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Quantification of Weather Impact on Arrival Management

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***Abstract*—Adverse weather has considerable impact on airport capacity and hence causes major delays for passengers, increased workload for air traffic controllers and cost for airlines. In Europe almost half of all regulated airport traffic delay is due to weather, in Austria even more than 95% of 2018 regulated airport traffic delays were caused by weather. As weather cannot be changed these massive delays cannot be avoided altogether, but early awareness due to accurate forecasts can help to mitigate its impact. In order to improve the decision making a quantification of the weather impact is a prerequisite as this allows to identify the relevant weather information needed and appropriate actions to mitigate the consequences. In this study weather impact was derived by evaluating traffic delays and related costs from fast time simulations. The simulations allow to study the sensitivity of the Air Traffic Management system to changes of traffic, weather and actions taken. In this way potential improvements were identified which will be addressed in future work. This paper gives an overview of the methodology used, conclusions from the evaluation and an outlook on further steps building on the achieved results.**

Keywords - adverse weather; airport capacity; fast time simulation; delay cost; arrival management

I. INTRODUCTION

A range of weather phenomena has negative impact on air traffic capacity. While for en-route traffic weather disruptions are mainly caused by thunderstorms the terminal traffic is affected by a wider range of events. Airport capacity can be reduced considerably by low visibility, strong winds, thunderstorms in the terminal area and runway closures due to snow. For air traffic control weather events are the source of increased workload, e.g. if air traffic needs to divert from planned routes to avoid thunderstorms. Air traffic delays are the source of major cost for the airline operators, inconvenient for passengers and ATFM (air traffic flow management) delays are a performance measure for air navigation service providers ([1]). Because of their importance delays are a central element in performance review reports such as the Network Operations Report [2] or the Coda Digest [3] issued by the European Commission Network Manager. The impact of weather seems to be relatively small compared to other causes when looking at average total airline-reported delay. The average delays per European flight in 2017 reported in [3] for ATFM weather and other weather delays are 0.23 and 0.38 minutes, respectively, compared to a total average delay of 12.4 minutes, which is dominated by reactionary[1] (5.46 minutes) and airline delay (3.34 minutes). When looking at the reasons for ATFM delays the contribution of weather is more important, with en-route weather contributing 13.5% and airport weather 19.2% of total ATFM delays. The other main contributions to ATFM delays are en-route capacity (25.5%) and airport capacity (15.5%), which means that weather has the largest contribution to airport ATFM delays and the second largest to ATFM en-route delays ([2]). When taking a less global view and looking at delay hotspots, especially for airport delays, the relevance of weather is getting more apparent. In 2017 at many of the top 20 European airport delay locations weather was the major contribution ([2]).

The importance of weather related delays is also reflected by research done on this topic. For example, Kicinger et al. [4] investigated the impact of weather forecast uncertainty on airport capacity prediction and showed that weather forecasts help to accurately predict airport capacity for various weather conditions. Steiner et al. [5] discuss the crucial effect of accurate forecasts of high-impact winter weather for efficient management of airport and airline capacity and highlight the need of data sharing and integrated decision making between stakeholders. Impact of deep convection and thunderstorms is also subject to ongoing research, e.g. Steiner et al. [6], [7] and Song et al. [8] investigated its implication both on the en-route flow management and for terminal area applications. A detailed analysis of how weather can and should be integrated in the NextGen initiative is given by Flathers et al. [9] and emphasizes the importance of translating weather forecasts into effects and impact on the ATM system. Klein et al. [10] used a high-level airport model to quantify the impact of weather forecast uncertainty on delay costs. By looking at model-estimated arrival rates the avoidable portion, if a perfect weather forecast would be available compared to current forecasts, of arrival delays and cancellations due to terminal weather were estimated. The study revealed an estimated cost of $330M per year due to weather forecast inaccuracies for FAA's OEP-35 airports.

