Improved airport operations planning by using tailored forecasts of severe weather

Günther, Yves[1], Pick, Andreas[2], Kern, Stefan[3] and Lorenz, Sandro[4]
German Aerospace Center (DLR), Institute of Flight Guidance, 38108 Braunschweig, Germany

And
Gerz, Thomas[5], Felix Keis[6], Martin Köhler[7]
German Aerospace Center (DLR), Institute of Atmospheric Physics, 82234 Oberpfaffenhofen, Germany

At airports Stakeholders, like ANSP, airport authority, ground service provider and airlines are driven by different goals. Therefore they very often just focus on their own processes and do not coordinate with other Stakeholders. That results in missing information, installation of buffer times and a lack of alignment. The new concept of a Performance Based Airport Management (PBAM) introduces Key Performance Indicators (KPI) to manage the processes and requires the involvement of all Stakeholders. As one enabler for PBAM pre-tactical planning of airport processes is identified. Particularly disruptive for the daily airport business are weather events like thunderstorms or snow fall and freezing rain. Today impacts on the operations are awaited but mostly not considered in pre-tactical planning (timeframe up to day of ops) of operational processes. Often, the present meteorological services do not meet the needs of operators at an airport or the delivered products are not specific enough. The disruptive impact of adverse weather on an airport could however be mitigated by using dedicated and tailored observations and forecasts of weather and integrating them into the information sharing and decision making processes. Through a reliable and robust weather forecast air traffic can be operationally influenced much earlier and necessary decisions can be initiated.

I. Introduction

The growth in aviation poses challenges to all parties participating in the Air Traffic Management (ATM) system. Organizations such as air traffic control, airlines and airport operators therefore develop new and improved methods and procedures to make air travel more efficient and safe. With the goal of a competitive European Air Traffic Management, the European Commission is pushing her Single European Sky (SES) initiative by implementing the "Performance Based Air Traffic Management (ATM)". The evaluation criterion for the „Performance Based Air Traffic Management“ is based on defined key performance indicators (KPIs). KPIs are, for example, punctuality, delay, capacity, security. The airport is operating within the "Air-to-Air" process and therefore plays an important role within the Single European Sky. The European airspace management can thus be designed only efficient if the airports are operated according to similar criteria.

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[1] Research Associate, Institute of Flight Guidance, yves.guenther@dlr.de
[2] Research Associate, Institute of Flight Guidance, andreas.pick@dlr.de
[3] Research Associate, Institute of Flight Guidance, stefan.kern@dlr.de
[4] Research Associate, Institute of Flight Guidance, sandro.lorenz@dlr.de
[5] Head of Dep. of Transport Meteorology at the Institute of Atmospheric Physics, thomas.gerz@dlr.de
[6] PhD student, Institute of Atmospheric Physics
[7] PhD student, Institute of Atmospheric Physics, martin.koehler@dlr.de,

Stakeholders of an airport are nowadays often responsible only for their own processes at the airport. They plan and organize them inside own operational centers (as airline operations center, operations control center of the ground handler, airport operations center of the airport operating company etc.). Because of this spatial separation information exchange, communication and mutual agreements usually take place only rudimentary. For example, delays or information about early aircrafts (as North Atlantic waves) are exchanged between the stakeholders too late. This results in suboptimal cooperation and coordination processes. The processes are not perfectly matched. Reasons for action are not communicated, which also can lead to conflicts and misunderstandings. Both lead ultimately to the fact that the control and regulation of airport processes is not running optimally.

In 2006 a new concept, called Total Airport Management (TAM) was introduced by the German Aerospace Center and the Eurocontrol Experimental Center[1]. This concept describes basic changes to Airport Operations for the period after 2020, with a view to the pre-tactical planning horizon (away from the present-day ad hoc and tactical point of view). It is intended in this concept that stakeholders of an airport develop strategies together for each day of operation with a horizon of several hours in advance up to the whole day. They orient towards Key Performance Indicators (KPI) giving them an impression of how the airport is running. As evolution of that early concept DLR came up with the concept of "Performance Based Airport Management (PBAM)" concentrating on KPIs as drivers for airport steering and control.

The intention of this paper is to identify the impact of a pre-tactical planning, representing a situation with all stakeholders working together to reach an overall goal.
To begin with, the parameters of weather forecast will be discussed and methods how to improve their accuracy. Both a winter weather and thunderstorm scenario are considered, whereat only thunderstorms are considered in the simulations. This information is used to set up simulation scenarios based on a fast-time simulation tool coupled with a planning tool to assess the influence of pre-tactical and improved weather forecast. In the end the results are presented and discussed.

II. Improving Weather Forecast for a more accurate pre-tactical planning

Two of the most relevant weather scenarios which hinder or even jeopardize air traffic in Europe are thunderstorms with wind shear, turbulence, lightning, hail and heavy rain and winter weather events with snow, freezing rain, ice pellets and icing surfaces. We introduce measures to analyze observations and to predict the weather for the next hours for a summer weather and a winter weather event.

A. A Winter Weather Scenario

Airport operations in winter are significantly impacted by weather conditions such as snow fall, freezing rain and drizzle, as well as low ceiling and visibility. Delays and cancellation of flights are often resulting from these weather conditions. Runways and taxiways must be kept free of or cleared from snow and ice and aircraft have to be de-iced before take-off. Planning and managing the air traffic can be significantly impacted through these procedures. To optimize the procedures under those conditions, the very short-term forecast (termed "nowcast") of the onset, duration an type of precipitation and icing on the surface or the aircraft at ground are of particular interest for the airport management. The automated winter weather nowcasting system WHITE[3] is designed to fulfill the expectations. It assimilates multiple real-time and remotely sensing data sources, combines critical parameters for different winter weather scenarios by means of Fuzzy Logic and generates winter weather objects. Those objects determine the precipitation type and hazard's intensity. By predicting the situation over a period of two hours ("nowcasting") also the beginning and the duration of the icing conditions within the investigation area are estimated.

