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THE NETWORK FLOW ENVIRONMENT: SLOT ALLOCATION MODEL EVALUATION WITH CONVECTIVE NOWCASTING

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Abstract

The purpose of this paper is to evaluate a slot allocation heuristic algorithm close to Eurocontrol's Computer-Aided-Slot-Allocation. The heuristic algorithm represents a First-Planned-First-Serve approach for tactical Air Traffic Flow Management slot allocation in order to balance air traffic demand with network capacities. It is part of DLR's Network Flow Environment (NFE) introduced in this paper, which allocates tactical Air Traffic Flow Management slots throughout the whole European Air Traffic Management Network by satisfying the objective of optimal network delay minimization. In order to quantify delay cost reduction applying a binary integer programming approach, the First-Planned-First-Serve heuristic serves as delay allocation reference for individual adverse impact scenarios. Short-term convective forecasts (nowcasts) serve as use-case to generate demand-capacity-imbalances. It shows, that the First-Planned-First-Serve heuristic is capable to generate representative slot allocation data for operational scenario setups. In terms of delay performance, results can be improved by optimization for large-scale Air Traffic Flow Management problems.

1 Introduction

Air Traffic Flow Management (ATFM) in Europe is the function to balance air traffic demand with system capacities of airports and air traffic control (ATC) airspaces, called *ATC sectors*. Several ATFM sub-functions exist, which are assigned to four time-related execution phases [9]: (i) The Strategic Phase starts at least 6 months before the day of operation and ends approximately 7 days before. This phase includes flight plan processing, coordination actions and pre-planning in terms of predicting highly congested network elements caused by respective traffic load of e.g. public mass events. Bottlenecks of traffic flows within the European Air Traffic Management Network (EATMN) are identified. (ii) The Pre-tactical Phase applied during the six days before the day of operation allocates a range of Air Traffic Flow and Capacity Management (ATFCM) measures, like e.g. rerouting scenarios to individual groups of flights [10]. Furthermore, pre-tactical capacity regulations are planned according to the actual information state. (iii) The Tactical Phase conducted on the day of operations regularly updates traffic rates and capacities. Especially in the case of adverse network impact, capacity profiles dynamically fluctuate according to traffic complexity patterns. A demand-capacity-balancing (DCB) process is applied, which integrates dynamic airspace management and pre-flight departure slot allocation. Finally, during phase (iv), ad-hoc activities conducted collaboratively by controllers and pilots, are applied to stabilize traffic flows within impacted airspaces and congested airports. Fig. 1 depicts the time line and functions of the described ATFCM phases.

Weather is one of the major reasons for

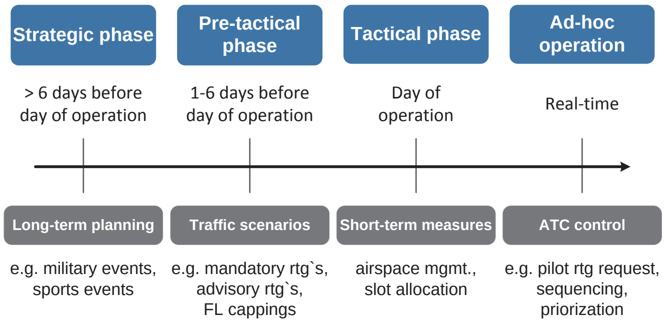

Fig. 1 ATFCM phases and functions.

ATFM related delay[1] in the EATMN [6]. In 2012, only *ATC capacity and staffing* constituted the single major reason causing higher average delays of around 0.4 minutes per flight, whereas *weather* caused an average of approximately 0.1 minutes per flight. In total, 3.4% of flights where affected by ATFM en-route delays. On the other hand, weather related delay might not be necessarily short-term ATFM related, e.g. in the case of long-term weather events like winter weather at airports. Those conditions affect airport airside operations like turn-around and taxiing due to time consuming snow removal or de-icing procedures [22].

During summer, convection is the major cause of weather related ATFM delay. Especially terminal airspaces in the vicinity of airports, characterized by high demand rates and traffic diversification, show high delay sensitivities on disrupting events [17]. Due to the short lifetime of thunderstorm cells of only few hours [14], the forecast of convective events is challenging. Computation times of complex numerical meteorological forecast models usually exceed this lifetime by hours. Moreover, an accurate representation of the atmospheric state is computationally demanding [23]. Therefore, convection can efficiently be forecasted only for a small period of time. Accurate forecasts of dimension, size, motion direction and speed of individual convective cells need alternative approaches. This is why algorithms have been developed during the last years to detect, track and nowcast (short forecast) severe convective cells to generate tailored data on convection for the application in aviation [21] [12] [16].