The focus of this study is on one of the top 20 airport delay locations in Europe, Vienna International Airport (LOWW). While the results presented are specific to this airport the developed method can be transferred to other locations. As the results are depending on traffic and the importance and frequency of weather phenomena will vary between locations,

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[1] Delays resulting from an aircraft's late arrival from a previous flight. Consisting of rotational delay, due to the same aircraft being delayed on its next flight, and non-rotational delay, i.e. another aircraft is delayed due to late arrival of passengers, crew or cargo from a previous flight ([3]).

the outcomes and conclusions could be considerably different for other locations. Table I shows the 2018 ATFM delay statistic for LOWW, where 95% of ATFM delay minutes were caused by weather. Looking at the distribution of the ATFM weather delays according to the weather phenomenon, shown in Table II for 2017 and 2018, reveals that LOWW is mostly affected by low visibility (29-38% of weather delays), and thunderstorms (46-65% of weather delays). Comparing the numbers of 2017 and 2018 reveals a considerable variation of weather phenomenon impact between years, most pronounced for low visibility and wind in the two years shown. One reason for a high variability between years is, that single events, e.g. a single day with constant low visibility, cause more than 6000 delay minutes alone. Hence even phenomena which seem to be less important based on the numbers shown, e.g. snow, can have major impact on the air traffic system.

TABLE I. 2018 LOWW ARRIVAL DELAYS

Delay reason	**Jan – Dec 2018**	
	minutes	***share***
Aerodrome Capacity	2,776	3%
ATC Capacity	0	0%
ATC Equipment	1,157	1%
ATC Staff	0	0%
Weather	77,973	95%
Other	21	0%
Total	**81,927**	**100%**

Data source: Network Manager Interactive Reporting Tool.

TABLE II. LOWW WEATHER DELAYS

Delay reason	**Jan – Dec 2017**		**Jan – Dec 2018**	
	minutes	***share***	***minutes***	***share***
Low visibility procedures	43,548	38%	22,814	29%
CB / TS	52,867	46%	50,276	65%
Strong winds	15,827	14%	3,705	5%
Snow	2,718	2%	795	1%
Other	0	0%	383	0%
Total	**114,960**	**100%**	**77,973**	**100%**

Data source: Network Manager Interactive Reporting Tool.

Looking at ATFM delays alone is not sufficient to reveal the entire weather impact, as ATFM delays are a reaction to forecasted or already observed weather in order to reduce its impact. If in case of adverse weather, no ATFM measures are taken, there will be no ATFM delay, yet there will be major impact due to long airborne delay, which is more expensive than ground delay, flight diversions and potential air traffic control workload overload. Hence, the challenging task of managing weather in the ATM system is to balance ATFM measures to minimize the overall weather impact.

As a first step to minimize the weather impact it is necessary to have a quantitative measure. In section II the methodology used in this study to derive weather impact in form of delay cost from fast time simulations is described. Case study results applying this methodology are then discussed in section III, followed by a discussion of identified potentials to reduce the weather impact, which will be subject of future assessments, in the conclusion.

II. METHODOLOGY

To evaluate forecast performance and its value for a specific application it is necessary to quantify the impact in a well measurable and comparable form. At the beginning of the study an approach based on standard ATM key performance indicators (KPI) was contemplated (see Steinheimer et al. [11]). The idea was to combine several KPIs from different performance areas in one measure representing performance of the integrated ATM system considering the needs of all stakeholders. However, as it turned out many of the established KPIs are no suitable utility measures for decision making, i.e. they can be optimized by taking decisions against one's true believe[2]. Traffic complexity, for example, could be minimized by always assuming worst weather conditions resulting in air traffic restrictions, as complexity is usually reduced if traffic density is reduced.

Airline costs for arrival delays and diversion costs were identified as a suitable measure for weather impact in terminal airspace, while impact on ATM workload and procedures can be considered to be of secondary importance. This is based on the fact that ATM procedures are designed to be safe also in case of forecast errors. For example, in case of over delivery because a low visibility situation was not forecasted, contingency measures, such as holding patterns outside the terminal airspace, can be taken. Standard KPIs are evaluated in addition as qualitative measures of weather impact.

