIP in Subsection V-A, and present a new constraint in Subsection V-B.

### A. Prior MIP

We refer to [10] for the complete MIP, here we focus on the restrictions on the ATCO shifts integrated in our model. The constraints enforce:

- A maximum number of movements that any ATCO handles during any period
- A maximum number of airports that any ATCO handles during any period
- A maximum number of ATCOs assigned to the same airport during any period
- A maximum ATCO shift length
- A minimum ATCO shift length
- A maximum number of consecutive periods during which an ATCO may work “in position” (a maximum continuous time “in position”)
- A minimum number of consecutive periods during which an ATCO must work “in position”
- That no ATCO is assigned to an airport for which he/she does not hold an endorsement, that is, that ATCOs are assigned only to those airports, for which they hold endorsements
- That all movements at an airport during a period are handled by some ATCO
- That at least one ATCO is assigned to an airport during all periods for which the airport is open
- That two airports with simultaneous movements in a 5-minute interval during a period are not assigned to the same controller during that period

As objective function we choose the minimization of the number of ATCOs.

### B. New Constraint

We introduce a constraint that enforces an airport with impactful weather during an hour  $h$  to be handled in single mode during that time. We use some notation from the MIP in [10]:

- Binary variable  $period_{i,a,h}$ , which is 1 iff controller  $i$  is assigned to airport  $a$  during period  $h$
- Binary variable  $y_{i,h}$ , which is 1 iff controller  $i$  is at work during period  $h$

We introduce a new binary parameter  $s_{a,h}$ , which is 1 iff airport  $a$  must be operated in single mode in period  $h$ , and a new Constraint (2): If an airport  $a$  must be operated in single

mode in period  $h$  (because of impactful weather at  $a$  during  $h$ ), an ATCO assigned to  $a$  in  $h$  may not be assigned to any other airport in  $h$ . This substitutes the old Constraint (2) in [10].

$$\sum_{\substack{a' \in \\ A \cup A^+}} period_{i,a',h} \leq y_{i,h} \cdot mA - (mA - 1)s_{a,h} \cdot period_{i,a,h} \quad \forall i \in C, \forall h \in P, \forall a \in A \quad (2)$$

## VI. EXPERIMENTAL STUDY: SWEDEN

We follow steps (1)-(7) from Section II.

**(1) Identify impactful weather phenomena for each considered airport:** We considered AP1-5, and the impactful weather phenomena were identified as described in Subsection III-D, Table II.

**(2) Define threshold values for the impactful weather phenomena:** We deduced threshold values for the impactful weather phenomena from Table II in Subsection IV-A, and the chosen values are listed in Table III.

**(3) Choose exemplary historical dates at which all considered weather phenomena are present.** We downloaded weather data for November 2019 and July 2020 and chose two exemplary dates:

- November 13, 2019: A winter day during which three out of the five considered weather phenomena occurred: snow, low visibility, and precipitation.
- July 29, 2020: A summer day during which four out of the five considered weather phenomena occurred: low visibility, wind, precipitation, and convective activity.

**(4) Calculate probabilities for the weather phenomena exceeding the threshold values from (2).** Using the procedure described in Subsection IV-B, we obtain the probabilities for the occurrence of snow, low visibility, precipitation, strong winds and convective activity (if present) for all hours at all airports during November 13, 2019 and July 29, 2020 presented in Figure 2 and Figure 3, respectively.

**(5) Calculate probability for any impactful weather phenomenon occurrence for each hour of the exemplary dates.** Using the procedure described in Section IV-B, we obtain the probabilities for the occurrence of any impactful weather for each hour at all airports during November 13, 2019 and July 29, 2020 given in Figure 4 and Figure 5, respectively.

**(6) Obtain flight movement data for all airports at the chosen dates.** We obtained the number of movements per hour at each airport using FlightRadar24 historical flight data. The movement data for November 13, 2019, and July 29, 2020, is shown in Fig. 6(a) and (b), respectively. We use only hours 12-20 for November 13, 2019, and 8-16 for July 29, 2020.

**(7) Calculate a distribution of the necessary number of ATCOs for RTC staffing.**

As described in Section IV-C, for all  $2^{|A| \cdot |T|}$  scenarios, we solve our MIP from Section V using Gurobi optimization software installed on a very powerful Tetralith server [38], utilizing the Intel HNS2600BPB computer nodes with 32 CPU cores, 384 GiB, provided by the Swedish National Infrastructure for Computing (SNIC). The computational time

of each run of our optimization program on this powerful machine varied between 40 seconds and 3 minutes. Using the average runtime of 110 seconds, this yields a total average runtime of 7.8h and 31.3h for November 13, 2019, and July 29, 2020, respectively.