This work focuses on an evaluation of ATFM measures in terms of slot allocation. Within the Network Flow Environment (NFE)[2] a deterministic EATMN slot allocation model is implemented, which is based on binary integer programming [2, 4, 20], minimizing overall system delay. Moreover, a heuristic slot allocation submodel assigns time slots similar to Eurocontrol‘s Computer-Aided Slot Allocation (CASA) algorithm. Heuristic delay results are evident to validate optimization-based results applying adverse impact information. Therefore, heuristic delay results need to be evaluated to serve as delay reference of individual traffic and weather scenarios. ATFM delay data is heuristically generated for two large-scale scenarios each covering a complete day. One scenario is affected by strong convective activity, whereas the other is almost undisturbed. Results are compared to historic ATFM delay data to quantify the statistical quality.

1.1 Analysis Approach

At present, NFE‘s heuristic algorithm for tactical slot allocation (NFE-CASA) is implemented in a static environment, in which only necessary system constraints and parameters are involved. Since an integration of nowcasting information into the tactical slot allocation process demands procedural adaptations of dynamic parameters as *iterative* system input, the evaluation is *not* focusing a complete data reproducibility. Representative input parameters are:

- considered allocation time periods,
- fixed slots from previous allocation runs, and
- handling of ATFM slots by airspace users.

We rather *compare* static allocation and delay data to historic system delay. Doing so, an

[1] ATFM departure delay is quantified by absolute departure delay compared to the airline schedule.

[2] NFE was developed at the DLR Institute of Air Transportation Systems.

evaluation of the implemented *baseline* version of NFE-CASA, which may be adapted later to perform more dynamically, and therefore realistically, is conducted.

The evaluation approach is shown in fig. 2. It is divided into three steps: (i) evaluation of NFE-CASA against historic ATFM departure delay data on a less impacted day, which is characterized by an average low number of regulations. Since for ATC operations, capacity profiles serve as guideline values for the management of upcoming traffic counts, capacity profile calibration of historic profiles in an arranged scope is part of this step. The second step (ii) constitutes an evaluation of NFE-CASA against historic ATFM departure delay data on a dynamic day with convective activity with and without the integration of nowcasting information. Finally (iii), a comparison of optimization against heuristic results provides potential of delay reduction due to a mathematical delay minimization approach.

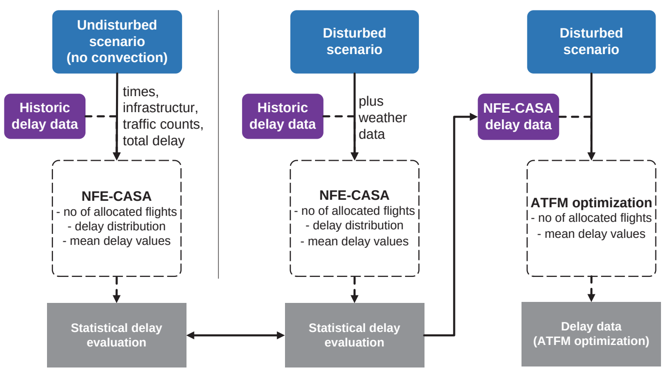

Fig. 2 Evaluation approach.

Convective nowcasting information is considered by temporal adjustment of the duration of en-route weather regulations. The effective regulation time is adjusted according to the existence of 60-minute-nowcasts within a sector. Delay distributions on affected flight counts within a range of defined delay limits as well as respective correlation data, total number of affected flights, maximum total and mean delays are evaluated. The study is not representing a performance analysis of Network Management (NM) operations in terms of equity or fairness of ATFM delay allocation. The developed network model rather focuses on the computation of network performance under given constraints, like e.g. traffic load and network distribution or external adverse impact scenarios.

2 Computational Implementation

The slot allocation problem is implemented in MATLAB™ and uses pre-compiled libraries of the SCIP (*Solving Constraint Integer Programs*) 3.0.1 software framework [1] together with the SoPlex linear programming solver. SCIP is executed within NFE‘s computational work-flow to solve large-scale linear programming (LP) optimization problems. An application programming interface is implemented, which uses SCIP libraries adapted to the ATFM problem specification.

2.1 NFE framework

NFE allocates ATFM departure slots (*Calculated Take-Off Time*, CTOT), like it is actually applied for the tactical balancing of traffic demand with system capacities in Europe. Departure slots result in (pre-)departure ATFM delay of flights planned to enter highly congested network elements along their individual estimated trajectory. The modeling approach for the handling of ATFM comprises both types of capacitated network elements: airports and ATC sectors.

NFE is divided in two functional sections depicted as *horizontal* process flows of submodules in fig. 3: (i) data preparation and processing and , (ii) demand-capacity-balancing (DCB, slot allocation). Large-scale network modeling demands accurate and extensive data extraction, structuring, processing and fusion functionalities. Apart from traffic data, infrastructural (also called *environmental* data in this context) and adverse impact data, e.g. weather, needs to be extracted and matched according to the given time-frame and granularity specification. A database is generated which is passed forward to the DCB section to generate a most optimal DCB solution.