Basis for evaluating the weather impact is a traffic demand. This can be artificially generated, e.g. randomly, or actual traffic can be used. Using traffic demand of a day without weather disturbance proofed most useful for a multi scenario analysis. Based on a weather forecast airline measures and ATM measures are applied to the initial traffic. The airline measure considered in this study is to increased maximum holding time in case of forecasted adverse weather. Maximum holding times are modelled using a gamma distribution where the mean is set based on the forecasted weather. The weather dependent ATM measures applied are ATFM regulations based on the weather forecasts, i.e. based on the forecast the maximum acceptable arrival rate is defined and flights not already departed at the regulation issue time are delayed on the ground to ensure the arrival rate is kept at acceptable levels. The traffic derived in that way is the input to a fast time air traffic simulation.

Based on the actual weather the ATM procedures, i.e. spacing on final approach and runway in use, are defined for the simulation. Wind and thunderstorm areas which are avoided by air traffic are further inputs for the simulation.

[2] In meteorology suitable quality measures for forecasts ensuring careful assessments and honest predictions are based on proper scoring rules ([12]).

Output of the air traffic simulation are a number of KPIs which are then used in a cost model to derive delay and diversion costs for the simulated day.

The described simulation procedure is performed for multiple scenarios to quantify the weather impact. The four basic scenarios are shown in Table III. The scenarios are defined along two dimensions, the occurrence of the weather event and if action to mitigate the weather event was taken or not. The *n*, or none scenario, is the case when no action was taken and the weather did not occur. In the false alarm scenario *f* action was taken, but the weather event did not happen. In case of the hit scenario *h* action was taken and the event actually happened, while in the missed scenario *m* the weather event happens without preventive action taken.

TABLE III. EVALUATION SCENARIOS

	Weather observed	
Action taken	***Yes***	***No***
Yes	*h*	*f*
No	*m*	*n*

By evaluating the costs for these four scenarios the impact of weather with and without preventive action taken can be compared to the case without disruptive weather. The false alarm scenario allows to investigate the cost of the action taken. From the four scenarios also the cost – loss ratio for the considered event can be derived. This is the ratio of the cost for taking action to protect against the weather impact to the part of the loss which can be prevented if the event actually happens. This ratio is equal the probability threshold from which it is beneficial to take action in case probabilistic weather forecasts are available (refer to Murphy [13]).

A. Air traffic simulator

For performing the simulations, a sophisticated air traffic simulator, NAVSIM[3], was used. NAVSIM is able to simulate air traffic world-wide runway to runway and gate-to-gate. The simulation is based on sophisticated simulation techniques and applies detailed aircraft performance and navigation data. To evaluate the air traffic in the terminal area of LOWW, advanced arrival manager functionality was integrated. Besides detailed implementation of the LOWW arrival procedures among other things a weather avoidance algorithm, to avoid adverse weather areas, as well as distance and time based separation on final approach were implemented. A full list of implemented features is given in [11].

To make sure the results obtained from the simulation are realistic and can be used for a quantitative evaluation, the simulations were validated by comparing to real traffic. For these validations the simulation was initialized with the real flight positions at entry of the terminal airspace and the resulting simulated flight trajectories were compared to the equivalent real trajectories. The validation showed that the simulation is replicating real flight trajectories to a large extent. Differences identified were reviewed by air traffic controllers to ensure the simulated flight paths are realistic. Final conclusion of the validation was, that the simulator generates realistic flight paths and its output can be used for the impact analysis.

B. Key performance indicators

For the quantification of the weather impact based on the cost accrued to airlines because of weather related delays and diversions the relevant KPIs needed from the simulation are number of diverted flights, ATFM delay for every flight and the airborne delay in terminal airspace.

The number of diverted flights is recorded by the simulation. A flight diverts in the simulation if its assigned maximum holding time is shorter than the expected holding time calculated on entry of the terminal airspace. The maximum holding time is randomly assigned to every flight around a prescribed mean depending on the evaluation scenario, i.e. it is higher for “action taken” scenarios.

The ATFM delay is determined when the traffic input to the simulation is generated. Depending on the ATFM regulation issued, which is based on the expected weather, the regulation process assigns the required ATFM delay to flights in order to keep the arrival rate in line with the regulation.