If weather impact is ignored (scenario  $X = 0$ ), 5 ATCOs suffice for the considered 9-hour periods both for November 13, 2019, and July 29, 2020. Taking into account the impact of weather by using the procedure from Subsection IV-C, we obtain the following distributions of the number of ATCOs (see also Figure 7 for pie diagrams):

- November 13, 2019: 5 and 6 ATCOs necessary with a probability of 87.132% and 12.868%, respectively.
- July 29, 2020: 5, 6, 7, and 8 ATCOs necessary with a probability of 0.079%, 48.443%, 51.198%, and 0.279%, respectively.

Hence, 5 ATCOs will be sufficient with 87.132% probability on November 13, 2019, if staff scheduling wants to be sure to avoid critical situations, they can schedule 6 ATCOs and this number will always be sufficient. For July 29, 2020, 5 ATCOs will be enough only with negligible probability; 6 ATCOs will be sufficient with nearly 50% probability; if 7 ATCOs are scheduled, this will avoid critical situations with 99.721%.

We can clearly observe the impact the weather has on planning: if we optimize the number of ATCOs without taking weather into account, we would plan to schedule 5 ATCOs. And while these are sufficient with 87.132% probability for November 13, 2019, when weather is integrated, for July 29, 2020, they are only with a negligible probability of 0.079%.

## VII. CONCLUSION

We proposed a method to account for weather impact on ATCO work in RTC staff scheduling. We highlighted that no measures or classifications for weather impact exist, and used structured interviews with experienced ATCOs to deduce taskload-driven impact factors for five weather phenomena at five Swedish airports. We identified different sources for numerical thresholds for these impactful weather phenomena, and used probabilistic weather modeling to obtain the probability of any impactful weather phenomenon occurring at an airport during an hour. Based on this modeling, we applied our prior MIP for RTC staff scheduling (extended by a constraint requiring an airport with impactful weather occurrence to be operated in single mode) to all possible scenarios of weather evolution at the airports in consideration, and deduced a distribution of the necessary number of ATCOs to control all these airports during the chosen time period.

Our experiments for five Swedish airports and days with 3-4 weather phenomena occurring clearly show the possible impact of weather: the five ATCOs that would be scheduled taking all legal and shift-related constraints into account are not sufficient for the RTC without possibly yielding situations compromising safety due to weather. An increased number of ATCOs planned for the shifts can guarantee (six ATCOs for November 13, 2019) or ensure with 99.721% (seven ATCOs for July 29, 2020) that critical situations can be avoided.

		Nov 13	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	snowfall	1	1	1	1	1	1	1	1	1	1	1	1	0.5	0.5	0.5	1	1	1	1	1	1	1	1	1	1	0.1
	low visib.	1	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.65	0.65	0.65	0.6	0.6	0.6	0.7	0.7	0.7	0.85	0.85	0.85	1	1	1	1	0.75
	t.precip.	0.8	0.8	0.9	0.9	0.9	0.8	0.8	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AP2	snowfall	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	low visib.	1	1	1	1	1	0.4	0.4	0.4	0	0	0	0	0	0	0.4	0.4	0.4	0.8	0.8	0.8	1	1	1	1	1	
	t.precip.	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
AP3	snowfall	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	low visib.	0	0	0	0	0	0.1	0.1	0.1	0.5	0.5	0.5	0.3	0.3	0.3	0	0	0	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.1	
	t.precip.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
AP4	snowfall	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	low visib.	0.1	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.3	0.3	0.1
	t.precip.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
AP5	snowfall	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	low visib.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	
	t.precip.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Figure 2. Probabilities for occurrence of different weather phenomena at AP1-AP5 for November 13, 2019.

		Jul 29	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	t.precip.	0.2	0.2	0.4	0.4	0.4	0.5	0.5	0.5	0.7	0.7	0.7	0.9	0.9	0.9	1	1	1	1	1	1	1	1	1	1	0.4
	wind	0	0	0	0	0	0.4	0.4	0.4	0.6	0.6	0.6	1	1	1	0.7	0.7	0.7	0	0	0	0	0.1	0.1	0.1	0
	convectiv.	0	0	0.7	0.7	0.7	0	0	0	0.45	0.45	0.45	0.3	0.3	0.3	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0	0	0	0.7
AP2	low visib.	0	0	0.5	0.5	0.5	0.4	0.4	0.4	0.35	0.35	0.35	0	0	0	0.5	0.5	0.5	0.8	0.8	0.8	0.8	0.5	0.5	0.5	0.5
	t.precip.	0	0	0	0	0	0.3	0.3	0.3	0.2	0.2	0.2	0.8	0.8	0.8	1	1	1	1	1	1	1	1	1	1	1
	wind	0	0	0	0	0	0.51	0.51	0.51	0.36	0.36	0.36	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AP3	convectiv.	0	0	0	0	0	0	0	0	0.2	0.2	0.2	0.4	0.4	0.4	0.45	0.45	0.45	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	low visib.	0.4	0.4	0.8	0.8	0.8	0.3	0.3	0.3	0	0	0	0	0	0	0	0	0	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.5
	t.precip.	1	1	1	1	1	0.9	0.9	0.9	0.1	0.1	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AP4	wind	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	convectiv.	0	0	0	0	0	0	0	0	0.25	0.25	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	S
	low visib.	0.25	0.25	0.7	0.7	0.7	0.15	0.15	0.15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AP5	t.precip.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	wind	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0.1	0.1	0.1	0.1	0	0	0	0	0	0
	convectiv.	0.15	0.15	0.25	0.25	0.25	0.4	0.4	0.4	0.45	0.45	0.45	0.15	0.15	0.15	0.5	0.5	0.5	0.5	0.5	0.5	0	0	0	0	0
AP5	low visib.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0
	t.precip.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	wind	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0.1	0.1	0.1	0.1	0	0	0	0	0	0