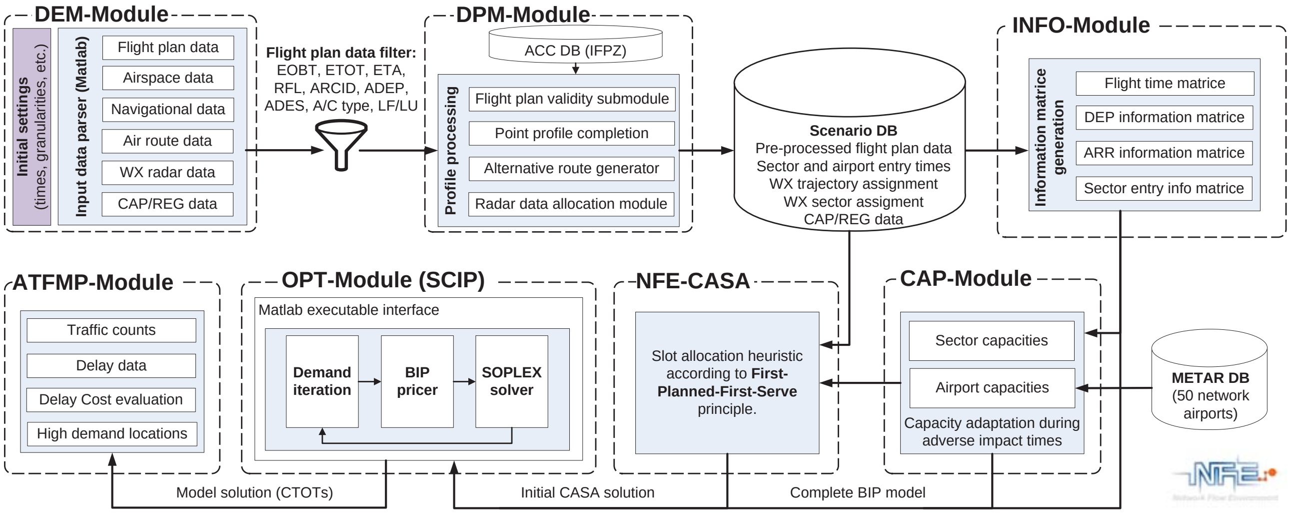

Fig. 3 NFE structural data and processing flow.

2.2 Data preparation and processing

In the data preparation and processing section, data is extracted from several different sources. The Eurocontrol Demand Data Repository (DDR2) [7] (AIRACs 6-11/2012) and the European AIS database (EAD) [8] serve as data sources of environmental data types (airspaces, navigational data, ATS route data, capacity and regulation data). The applied traffic data contains estimated flight plans provided by the Eurocontrol Human Machine Interface (CHMI) [5].

Data Extraction Module (DEM)

The Data Extraction Module (DEM) stands at the beginning of the NFE data preparation and processing section and extracts all data types according to initial settings, like day of choice and geographical area of interest. The Initial Flight Plan Processing Zone (IFPZ) represents the default setting, containing a wider area including Europe and some of its neighboring states.

The *airspace model* is provided in fig. 4. It contains 637 individual sector volumes, representing approximately 1400 traffic flows of the EATMN. The model contains two types of sectors: collapse sectors and elementary sectors. Collapse sectors may tactically be split vertically or laterally. Sector splitting constitutes one of the first measures when demand exceeds airspace capacity. Elementary sectors represent smallest capacitated airspace volumes, whereas the sum of discrete capacities of elementary sectors generally exceeds capacity of their correlated collapse sector. This is due to the higher number of controllers being in charge for the same airspace volume.

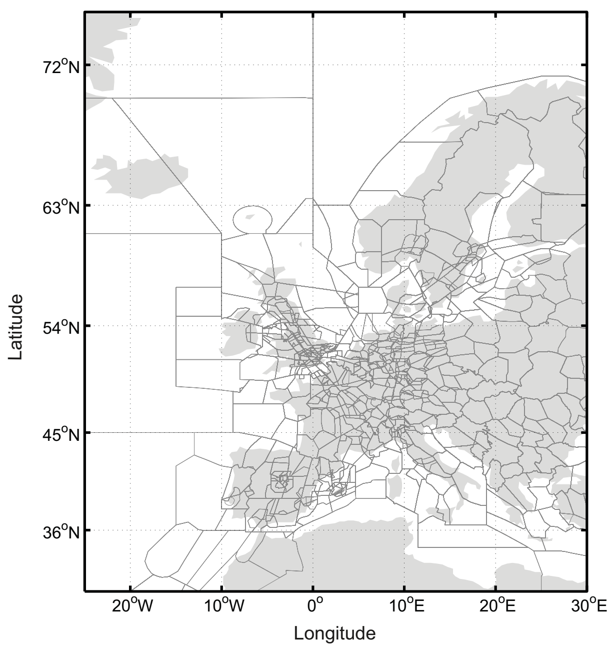

Fig. 4 Static sector model within NFE.