The airborne delay is the additional time of flight between entry into terminal airspace and touchdown compared to the time required in a low traffic situation. The delay is calculated as difference of the actual flight time from entry into the traffic volume until touch down and the time filed for this segment in the flight plan. The time filed in the flight plan is usually shorter than the shortest achievable time, as it does not take into account transition routes between STAR (standard arrival route) endpoint and runway because the runway in use is unknown at the time of filing the flight plan. This means that there will be an airborne delay for every flight even if it is totally unrestricted. Hence the arrival delay needs always to be viewed in comparison to an undisturbed scenario. Fig. 1 shows an example of an actual flight path, the flight path filed in the flight plan and the shortest possible path in an undisturbed situation to illustrate the airborne delay calculation.

Additional output from the simulation includes many more data, such as holding time, holding distance, track-miles in terminal airspace and number of air traffic controller commands, for every flight. These quantities can be used to consider other important aspects beside airline delay cost, e.g. controller workload or environmental impact, but will not be further discussed in this study.

C. Cost Model

For estimating cost of delay often simplified values are used as given in [14]. Using a single value for estimating the cost of delay regardless of aircraft type and delay duration (e.g. 100 Euro / minute ATFM delay given in [14]) is useful and necessary when estimating the cost of delay on network level without detailed knowledge of the delay distribution. When the intention is to quantify the impact of weather at a specific location in a specific scenario such a general approach is not productive. In this case it is essential to consider the cost based on aircraft type and amount of delay. The reason for that is,

[3] NAVSIM ATM/ATC/CNS Tool is developed by Mobile Communications Research & Development Forschungs GmbH in co-operation with University of Salzburg

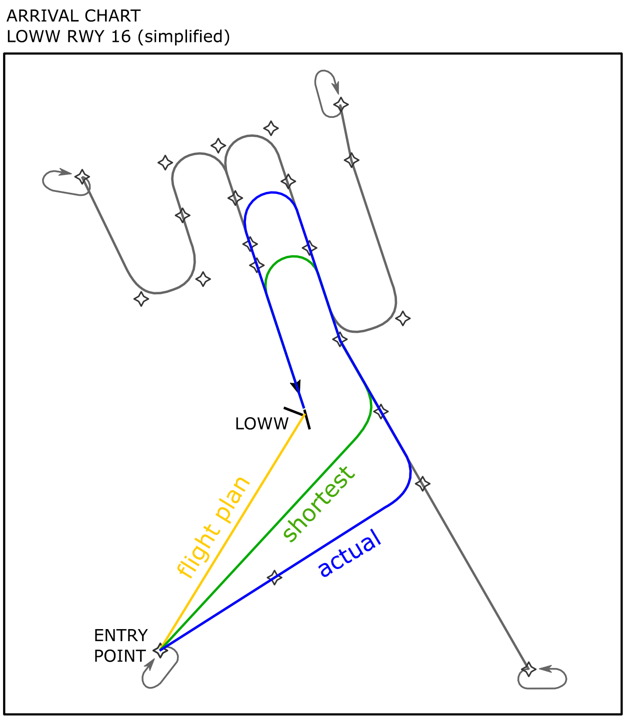

Figure 1. Visual representation of airborne delay. Example of actual (blue), shortest possible (green) and flightplan (yellow) flight path between terminal airspace entry and touchdown. Full transitions to final and holdings at entry points are shown in grey.

that the cost of delay depends heavily on these variables. The cost of delay is not a linear function of time, but is increasing in steps. This is because major cost contributions increase rapidly when certain delay durations are exceeded, but are relatively constant between those thresholds. One example is passenger cost related to missed connections. As long as a passenger reaches the connection flight no additional cost accrues, once the connection is missed high cost for arranging an alternative connection are incurred, these costs stay however constant again until the next threshold is reached, e.g. need for hotel accommodation because no alternative connection is available on the same day. Cook and Tanner [15] give detailed cost estimates based on aircraft type, delay length and flight phase. Even this more detailed data lacks valuable details as for example it cannot consider the actual number of connecting passengers on an individual flight. However, an evaluation considering this level of details is not possible as such information is not disclosed by airlines for competitive reasons.