On the 20th of January 2013 Frankfurt Airport had to suspend flight service for several hours in the afternoon, because aircraft de-icing wasn't possible any more. Also for Munich Airport the German Meteorological Service DWD forecasted freezing precipitation for the period from 15:30 UTC until 18:00 UTC. In fact, only at 17:00 UTC freezing drizzle was observed which had no adverse effect of the airport operations. By assimilating the most recent measurement data WHITE was able to predict this situation correctly for 1 hour in advance. This information status leads to advantages in the decision process of Stakeholders regarding the pre-tactical planning.

In Figure 1 the weather situation as analyzed and predicted by WHITE is shown for the lowermost model layer (2 m above the ground). At the analysis time, a south westerly warm air stream poured into the investigation area. The uplift of this stream over the prevailing cold air resulted in the formation of the distinct warm front. Solid precipitation melted or even evaporated within the embedded warm air and super-cooled in the bottom cold air (see vertical profiles and nowcast of the weather object at Munich Airport in Figure 2). At 16:30 UTC the system calculated no hazardous situation on the ground for Munich Airport. However, the nowcast of 15 minutes and 30 minutes produced freezing rain, whereas after 60 minutes the situation was expected to return to (non-freezing) rain, as was indeed the case. A comparison with the original measurements of the radar precipitation scan (green areas in Figure 1) proves that the system is able to detect areas without precipitation. Based on the precipitation scan alone one couldn't provide a sufficient situation assessment. The weather objects (red areas/black contour lines in the Figure provide nowcast that is consistent with the weather observed at Munich Airport.

Figure 1 also reveals spacious areas of freezing precipitation in northern Central Franconia and western Upper Palatinate. Also these areas are consistent with weather observations. For example at Nuremberg airport freezing precipitation was observed at 16:00 UTC, 17:00 UTC and 18:00 UTC. At 17:00 UTC and 18:00 UTC freezing precipitation was reported from the city of Regensburg. At 16:00 UTC cloudy sky without precipitation was reported from there. At 18:00 UTC the freezing precipitation arrived at the city of Straubing. Moreover, the southerly object's delimitation can be traced with the aid of several weather observations. For example at the smaller airfields of Niederstetten (about 85 km southwest of Nuremberg) and Neunburg on the Danube (about 45 km northeast of Augsburg) no significant winter weather was observed throughout the afternoon.

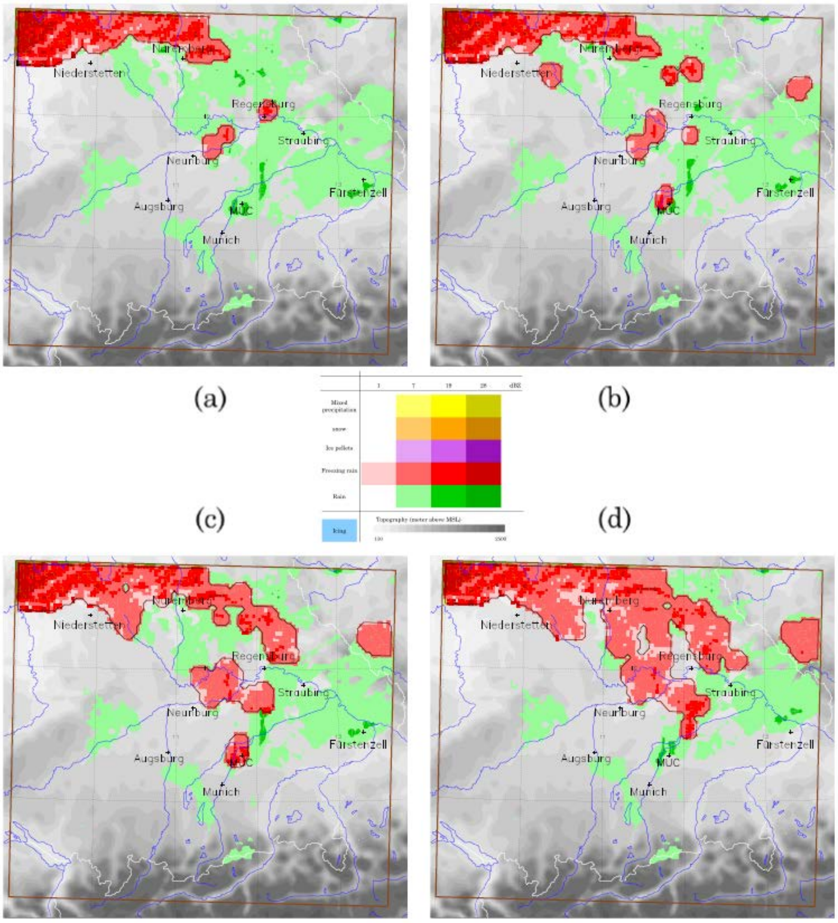


Figure 1: Illustration of winter weather objects of WHITE in the lowermost model layer (2m above the ground) for January 20, 2013, 16:30 UTC in the investigation area. Green shaded areas represent the raw radar reflectivity data. System objects are black-rimmed. (a) shows the situation at the time of analysis, (b) shows the nowcasting +15 minutes, (c) the nowcasting +30 minutes and (d) the nowcasting +60 minutes.