Fig. 5 shows the lateral and vertical airblock structure of the Munich ACC (EDMMACC) collapse sector EDMMALP. Airblocks represent

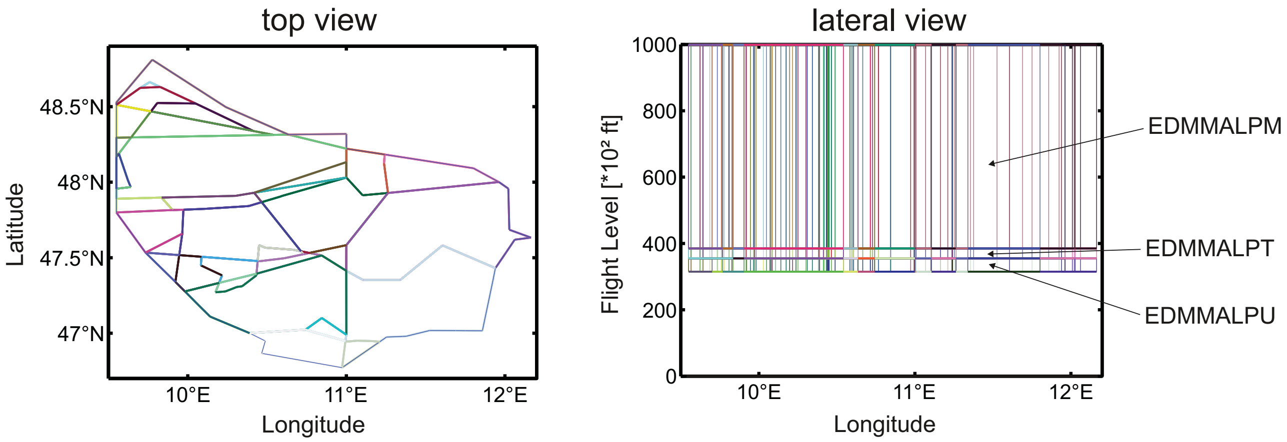

Fig. 5 Collapse sector *EDMMALP* split into its airblock structure.

smallest defined airspace volumes for sector definition in the DDR2 data structure. EDMMALP can be split vertically or laterally. Vertical elementary sector IDs are EDMMALPU (upper), EDMMALPT (top) and EDMMALPM (megatop). Top- and megatop volume are joined most of the time.

Applied flight plan data contains elapsed flight time, air route indicator, navigational point information including departure and destination airports, flight level indicator and estimated time-over (E/TO). Table 1 provides an excerpt of a point profile, which is generated according to an airlines flight plan input. NFE applies estimated flight plan profiles according to tactical ATFCM operations to generate demand profiles for each network element.

Table 1 Raw point profile excerpt: EDDF `MARUN 8D` departure route.

Time	*Route*	*Point*	*FL*	*ETO*
0	MARUN 8D	EDDF	000	04:13
1	MARUN 8D	FFM	027	04:14
3	MARUN 8D	48%	080	04:16
4	MARUN 8D	MTR	115	04:17
6	MARUN 8D	61%	160	04:19
7	MARUN 8D	TOBAK	179	04:20
9	MARUN 8D	APROX	203	04:22
10	Y150	MARUN	219	04:23

Convective radar data is provided by Rad-TRAM[3] (radar tracking and monitoring) [16]. The algorithm uses weather data to deliver current reliable lower air space thunderstorm information. Moreover, it displays hazardous objects (black-contour polygons in fig. 6) for air traffic within thunderstorms by marking areas with a radar reflectivity at a predefined value or above. The default value is 37dBZ, indicating strong hail and precipitation. The black arrows indicate 1-hour nowcasted locations of polygon center points. The 60-minute-nowcast is updated every 5^{th} minute. The application of Rad-TRAM data increases ATFCM performance due to (i) reducing hazardous thunderstorm areas to indicated *no-go-areas*, (ii) therefore defining most accurate reduced impact periods for airports and sectors, and (iii) high nowcasting quality and update rate.

Data Processing Module (DPM)

The Data Processing Module (DPM) is in-line with a flight plan data filter for the generation of specific traffic scenarios. It is capable to reduce the master-set of flight plans according to time- and operational constraints, like e.g. late-updater (LU) declaration. Most relevant in terms of realistic demand generation are time-constraining scenarios, for which only a subset of flight plans are extracted, e.g. with an EOBT within a given period of time. Demand uncertainty is not yet represented within the model.

DPM completes every point profile by adding (i) additional points for every minute, (ii) geographical coordinates to each point according to

[3] The algorithm was developed at the DLR Institute of Atmospheric Physics.