Estimating the cost of diversion is even more complicated as this varies even more depending on the situation. In situations where after a diversion to a close airport the original destination can be reached after a short stopover, this diversion can incur less cost than waiting in a holding pattern. On the other hand, when after a diversion the crew cannot continue to the initial destination and a replacement crew or alternative transport needs to be organized, the resulting costs will be significant. The cost estimates used for diversions in this study are based on [14], where estimates are given for regional, continental and intercontinental flights. For simplification the

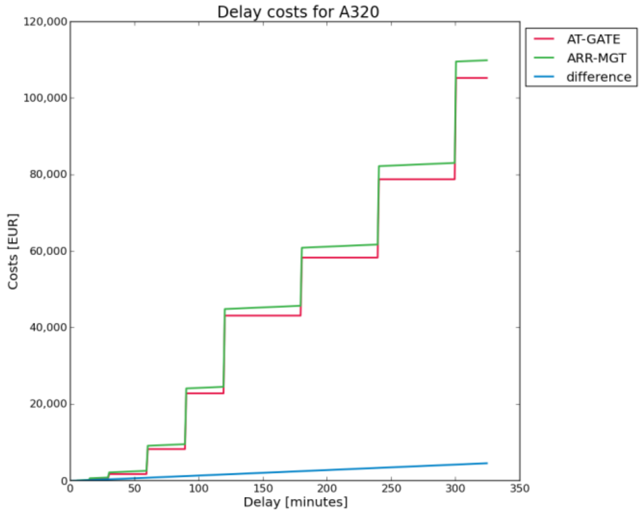

Figure 2. Delay costs for A320 for at-gate (red) and arrival management (green) delays as given by [15]. The blue line shows the difference.

type of flight is derived based on aircraft type rather than departure aerodrome in the evaluations presented here.

In [15] cost of delay is given for different flight phases, relevant for this study are the at-gate and arrival management phases for the ATFM and airborne delays, respectively. Fig. 2 shows the delay costs for an A320 aircraft as function of time. As aircrafts can be affected by both ATFM and airborne delays it is necessary to account for that in a suitable way. The delays cannot be treated independently, because the major part of the delay cost is related to passenger cost, which depends on the total delay irrespective of the flight phase. This is also obvious when looking at the difference of at-gate and arrival management delays (cf. Fig. 2). The difference is linear in time, consistent with the contributions it represents, e.g. fuel cost, which are a function of flight time. Following this analysis, the total cost of delay is calculated based on at-gate delay cost for the total delay increased by the in-flight costs for the airborne delay time.

Cook and Tanner [15] suggest to derive costs for aircraft types not explicitly covered based on maximum takeoff weight. In this study a simpler approach is used: aircraft types where no costs are available are mapped manually to similar aircraft types covered in the cost estimates.

The total cost for an evaluation scenario as discussed above (Table III) is calculated as the sum of total delay cost for all flights plus cost of diversions, if any occurred.

III. RESULTS

Applying the method described the impact of various weather phenomena on arrival management were investigated. In the following results for a runway closure event due to heavy snow and a low visibility event will be discussed in detail. The other studies not discussed here included a comparison of distance based to time based separation on final approach, as well as a case with heavy thunderstorm in terminal airspace and at the airport. Also for these events interesting insights have been obtained from the analysis, which will help to improve procedures and integration of weather forecasts in the future.

A. Heavy snow event

This evaluation is based on a synthetic example in which a runway closure is assumed during the morning peak hour of LOWW. The runway is closed for 45 minutes, which is approximately the time needed to perform a full snow clearing on the runway, between 06:10 and 06:55. In addition, the assumed wind situation does not allow for using the second runway, i.e. there are no landings possible during this period. The four scenarios according Table III simulated for the event are:

- *None (n)*: Runway not closed. No traffic regulation applied; average maximum holding time: 20 minutes.
- *Missed (m)*: Runway closed. No traffic regulation applied; average maximum holding time: 20 minutes.
- *Hit (h)*: Runway closed. Traffic regulation with acceptance rate of zero arrivals between 06:10 and 06:55 issued at 05:00; average maximum holding time: 30 minutes.
- *False alarm (f)*: Runway not closed. Traffic regulation with acceptance rate of zero arrivals between 06:10 and 06:55 issued at 05:00; average maximum holding time: 30 minutes.