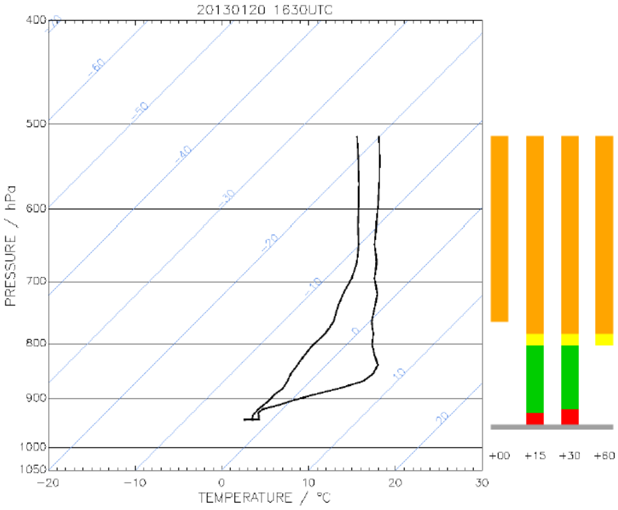
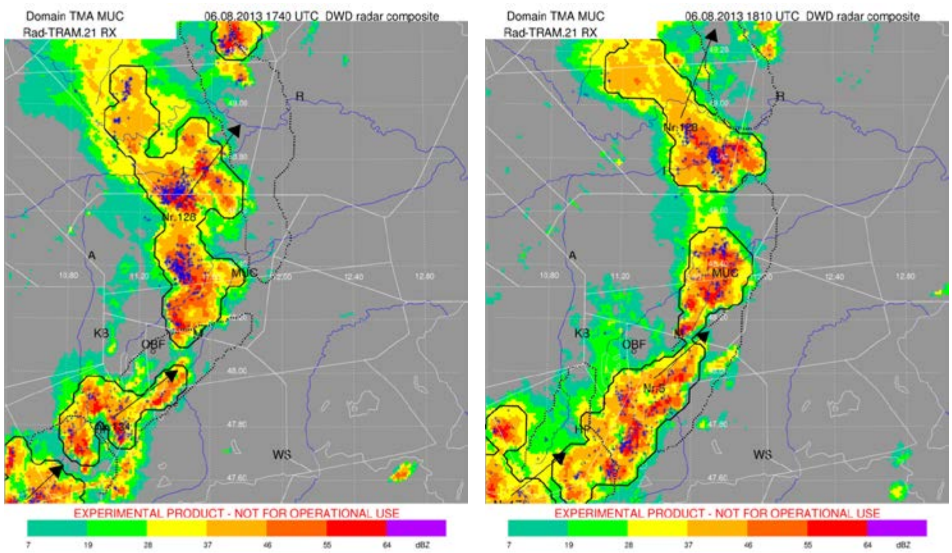


Figure 2: Profiles of temperature and humidity of January 20, 2013, 16:30 UTC at Munich Airport illustrated by a simplified Skew-T diagram. The color bars on the right symbolize the vertical system objects at this location for the time specified. Colors correspond to the legend of Figure 1.

B. A Thunderstorm Scenario

Thunderstorms are related to hazardous phenomena like turbulence, icing, hail, heavy rain, lightning and reduced visibility that can lead to considerable obstructions in the air transport system. For instance, if a thunderstorm passes an airport, ground operations might have to be stopped and flights have to be re-routed in holding patterns or even diverted because of hazardous weather phenomena in the airport's terminal maneuvering area (TMA). On-time, tailored and self-explaining meteorological information on thunderstorm development can be provided in the time period from observation and analysis up to six hours ahead by nowcast and forecast techniques. This offers a great opportunity to the Stakeholders to find an optimal solution.

For the analysis and prediction of thunderstorm cells up to 1 hour ahead, reflectivity data from the German weather radar network, provided by the German Meteorological Service, DWD, are assessed by the algorithm Rad-TRAM[4] in order to recognize and mark precipitation regions with heavy rain and hail. Figure 3 depicts thunderstorm cells on 6th of March 2013 in the Terminal Maneuvering Area (TMA) of Munich Airport between 17:40 and 19:10 UTC. Analyzed and 1-hour predicted cell contours are shown. Analysis and nowcast are repeated every 5 minutes when new radar data are available.