Figure 3. Probabilities for occurrence of different weather phenomena at AP1-AP5 for July 29, 2020.

		Nov 13	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		1	1	1	1	1	1	1	1	1	1	1	1	0.8	0.8	0.8	1	1	1	1	1	1	1	1	1	1	0.775
AP2		1	1	1	1	1	0.4	0.4	0.4	0	0	0	0	0	0	0	0.4	0.4	0.4	0.8	0.8	0.8	1	1	1	1	1
AP3		0	0	0	0	0	0.1	0.1	0.1	0.5	0.5	0.5	0.3	0.3	0.3	0	0	0	0	0.1	0.1	0.1	0.2	0.2	0.2	0.1	0.1
AP4		0.1	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.3	0.3	0.1	0.1
AP5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0.1	0	0	0	0	0	0	0	0.2

Figure 4. Probabilities for occurrence of any impactful weather at AP1-AP5 for November 13, 2019. Considered hours are highlighted in yellow.

		Jul 29	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		0.2	0.2	0.7	0.7	0.7	0.82	0.82	0.82	0.9571	0.9571	0.9571	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.7
AP2		0.4	0.4	0.8	0.8	0.8	0.51	0.51	0.51	0.36	0.36	0.36	0.88	0.88	0.88	1	1	1	1	1	1	1	1	1	1	1	1
AP3		1	1	1	1	1	0.915	0.915	0.915	0.325	0.325	0.325	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AP4		0	0	0.5	0.5	0.5	0.1	0.1	0.1	0.5	0.5	0.5	0.15	0.15	0.15	0.5	0.5	0.5	0.5	0.1	0.1	0.1	0	0	0	0	0.5
AP5		0.15	0.15	0.25	0.25	0.25	0.52	0.52	0.52	0.6425	0.6425	0.6425	0.235	0.235	0.235	0.775	0.775	0.775	0.5	0.5	0.5	0	0	0	0	0	0

Figure 5. Probabilities for occurrence of any impactful weather at AP1-AP5 for July 29, 2020. Considered hours are highlighted in yellow.

Nov 13	12	13	14	15	16	17	18	19	20	Jul 29	8	9	10	11	12	13	14	15	16
AP1	2	1	1	0	0	1	0	0	0	AP1	0	0	0	0	0	0	1	1	0
AP2	6	2	2	4	6	1	4	5	1	AP2	0	0	1	2	1	1	1	0	3
AP3	0	0	0	2	2	0	2	2	0	AP3	0	0	0	0	1	1	0	1	1
AP4	0	0	0	1	0	0	1	0	1	AP4	0	1	1	0	0	0	0	0	0
AP5	5	4	5	2	4	4	4	6	5	AP5	3	0	0	0	1	1	3	4	0

Figure 6. The number of flight movements for five airports on a) November 13, 2019, and b) July 29, 2020.

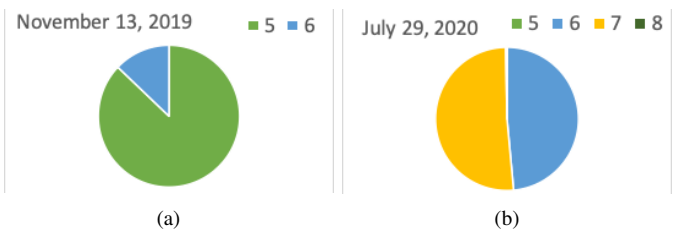


Figure 7. Distribution of the necessary number of ATCOs for (a) November 13, 2019, and (b) July 29, 2020.

We highlighted the importance of developing meteorological products tailored to the needs of airports staff planning.

This is particularly important for remote towers.

One direction for future work is the practical validation of our work. This includes both (simulation) trials to assess the validity of our assignments and additional interviews to confirm the presented results.

We assumed the weather phenomena to be independent. Of course, this is a simplified assumption, and in future work, we aim to study the interdependencies of the weather phenomena and include these into the computation of probabilities to improve the accuracy of our planning.

Often, with the occurrence of the considered weather event, the number of VFR movements reduces. Hence, it would be interesting to evaluate if this reduction has any influence on the impact on taskload associated with different weather phenomena.

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