The *h* and *f* scenarios are based on the forecasted closure of the runway, as a wind situation is assumed which does not allow for the use of the second runway during this time, the acceptance rate is set to zero arrivals. The forecast is also reflected in the average maximum holding time, where it is assumed that airlines carry extra fuel in case of predicted snow. The *m* and *f* scenario are simplified in the way, that a regulation would be issued once the event happens unexpectedly or would be cancelled once it is clear that the expected restriction will not happen. The impact of this simplification should be limited as the duration of the considered event is rather short.

The results of the event evaluation are given in Table IV and contain 75 flights which landed during the two-and-a-half-hour simulation time. The reference scenario *n* where the runway closure does not happen and no precautionary measures have been taken has by far the lowest cost. The false alarm scenario *f*, where action was taken but the runway was not closed shows already considerable cost. If no action is taken and the event occurs, scenario *m*, clearly the highest cost is incurred. The *h* scenario, where action was taken well in advance, i.e. based on an accurate weather forecast, still shows high cost but the actions reduced the cost considerably compared to the *m* scenario. So for the event evaluated here a perfect forecast, as considered in the *h* scenario, can save 50,604 Euro of delay costs. In the real world there is of course a forecast uncertainty, both regarding the weather and regarding the actual time needed for cleaning. That means the actual achievable saving will be lower than the amount found here, but there is a clear indication of the forecast value. One should also keep in mind, that the cost model also involves simplifications and uncertainty, so there is definitely an uncertainty in the results.

The cost – loss ratio derived from the cost for the four scenarios is 0.46, i.e. in case a well calibrated probability forecast would be available it would be beneficial in the long run to take action if the forecast probability of the event occurring is higher than 0.46.

TABLE IV. HEAVY SNOW EVENT - KPIS

	n	*f*	*m*	*h*
Diversions	0	0	15	3
Holding time [min]	46	71	239	291
ATFM delay [min]	0	823	0	823
ATFM delay cost [€]	0	19,710	0	19,710
Airborne delay cost [€]	40,063	63,856	52,268	82,754
Total delay cost [€]	40,063	83,566	52,268	102,464
Diversion cost [€]	0	0	124,500	23,700
Total cost [€]	**40,063**	**83,566**	**176,768**	**126,164**

KPIs for 2.5-hours simulation time incorporating 75 flights.

B. Low visibility event

In situations with low cloud base and reduced runway visual range so called low visibility procedures need to be put into force. Depending on cloud ceiling and runway visual range the spacing of aircrafts on final approach must be increased from 2.5 nautical miles to 4 nautical miles or 6 nautical miles. That means that the runway capacity for landing aircrafts is reduced from above 40 under normal conditions to 25 or 18. If this happens during a traffic peak hour, it causes major disruptions.

Results shown here are based on an event during the morning rush hour. In a one-hour timeframe low visibility procedures have been in force, most of the time with 4 nautical miles spacing, with a 15-minute interval of 6 nautical miles spacing. Again four scenarios according Table III have been simulated:

- *None (n)*: Low visibility situation does not happen and no traffic regulation applied.
- *Missed (m)*: Low visibility situation happens. Traffic regulation is issued once the event happens. The acceptance rate is set to 25 for the duration of the traffic peak once 4 nautical miles spacing needs to be applied. At the onset of the period with 6 nautical miles spacing the acceptance rate is reduced to 18.
- *Hit (h)*: Low visibility situation happens. A traffic regulation was issued with a lead-time of one hour setting an acceptance rate of 30 arrivals for the duration of the expected event. Once the event happened the regulation was updated to an acceptance rate of 25 for the duration of the event.
- *False alarm (f)*: Low visibility situation does not happen. A traffic regulation with acceptance rate of 30

arrivals was issued with one-hour lead-time for the duration of the expected event.

In practice the flow management position together with the approach supervisor issues the regulation based on available weather information, traffic situation and staff availability. The regulations used in this study are based on general guidelines for low visibility situations. These are to issue a regulation with acceptance rate of 30 in case a low visibility situation is forecasted. Setting the acceptance rate slightly higher than the actual capacity in case the event happens accounts for the uncertainty of the forecast. Once the low visibility situation happens the acceptance rate is updated to reflect the actual situation. The *m* scenario represents a worst case situation with no available or wrong weather forecast, hence the regulations is applied for the duration of the full traffic peak. Due to the lack of a good forecast it is not anticipated, that the period with worst conditions, requiring 6 nautical miles spacing, is only very short. In the *h* scenario on the other hand forecast information is available and no reduction of the acceptance rate to 18 is applied. In the *f* scenario the regulation is not cancelled once the event is not happening, accounting for the fact that the occurrence might be expected delayed.