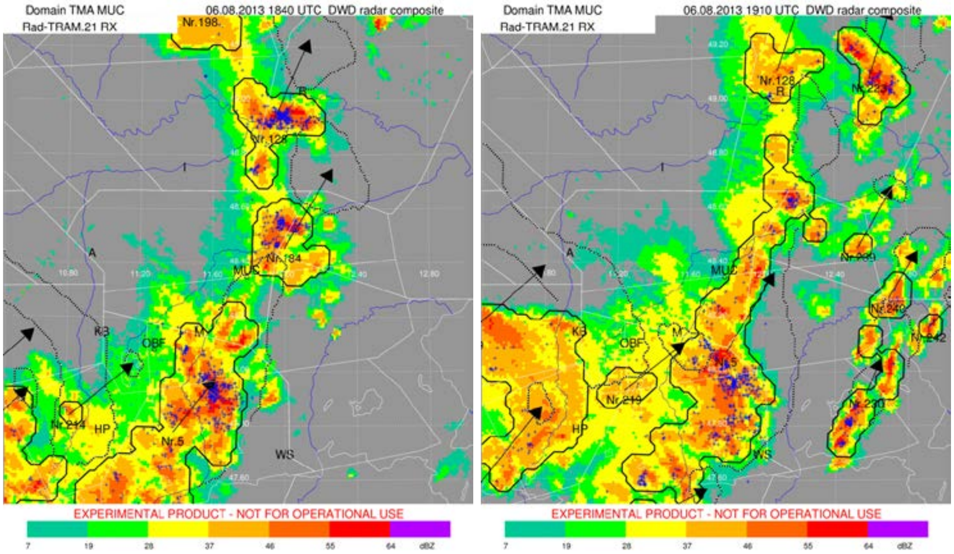


Figure 3: Reflectivity data (in dBZ) from the German weather radar network (color coded) and contours of the cells with heavy rain or hail as analyzed by Rad-TRAM in the TMA of Munich Airport. The solid black contours mark analyzed cells with a reflectivity of 37 dBZ or larger; the dotted lines are predicted cell contours 1 hour ahead. The arrows indicate the general motion of the cells.

The time horizon of 1 hour for predicting the movement of thunderstorm cells (achieved by Rad-TRAM) is extended to 6-hours predictions of the likelihood of thunderstorms in a given area by Cb-LIKE[5]. The fuzzy-logic algorithm Cb-LIKE combines hourly available output from the COSMO-DE model of DWD, namely convective available potential energy (CAPE), vertical velocity at 500 hPA pressure level, synthetic radar reflectivity, and cloud top temperature. The parameters are first transformed into fuzzy variables expressed by linguistic verbalisms with the help of the so-called fuzzy input sets. In a second step they are combined by an "if … then" decision rulebook and assigned to fuzzy output sets. The third step calculates the final output, the Cb likelihood as an indicator for the development of storms. The indicator comprises a range from 11.66 up to 88.33. The higher the value, the more the incoming model parameters suggest an occurrence of thunderstorms. Finally, skill scores, obtained by evaluating the algorithm during a test campaign in summer months, can be used to translate the likelihood into a thunderstorm probability.

DWD runs the COSMO-DE model in a so-called ensemble mode, i.e., at each output time data from several model runs are available. Before conducting the "fuzzy-logic" step, Cb-LIKE searches for the specific member out of an ensemble of five COSMO-DE model runs (from a time-lagged ensemble in our case) which matches best to the current weather situation, i.e. Cb-LIKE performs the so-called automated "best member selection" step. To this end, synthetic storm cells, detected from the synthetic radar reflectivity fields of the COSMO-DE model, are compared with real storm cells, detected by Rad-TRAM in the weather radar composite, for each COSMO-DE model run. The reflectivity threshold to differentiate potentially hazardous storm cells from non-hazardous rain patterns is 37 dBZ. An example of a 6-hours forecast of a Cb indicator is shown Figure 4.

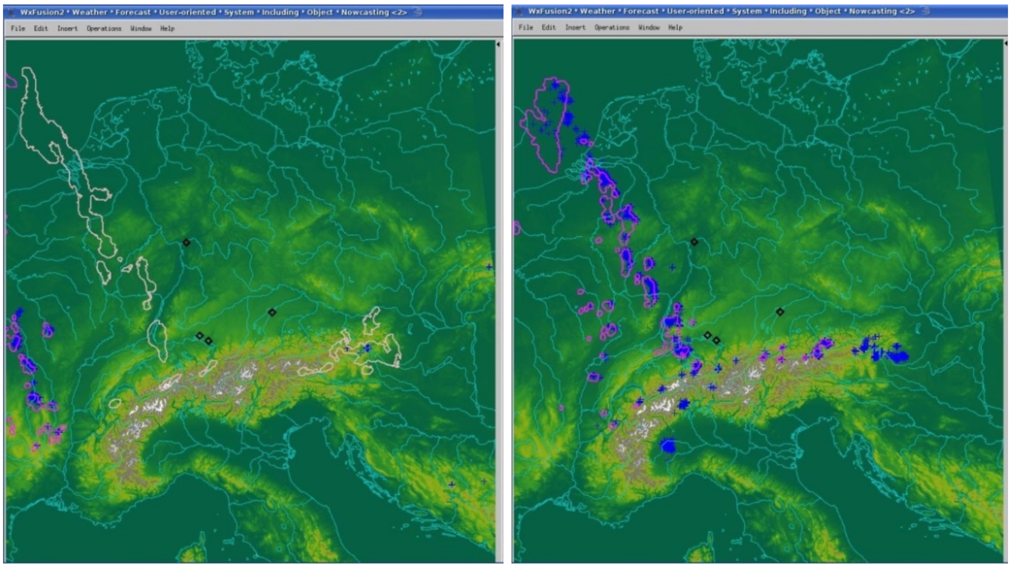


Figure 4: Example of a Cb-LIKE forecast. Left: 6-hour prognosis from 1200 UTC (white contours with an indicator of 50) together with the observed storm activity (blue crosses mark measured lightning activity, pink contour lines indicate the Rad-TRAM observations); the best member in this case was the COSMO-DE model run from 1200 UTC; right: observed storm activity (Rad-TRAM, lightning) at 1800 UTC.

In terms of the "seamless prediction" credo it is important to note, that the "best member selection" links the analysis and short-term nowcast by Rad-TRAM to the long-term forecast by Cb-LIKE such that consistent and non-interrupted meteorological information is available to the user. Especially in abnormal situations this offers the basis for an optimal decision finding.