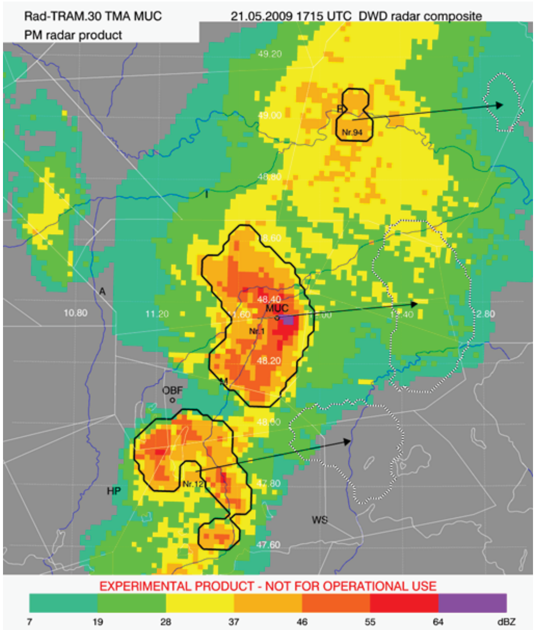

Fig. 6 Rad-TRAM image MUC TMA. (DLR-IPA / WxFusion GmbH)

AIRAC-conform navigation data, (iii) the sector profile and (iv) adverse impact location (e.g. Rad-TRAM) information. A minute-based point profile granularity is important to determine sector entry times most accurately, although the specified ATFM slot granularity of the model is less granular.

NFE also applies tactical pre-flight rerouting according to initiated routing scenarios during tactical NM. Flights planned to enter highly congested sectors or being assigned to high ATFM departure delay are proposed to be rerouted. Alternative route profiles are laterally designed as shortest paths around congested sector volumes. Thereby, the alternate cruise flight level is adopted from the estimated flight plan within a lateral en-route extension below 20%. Flight level capping is not yet represented within NFE. Entry times along the alternate profile are generated with TeMPle (Trapezoid Mission Profile), which is a sub-module of the Trajectory Calculation Model[4] (TCM) [19]. It approximates vertical mission profiles with trapezoidal profiles. Therefore, the alternate trajectory is efficiently parametrized in terms of sector entry times. Fig. 7 provides an example of an alternate lateral route profile. Nevertheless, the present study is not integrating pre-flight rerouting as tactical ATFM measure.

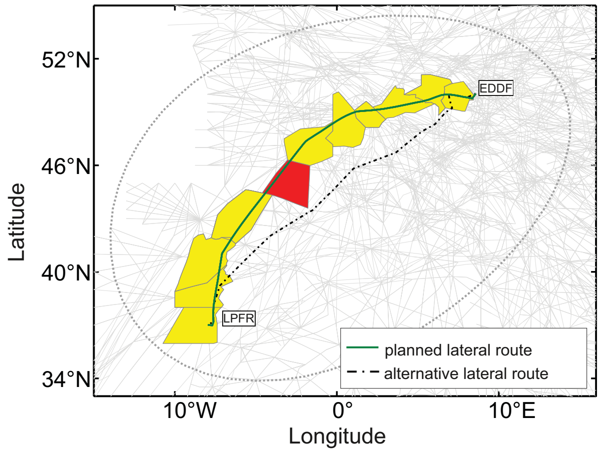

Fig. 7 NFE alternate route representation of a flight profile from EDDF to LPFR.

2.3 Demand-Capacity-Balancing (DCB)

Capacity Module (CAP)

The capacity module generates nominal capacities for airports and ATC sectors. These capacities are valid for time periods according to DCB time granularity, determining the length of a computed ATFM slot. This value is set to 15 minutes by default.

ATC sector capacities are provided by the DDR2 database. Apart from this, NFE provides two methodologies to generate nominal sector capacity vectors. The Monitor Alert Parameter (MAP) [11] generates static capacities according to sector design guidelines of the FAA and serves as baseline capacity generation algorithm to determine fast capacity estimations. Moreover, the Simplified Dynamic Density (SDD) [15] is a dynamic airspace complexity metric from which capacities can be generated *and* adjusted during adverse impact.

To generate airport runway (system) capacities, a process simulation model is applied. It receives individual airport data concerning the number of runways, aircraft mix and airport weather (wind, ceiling and visibility) [18]. It covers 50 high demand network airports for

[4]TCM was developed at the DLR Institute of Air Transportation Systems.

which service capacities are generated according to individual service values and respective flow-delay-functionalities. We used historic capacity profiles for the purpose of this study in order to provide a most realistic network input.

NFE-CASA

NFE-CASA is modeled to consistently and reproducibly calculate CTOTs and the respective ATFM delay throughout the EATMN for given traffic demand and capacity profiles. It is designed in a static environment without dynamic system behavior to react on. Demand and capacity profiles are fixed within the given scenario, i.e. calculations are not performed iteratively on a gliding-hour-basis. In this case, previously allocated ATFM slots would influence network demand in consecutive iterations. However, the described effect demands to fix flights according to their planned departure time, e.g. when their departure airport is located outside the IFPZ. This mainly applies for long-haul flights.

FPFS serves as underlying principle for heuristic slot allocation. A Slot Allocation List (SAL) is generated for every capacitated entity containing flights in ascending order considering their estimated entry times (ETO). Slots are allocated accordingly, i.e. the earliest possible departure time $d \geq d_{0,f}$ is assigned to flight f so that no capacity overload occurs. Since a single flight might enter more than one regulated entity, the most penalizing regulation (causing the highest delay) dominates its calculated departure time.