The results of the simulation evaluation are given in Table V and are based on 103 flights landed during the four-and-a-half-hour simulation time. The *m* scenario, where no mitigation action was taken and the low visibility situation occurred, shows, as expected, the highest cost of all scenarios. However, the *f* scenario where action was taken although the event did not happen shows the lowest cost of all scenarios. This is counter intuitive because one would expect, that the cost for the unnecessary, as the low visibility situation is not happening, ATFM delays would increase the total cost compared to the *n* event. The reason total cost is decreasing is that the ATFM delays for the 21 regulated flights are all below 15 minutes, on average approximately 8 minutes, which means the cost is limited. On the other hand, the ATFM regulation distributes the traffic better over time, hence reducing traffic peaks, which means the traffic is more efficient in terminal airspace. The resulting reduction in airborne delay is saving more cost than incurred by the regulation delay. This means the cost – loss ratio derived from these results is negative, as it would be beneficial to always take measures, even if the event is not expected.

This raises the questions why airlines who are in general very cost sensitive are not adjusting their flight schedule accordingly or if the evaluation is flawed. There might be marketing reasons for airlines operating a hub and spoke system to not distribute their flights more evenly, even if the shifts would be less than 10 minutes. Having an earlier scheduled arrival time might increase sales. Another reason could be, that even a 10 minutes shift in scheduled arrival time could bring transfer times below a limit, so that certain connection could not be offered. That could mean that the observed effect is caused by using traffic demand as input for the simulation, where many flights might be scheduled at a similar time, while in reality the arrival is spread out by various effect, e.g. early / late departures, shortcuts along the route. To investigate this and test the sensitivity of the evaluation to small shifts in traffic, the evaluation was done with various variants of traffic. All variants use traffic from the same day, which was a day with no disruptions in arrival traffic to Vienna. This makes sure that no effects of traffic regulations taken in reality affect the results. Four traffic variations were used: The unaltered traffic demand (full results shown in Table V). Two cases with random variations applied to traffic demand entry times. Shifts were up to ten minutes in both directions in one case and up to five minutes in the other case. In addition, the evaluation was also done based on traffic load.

TABLE V. LOW VISIBILITY EVENT - KPIS

	n	***f***	***m***	***h***
Diversions	0	0	0	0
Holding time [min]	54	33	77	35
ATFM delay [min]	0	172	211	191
ATFM delay cost [€]	0	1,010	3,790	1,590
Airborne delay cost [€]	56,936	54,758	60,534	56,422
Total delay cost [€]	56,936	55,768	64,324	58,012
Diversion cost [€]	0	0	0	0
Total cost [€]	**56,936**	**55,768**	**64,324**	**58,012**

KPIs for 4.5-hours simulation time incorporating 103 flights.

TABLE VI. TRAFFIC SENSITIVITY

traffic	***n***	***f***	***m***	***h***	***C / L***
Demand	56,936 (0)	55,768 (-1,168)	64,324 (7,388)	58,012 (1,076)	-0.23
Demand +/- 10min	63,799 (0)	66,135 (2,336)	71,028 (7,229)	66,977 (3,178)	0.37
Demand +/- 5min	54,348 (0)	55,684 (1,336)	67,916 (13,568)	58,051 (3,703)	0.12
Load	19,573 (0)	19,121 (-452)	27,382 (7,809)	20,380 (807)	-0.07

KPIs for 4.5-hours simulation time incorporating 103 flights.