III. Air Traffic Simulation

As part of a concept development, it is important to carry out an investigation of the effectiveness of the intended purpose or a performance evaluation. Especially in the early stages of development strengths and weaknesses can be identified using fast-time simulation tools. Looking ahead this knowledge can be used to derive any optimizations. The validation of pre-tactical planning, represented by the TOP Operations Planner (TOP), was carried out using the fast-time simulation environment of AirTOp.

A. Scenario Definition

The objective of improving operational efficiency of an airport by introducing a pre-tactical planning as well as improved weather forecast shall be proven. For the validation of a pre-tactical environment different scenarios were used. By comparing different scenarios the efficiency of pre-tactical planning and improved weather forecast can be evaluated (Table 1). Scenario 1 in contrast to scenario 2 shall prove a general efficiency increase due to pre-tactical planning, whereat Scenario 3 and 4 are used to assess the impact of improved weather forecast in pre-tactical planning.

Table 1: Simulation scenarios

Scenario	Weather	Planning
1	no weather impact	no pre-tactical planning
2		Pre-tactical planning (TOP)
3	with weather impact	no pre-tactical planning (information available 5 min before occurrence)
4		Pre-tactical planning (TOP, information available 90 min before occurrence)

The pre-tactical planning is embodied in the Total Operations Planner (TOP) developed by the German Aerospace Center (DLR). It communicates with the fast-time simulation tool AirTOp by giving each individual flight takeoff and landing times. TOP continuously updates its planning's based on the flight plan information, airport capacity, weather information and the stakeholder objectives expressed by weighted target function (e.g. minimal delay) for a 24h (pre-tactical-) time horizon of a takeoff / landing sequence to control air traffic at an airport. Depending on the planning interval flight plan times are repeatedly exchanged between the two systems. AirTOp on the other hand is used to express the airports environment including airport infrastructure, routes, separations, etc. Based on multi-agent, interactions between each aircraft (agents) and their environment (infrastructure) can be replicated. It takes into account individual aircraft performance and provides the ability to address individual elements of the infrastructure and to impose various rules.

Based on weather data from the Munich airport, a stormy day (including thunderstorms) has been selected, which has a characteristic effect on air traffic. Side effects such as hail, lightning, heavy rain or turbulence lead to evasive manoeuver in contrast to the thunderstorm cell, and terminating the aircraft ground handling. The corresponding weather data were projected onto the traffic-related conditions of a mid-sized airport. The flight plan used for all scenarios is based on a real flight plan of the 14th of October 2013. As object of investigation the year 2020 as well as a model of a mid-sized airport with crossing runways was used. The traffic demand was increased according to the traffic forecast of the intraplan-Consult GmbH by 15%.[6] For the simulation of different scenarios, different methods and standards apply, which are described in the following section.

A. Simulation setup

At the beginning of the setup, infrastructural components, like Runways, Taxiways or Parking positions have been implemented in the simulation environment. Furthermore approach, departure procedures, Holdings as well as separation standards, have been set up equal for all scenarios. Figure 5 shows the approach routes (black), the vectoring areas (light gray), the departure routes as well as the missed approach routes (red) for the simulated airport.

Figure 5: Terminal Menoeuvering Area

Entailed by the pre-tactical planning, target times of flights can require holding an aircraft at the departure airport or delaying it along the flight path. To ensure this to be implemented in the simulation the entire flight path between origin and destination has to be included. This is represented by the blue lines shown in Figure 6.

Figure 6: Flight routes from and to Hamburg

Beside the infrastructure of the airport and airspace, special rules and procedures had been implemented for the weather scenarios. This is among other things a redirection to an Alternate, stopping of ground handling during thunderstorm and a missed approach procedure. During Thunderstorm the airport capacity is reduced to zero and no aircraft is able to takeoff, land and there is no ground handling. This results partly from the lightning phenomena occurring as well as the high side wind which does not allow a take off and land at the airport. To simplify the scenarios, the thunderstorm was projected directly across the airport, without aircraft having to fly around the thunderstorm cell on the arrival and departure routes (see Figure 7).

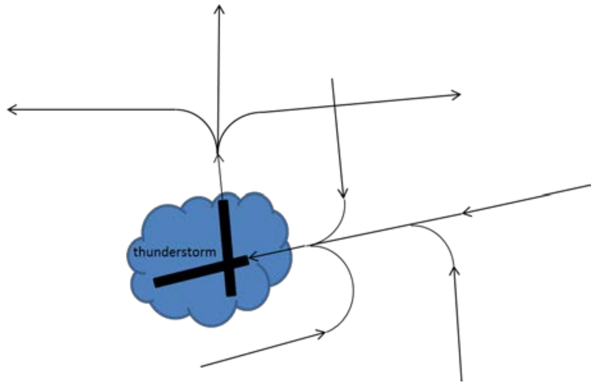


Figure 7: Thunderstorm cell over airport

The scenarios including weather phenomena differ in having a pre-tactical planning and not having one. Associated with pre-tactical planning the information about the weather situation is available 90 minutes before occurrence and will take place with 100% assurance in the way it was forecasted. The scenario without pre-tactical planning and improved weather forecast requires an ad hoc reaction (information 5 min before occurrence available) by the airport stakeholders. Based on the high quality of the weather forecast in scenario 4, aircraft will use the information to fly directly to their alternate even before reaching the holding in case of a thunderstorm. This will be conducted only in the case when the runways are still closed for the next 20 minutes. In contrast to these procedures, aircraft in scenario 3 will stay in Holding for 45 minutes before changing its destination. The duration of 45 minutes results from the assumption, that there is no concrete information about the reopening of the airport and the fact that aircraft have additional fuel, which makes a 45 minute holding possible.