A specific group of flights, referred to as Late Updaters (LU) receives a share of *reserved* capacity. Aircraft operators may be forced to file late flight plan updates (below 3 hours before EOBT). Therefore, a maximum share of $1/4$th of the total number of slots is assigned to be used preferably by LUs.

Mathematical Optimization Model (OPT)

The binary integer programming (BIP) optimization model determines, how to allocate departure slots according to an overall system delay minimization. According to NFE-CASA, the capacity limit is determined by the maximum number of flight entries into an entity during one time slot. We use the same binary decision variable like BERTSIMAS AND STOCK PATTERSON (1998) [3], that is

$$x_{f,d} = \begin{cases} 1 & \text{, if flight } f \text{ obtains departure slot } d, \\ 0 & \text{, otherwise.} \end{cases} \tag{1}$$

The objective function minimizes total delay cost $w_{f,d}$ for every flight $f \in F$ and slot $d \in D(f)$, whereas the set of slots $D(f)$ is limited.

$$Z(\mathbf{x}) = minimize(\sum_{f \in F} \sum_{d \in D(f)} w_{f,d} x_{f,d}). \tag{2}$$

The problem is characterized by two types of constraints. The first constraint ensures, that every flight departs only once. Every flight is assigned to exactly one departure slot d.

$$\sum_{d \in D(f)} x_{f,d} = 1 \quad \forall f. \tag{3}$$

Capacity restrictions apply for ATC sectors as well as to airport departure- and arrival-counts. If the calculated entry time of flight f in sector (or airport) s with delay d is assigned to time slot t, the coefficient $a_{(s,t),(f,d)}$ is

$$a_{(s,t),(f,d)} = \begin{cases} 1 & \text{, if } CTO_s(f,d) = \text{t}, \\ 0 & \text{, otherwise.} \end{cases} \tag{4}$$

Since the planned trajectories are fixed, the coefficient $a_{(s,t),(f,d)}$ serves as a projection of departure times to sector entry times. The sum of all entries assigned to slot t is restricted by its capacity $C_{s,t}$.

$$\sum_{f \in F} \sum_{d \in D(f)} a_{(s,t),(f,d)} x_{f,d} \leq C_{s,t} \quad \forall s,t. \tag{5}$$

Premature departure times are not assigned.

$$d \geq 0 \quad \forall d \in D(f). \tag{6}$$

The model is solved with SoPlex and optionally traverses an iterative decomposition stage

Table 2 Scenario structure. Two complete days are investigated.

Days	**Traffic Sample**			**Model Input**			**Reg Data**	
	IOBT		*#Flights*	*#Flights*	*#Airports*	*#Sectors*	*#Reg*	*#ER-WX*
	from	to						
31/07/2012	00:00z	23:59z	27710	23964	2837	638	70	-
10/07/2012	00:00z	23:59z	28696	24593	2837	637	112	24

in terms of (dual) variable pricing. This allows for covering large-scale-scenarios of a whole day in the initial flight plan processing zone (IFPZ) within moderate solving times.

3 Scenario specification

Two scenarios are investigated, which have been gathered during the summer campaign of DLR‘s project "Weather and Flying" in 2012 [13]. Each of both covers comprehensive flight plan data of a *complete* day, containing all flight movements with an Initial Off-Block Time (IOBT) between 00:00z and 23:59z. Comparability regarding traffic demand is ensured through matching weekdays of the same scheduling period (see tab. 2).

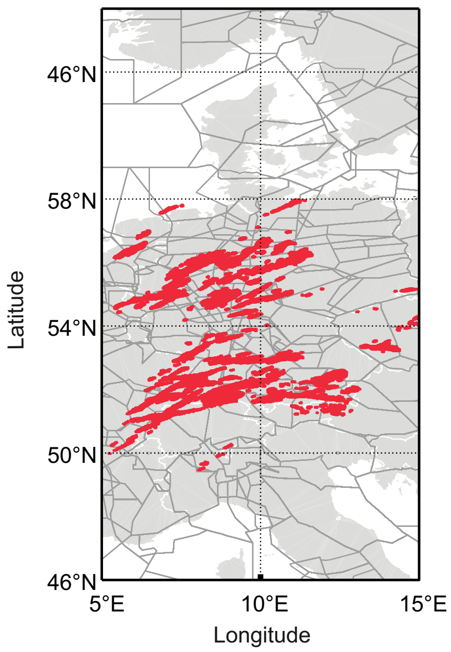

Fig. 8 Overall thunderstorm reflectivities (Rad-TRAM cells) in German airspace at 10/07/2012 between 15:00z and 19:00z (NFE).

The first day, Tuesday, July 31st 2012, constitutes a *zero-weather* day, since no weather-related regulation was initiated. However, a manageable number of 70 regulations was initiated throughout the day, from which 26 are considered en-route sector regulations. The majority is due to ATC capacity.

In contrast, Tuesday, July 10th 2012, was dominated by an extensive low pressure system over Northern Europe. Due to several fronts between warm and cold air masses, plenty of small embedded thunderstorms scattered throughout the IFPZ and especially through German airspace between 15:00z and 19:00z (fig. 8). In total, 112 regulations were initiated, from which 44 are considered en-route sector regulations and 9 are due to en-route weather.