Table VI shows the total costs for the four scenarios based on the four traffic variations along with the resulting cost – loss ratio. A rather high sensitivity depending on traffic can be observed for cost as well as cost – loss ratio. The most striking difference in cost results when using traffic load as input. The reason is that in traffic load data the actual entry and landing times are given, hence the implicit airborne delay caused by the too short time between STAR endpoint and landing in the flight plan (cf. Fig. 1) is not as distinct. The remaining airborne delay can be explained by differences between simulation and reality[4]. The differences in cost are less pronounced when only the difference to the *n* scenario of the respective traffic variant is considered (numbers in parentheses in Table VI). The variation in the cost – loss ratio is however very pronounced. This suggests that for a given weather event even small variations in traffic can considerably change the cost loss ratio. That means that for profitable use of probability forecasts in decision making an integrated approach considering weather and traffic information is required. In addition, one should also keep in mind, that there is also considerable uncertainty in the cost model as simplifications are unavoidable. Due to missing insight into airline cost drivers, e.g. number of transfer

[4] These differences arise because the runway in use might have been different on the day the traffic happened and in the simulation, so flying times from STAR endpoint to landing might differ. In the evaluation airborne delay costs are not reduced for flights landing ahead of schedule, so there is an intrinsic bias because some flights are quicker and some slower in the simulation compared to the real times in traffic load.

passengers, it is not possible to do exact real time cost estimates.

In addition to the uncertainties in the cost model and the discussed sensitivity to traffic, comparison of the results for the snow (Table IV) and low visibility (Table V) event shows, that the costs also vary considerably dependent on the severity of the weather event. One factor is the duration of the event, i.e. a notably longer low visibility event would have had much higher impact as the one-hour event shown here. The snow event shown is of comparable duration to the low visibility event, but results in much higher cost because its impact on capacity, requiring an arrival rate of zero during runway cleaning, is much higher. The applied measures and probability thresholds to take action are hence dependent on the severity of the weather event and the traffic situation. The presented methodology can be used to optimize the decision making process under various conditions.

IV. Conclusions

An approach to quantify weather impact on arrival management based on fast time simulation was presented. The used air traffic simulator was validated by comparing simulated traffic to real traffic, as well as by expert judgment of air traffic controllers. The outcome of this validation was positive for all weather situations investigated and suggests that the simulations can be used for sensitivity analyses. The method presented is based on airline cost of delay, which means in addition to the air traffic simulation also a reasonable cost model is needed. The presented cost model is based on delay costs, where a combination of ground delays due to ATFM regulations and airborne delays due to congestion in terminal airspace are considered.

While the presented method is considering the delay of each individual flight there are still many simplifications applied in the cost model. One important delay cost factor are passenger costs, especially for connecting passenger who miss their connection. While these costs are factored in on an average basis in the delay costs used ([15]), those costs depend heavily on the number of connecting passengers on a flight. As data on connecting passengers for each individual flight are not disclosed by airlines, this simplification is unavoidable and adds uncertainty to the evaluation. A further uncertainty factor is, that the considered delay costs are independent of time of day, while it must be expected that knock-on costs of delays, e.g. due to late arrival of the aircraft causing additional delays down the line, are higher for flights early in the day.

The analysis of the low visibility event suggests that the false alarm event, where traffic was regulated despite the event did not happen, has lower cost than the undisturbed event. This needs to be further investigated as there could be cost factors, which were not included so far. For example, marketing considerations could be the reason for not spreading the flights more evenly to avoid congestion, so the value of such a decision would need to be included in the cost – loss examination.

These uncertainties need to be considered when interpreting the results, especially the absolute costs for individual scenarios must be interpreted carefully. For example, the airborne delay calculation for traffic based on demand raises the need to use a suitable cost reference, as the delays are calculated against an unachievable reference. Despite the identified uncertainties and shortcomings of the cost model the analysis gives valuable insights when the various scenarios of a weather event are compared. In that way also the impact of varying mitigation actions can be observed. Further studies can build on the insights achieved to investigated how the decision making process and the actions taken can be optimized. For that, it will be important to clearly specify the optimization measures. The results show, that this can only be achieved if all stakeholders, specially the airlines who bear the major part of the delay costs, are included in the process.

The methodology presented here was developed for Vienna International Airport, but can in principle be adopted to other airports as well. To do so the fast time simulation needs to be adapted to include airport specific ATM procedures and also the scenario definition must be adjusted to local characteristics.

This study showed the feasibility of quantifying weather impact on the arrival management and will be the basis for further work to improve the arrival management processes and to better integrate the weather in air traffic management decision making. If the method can be applied also to en-route applications, needs to be investigated, as the impacts are less well defined there.

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