For scenario 3 and 4, aircraft flying to the runway during a closure of the runways will be forced to do a go around and fly to a Holding. Furthermore all ground handling processes are stopped. Based on a condition for push back clearance (terminal) or taxiing (apron) aircraft are prevented from leaving the parking position. Moving on ground to the parking position after landing is not restricted at any time.

IV. Pre-tactical Planning System (TOP)

The first pre-tactical planning systems were developed by DLR and DFS in 2003. Later the underlying planning algorithm was reworked is now used as a prototype in different DLR-projects as Total Operations Planner (TOP).

The main goal of TOP is to support human decision makers in the pre-tactical phase of operations planning and calculating arising KPIs with a time horizon of up to 24 hours at a local airport. This is done by performing a planning taking into account the present traffic and resource constraints, and predefined weights of the goals to be addressed in the planning process. Because of being a support tool for live interactive human communication at negotiation process including What-if capabilities, alternative solutions depending on individual preferences are expected within seconds. Fulfilling these contradictory goals, namely producing of possible exact prediction of events with optimized control suggestion within a very short time had to be solved aiming the main target a human centered decision system. Since the resolutions are not safety relevant and there is always still enough time to correct infelicitous suggestions (especially because of humans involved in the decision loop) one can slightly sacrifice exactness to meet the most important requirements.

In TOP the optimization problem is separated in two levels of abstraction. First, using a simplified model of an airport operating system, defined as a set of interacting traffic flows of abstract entities, using resources and control parameters, a prediction of future state will be calculated and optimized

towards individual objectives under constraints predefined in contract of quality of service. Based on predicted abstract results the detailed plan of target event times for all traffic objects will be generated taking into account some individual constraints for events and resources being skipped on traffic flow abstraction level.
Assuming that the exact time definition for events for which even the source data are burdened with uncertainties of more than 5 minutes and the realization of suggested solution alike, we decide to transform the final stage of the original problem. At the Events and Resources Level we assume a given table of possible event independent times for each resource (fulfilling capacity and temporal causality restrictions of original). Within this projection from continuous time space into discrete domain a solution has to be found as a simple scheduling of events for a subset of key resources.
The necessary set of possible times for resources can be generated with a feasible accuracy using an internal system simulation. This leads to the Traffic Flow Level. Basing on given operational procedures at an airport a deterministic traffic flow model of resource usage has been constructed, where individual input events are transformed into abstract flow streams traversing the process model according to predefined restrictions. Within the system simulation changes of model states take place at evenly distributed time stamps which leads to selected tapped flows corresponding to usage of certain resource and therefore founds a source for counterpart time series. The behavior of the system is controlled by parameter settings, which are used to optimize the total system performance towards a set of derived cost functions (defined on another subset of tapped flows, additionally expanded in the discrete space of model time intervals).
Such a planning takes place automatically every 5 minute of system time, assuming information changes not with such a high frequency. The weather information addressed in this paper is used as input indirectly. There is no algorithm in TOP implemented, which deduces capacity constraints out of the weather; this has to be part of scenario definition. In addition, TOP has no information about reachability of the planned (wished) times if they are basing on scheduled times or old estimates only. Therefore good estimate times as reliable basis for planning are needed. The result is presented in the Airport Operations Plan (AOP) and can be distributed. The results used in this presentation are individual landing and take-off times for each flight.
TOP is a prototype and in the actual state of development neglects net effects, because information about fleet planning of circulating flights and constraints at linked airports are not in focus and can be carried out by the operations centers of the addressed stakeholders.

V. Coupling of Traffic planning with Fast Time Simulation

Coupling the pre-tactical planning system TOP with the FTS tool AirTOp was done by exchanging a set of flight plan data: target times at runway planned from TOP, and estimated and actual times calculated with AirTOp. In case of the necessity to divert a flight to an alternate airport, this information is also sent to TOP which leads to the cancelation of the local arrival the concatenated departure flight.

The principle of coupling both systems can be described in the following steps:

1) FTS stops simulation at a defined time
2) TOP gets present estimated and actual times (and flights which are diverted)
3) TOP actualizes its AOP data (including capacity restrictions and actual flight information)
4) TOP calculates planning times for the pre-tactical time horizon
5) FTS gets new planning times
6) FTS sets time constraints depending on new planning times
7) FTS resumes simulation
8) start from 1)

This cycle can be performed by hand or by using interacting possibilities of the FTS.

In preparation of this, the underlying capacities and taxi times had to be phased. Due to the raw capacity model used in TOP and the realistic separation given in AirTOp, the planned and the realized traffic flow does not fit all the time. Figure 8 shows the difference for arrivals resulting from this. TOP is planning more pessimistic.

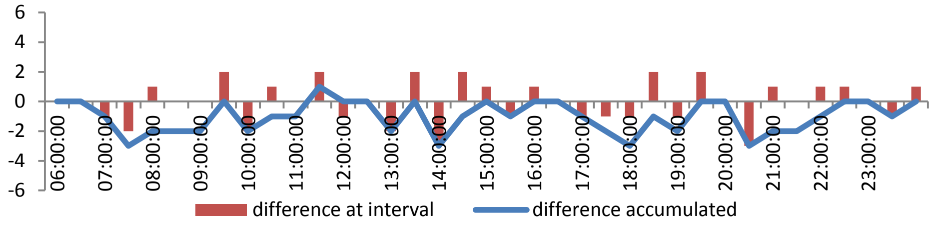


Figure 8: TOP is planning more / less movements than AirTOp realizes (arrivals only)

VI. Results / Conclusion

To generate results the scenario for FTS and TOP was defined as a normal day of traffic with a period of thunderstorm from 16:30 h to 18:00 h with a forecast time of 90 minutes (listed as scenario 4 in Table 1). The first aspect to address was the validation of the accuracy of pre-tactical traffic forecast by comparing the simulated traffic with the planned traffic. Only when the quality of traffic prognosis is sufficient, the effect of steering this traffic by establishing planning times can be investigated. Therefore a second aspect is the feasibility of PBAM-times through traffic simulation and measure the outcome.