4 Analysis Results and Discussion

Evaluating heuristic slot allocation results compared to those applied in real-world operations is conducted with focus on delay allocation across the total number of flights considered as ATFM restricted.

4.1 No convection: *Tuesday, 31/07/2012*

Tab. 3 provides slot allocation data of NFE-CASA compared to historic ATFM allocation data. Corresponding flight counts allocated within increasing delay limits are provided in fig. 9. 1884 flights fall below a maximum delay of 225 minutes, representing a share of 94.6% of the total number of restricted flights. Remaining flights are treated as flight cancellations in our model.

Since it is challenging to perfectly reproduce tactical ATFM decision making with a static model, we emphasize our intention to generate acceptable ATFM delay characteristics on individual traffic and impact scenarios. It is com-

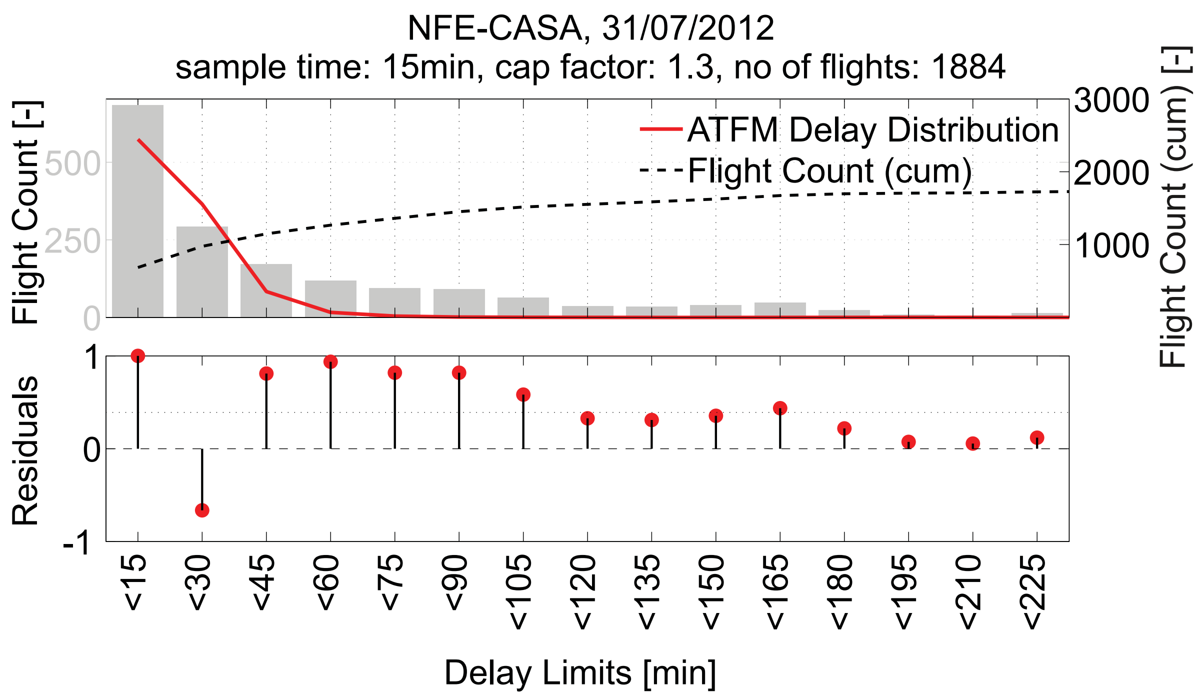

Fig. 9 Delay flight counts within increasing delay limits of $n{*}15min$. Normalized residual data corresponds to a maximum offset of 110 flights.

Table 3 Heuristic slot allocation results of 31/07/2012.

Measure	NFE-CASA	ATFM
∑ constrained flights [-]	1884	1044
∑ delay [min]	24736	16336
⊘ delay [min]	13	16
max delay [min]	132	95
Correlation (R^2)	.84	
Variance [min^2]	323	117

mon sense to scale demand and capacity profiles in real-world operations. This is generally done in strategic and pre-tactical operations. Nevertheless, capacity scaling is a collaborative process mainly dependent on upcoming traffic loads and traffic complexity. Apart from model calibration, we achieved best data fits of delayed flight counts generated with a global capacity scaling factor (cap factor) of 1.3. We believe, that this approach considers operational demand fluctuations, which are not represented by deterministic flight plan data. A correlation coefficient of .84 within the evaluated delay range indicates an acceptable data fit. Nevertheless, NFE-CASA overshoots the total delay sum as well as the number of constrained flights. On the other hand, median (MD) delays within delay limits of 15, 30 and 45 minutes are below those of ATFM slot allocation (fig. 10), even though calculated delay variance is considerably higher.