The data for measuring quality of traffic prognosis is generated by running scenario 4 with TOP and the FTS independent from each other. By comparing the average delay of a flight which is scheduled in a specific hour it can be shown that planned and simulated traffic flow match good. This indicates already well compatible systems. Single differences can be found in the hour after the thunderstorm, this is a result of the divergent rules of handling demand high traffic intervals. The FTS shifts traffic behind the closure and handles it after the First-Come-First-Served principle. TOP is using cost functions for generating a sequence. In this some flights come in for the delays, while others get no extra delay. In addition in TOP, due to the long planning horizon, the mandatory separations are only rough mapped, whilst FTS takes it exactly into account. The next Figure 9 shows the result for departures. TOP is planning more flights after the thunderstorm (positive values on the left axis). The other curves are showing the delay planned by TOP (blue) and realized by FTS (red). The closeness of both curves indicates a good quality of the traffic forecast by TOP.

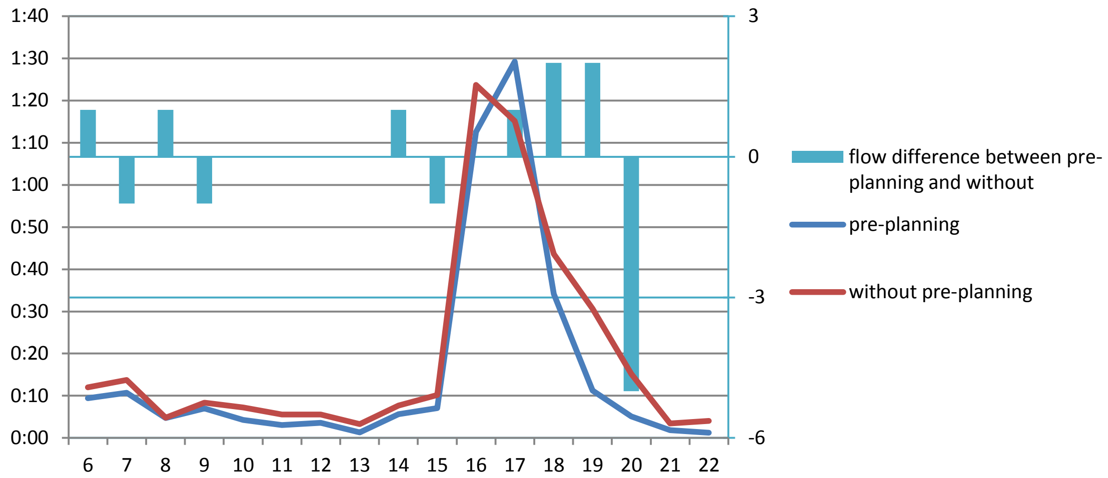


Figure 9: Average Departure Delay in hours and Flow Difference per hour

The feasibility of the planning times (using FTS) can be analyzed by comparing the average delay against schedule for all already realized flights. The delay can be divided into the part which results from the TOP planning and a second (additional) part which comes from FTS when it tries to realize the TOP time. The less the second part is, the more feasible pre-tactical times are. The difference (the blue part) shown in the next Figure 10 resulting from the difference in building sequences described before.

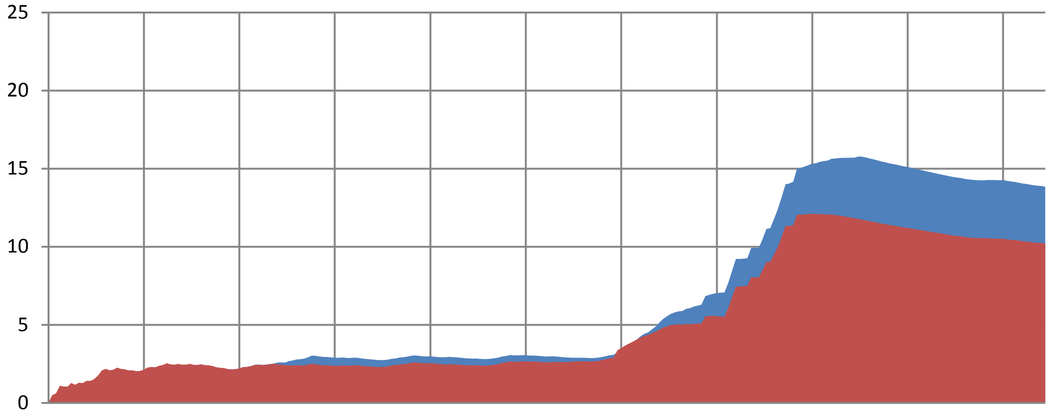


Figure 10: Average cumulative planned (red) and additional (blue) Arrival Delay in minutes per movement

To investigate the effect of improved weather forecast and the distribution of pre-tactical planning times 4 scenarios were run with the coupled TOP and FTS. All scenarios are with the described weather impact:

- TOP_05 weather forecast horizon is 5 minutes and pre-tactical planning is applied
- TOP_90 weather forecast horizon is 90 minutes and pre-tactical planning is applied
- WEA_05 weather forecast horizon is 5 minutes and pre-tactical planning is not applied
- WEA_90 weather forecast horizon is 90 minutes and pre-tactical planning is not applied

To build up realistic scenarios the weather impact was first forecasted without knowledge of the exact end of the thunderstorm. As a first assumption 2 hours of impact was taken. The real end of it, already after 1:30 h was then known 5 resp. 90 minutes before this end.

The following Table 2 shows different measured average delays for the whole traffic in minutes per flight from the different scenarios:

Table 2: Simulation scenarios

	Arrivals			**Departures**			
Scenario	**Diverted Flights**	**Total TouchDownDelay**	**SequencingDelay**	**Cancelled Flights**	**Total TakeOffDelay**	**Planned OffBlockDelay**	**DurationInQueue**
TOP_05	10	08:34	01:58	9	14:38	10:48	04:22
TOP_90	0	15:17	03:30	0	19:26	14:43	02:14
WEA_05	11	05:05	03:03	10	10:02	02:32	07:02
WEA_90	0	15:07	10:43	0	16:09	03:06	04:28

The column “Planned OffBlockDelay” shows delay planned from TOP resp. forced by weather impact. In the WEA scenarios this is only caused by flights which are put off to a time after the thunderstorm.

The main effect through improved weather forecast is the reduction of diversions and therefore the cancellation of the connected flight. The traffic can fully be planned and processed around the weather event.

Due to the not cancelled traffic the total delay increased from the 05-scenarios to 90-scenarios. But this could be acceptable because all the traffic was handled.

The outcome off using pre-tactical planning specially results in a reduced arrival sequencing delay (caused by holdings and path stretching in the vicinity of the airport) because the early known planning times which plan a delay can be prepared. The total touchdown delay is only slightly affected in the 90-scenario. The negative effect of TOP in TOP_05 is due to the late knowledge of the earlier end, because flights are already planned at a later time and if the runway is open again, no traffic is ready to use it. This shows encroachments and the sensitivity of a planning with not fully correct data.

By using pre-tactical planning the departure off-block times are evenly distributed according to the minimum time interval required to operate departing traffic. Departures stay at their parking position as long as possible and the taxi out and line up can be performed in a smoother way. Planning traffic in peak situations (e.g. forced by adverse weather) provides a sequence for the events, considering prioritizations and dependencies between flights and resources, and the flights can set up their processing to this given constraint. If there is no planning all traffic will be ready for next event at the same time and expensive waiting times, e.g. in runway queues, increase. Figure 11 illustrates the restart of airport operations immediately after the thunderstorm. The WEA scenario starts to build up a remarkable departure queue with increasing delays (red diamonds) caused by the fact that several movements had to be shifted to the end of the runway closure timed at 18:00 (see left ends of red indicator lines). In comparison to these results the TOP 90 scenario causes an overall less queue delay (blue triangles) due to the pre-planning process recognizable by the shorter blue indicator lines meaning that there are slighter differences in between planned and actual times.

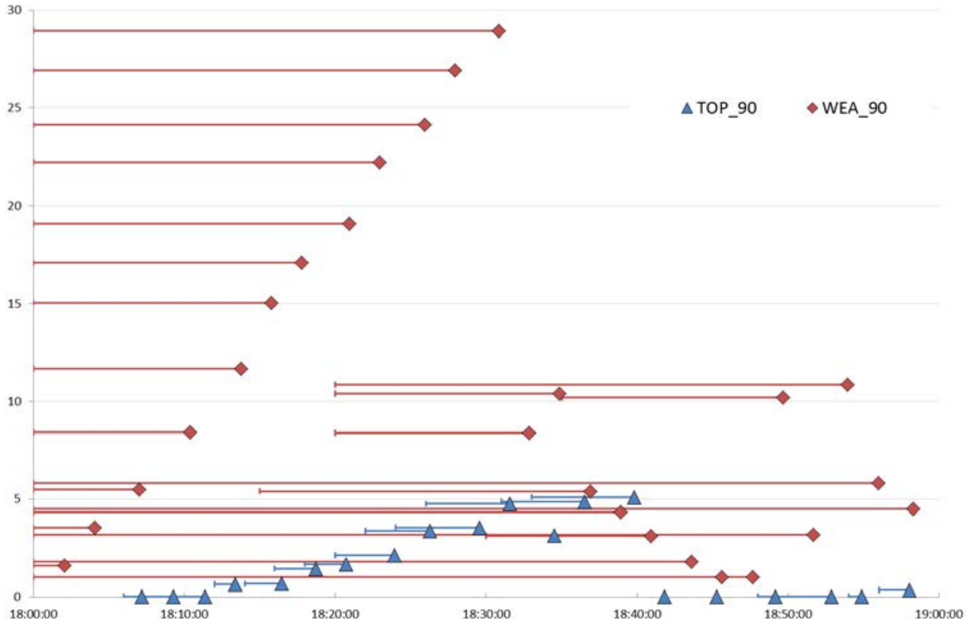


Figure 11: Queue Delay per flight in minutes plotted against Actual and Planned Take-Off Times

In general, the early knowledge of the weather and the impacted critical performance indicators, and the concept of pre-tactical planning times are necessary to be prepared for adverse weather conditions and a well-organized processing of the traffic situation. The results of this paper are based on only one specific scenario (Thunderstorm), which can be supplemented e.g. by other disruptive phenomena, whose results and influences also have to be taken into account for the assessment of a pre-tactical planning. Furthermore weak points of a pre-tactical planning have been identified, which require further analysis and modifications.

VII. References

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