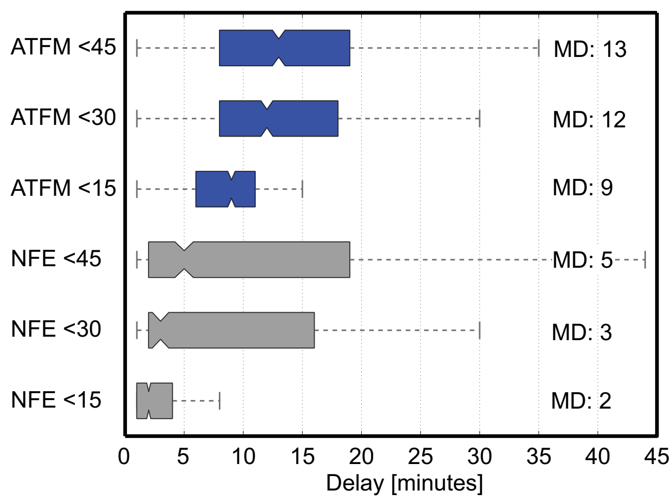

Fig. 10 Delay distributions for limits of 15, 30 and 45 minutes. NFE-CASA median (MD) values fall below those of operational ATFM allocation.

NFE-CASA spreads moderate individual delay values across a wider range of flights. We believe, that this is attributed to its actual inabil-

Table 4 Heuristic slot allocation results of 10/07/2012 with (NC) and w/o adapted regulation time periods.

Measure	NFE-CASA	NFE-CASA (NC)	ATFM
affected time slots [15min]	100	66	100
$\sum$ constrained flights [-]	2367	2239	2186
$\sum$ delay [min]	57278	53684	42609
$\oslash$ delay [min]	24.2	23.9	19
max delay [min]	225	223	147

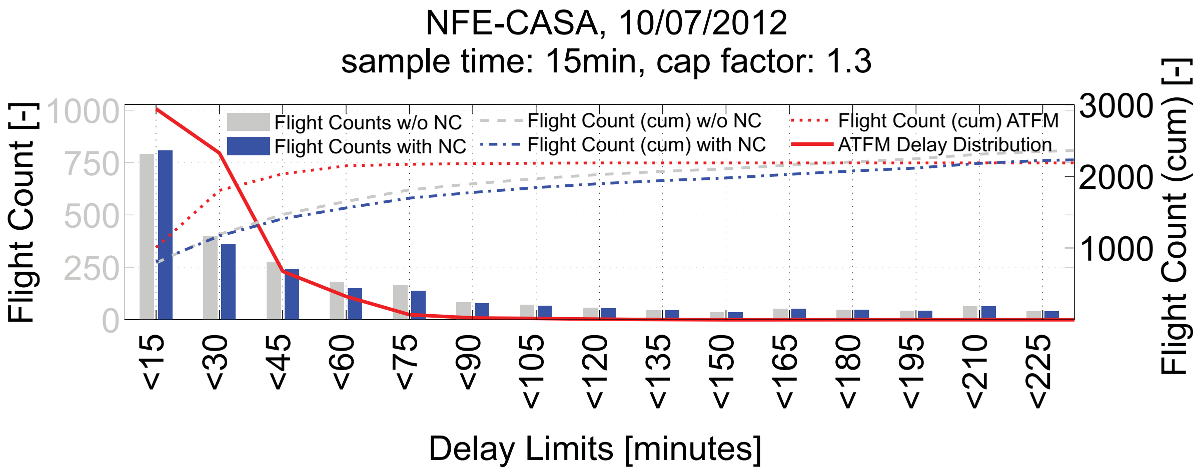

Fig. 11 Delay flight counts of NFE-CASA with (NC) and without nowcasting integration, represented through adapted regulation time periods. A total of 9 en-route regulations are considered from which 34 impacted slots are declared *not impacted* according to the 60-minute-nowcast.

ity to integrate system updates during its FPFS work-flow. Doing so might lead to a higher flexibility in identifying and *punishing* only a small share of network sensitive flights with higher delays and therefore reduce the total number of restricted flights. Moreover, an iterative FPFS execution would allow for fixing calculated departure times within a specified forerun, constituting an important characteristic of Eurocontrol‘s CASA algorithm.

4.2 Convective impact: *Tuesday, 10/07/2012*

As shown in fig. 8, Tuesday, July 10^{th} 2012, is characterized by distinct convective activity. Impacted en-route sectors show a maximum vertical top level of FL355, even though Rad-TRAM is designed to detect convective *bottom* volumes in the lower airspace. However, convective top volumes climb up to flight levels within the upper airspace.

In an initial step as part of nowcasting integration into the DCB process, we adjust the temporal scope of en-route sector regulations and leave the nominal capacity regulation value unchanged. Temporal adjustments are verified according to minimum necessary durations with regard to Rad-TRAM polygons being detected within a sector volume. Specifically, we define a polygon p being detected within a sector s for all points in time $d \in D$, for which its object-based sectional area is $A_d^{sp} > 0$. Rad-TRAM polygons covering route segments and navigation points at specific flight levels better reproduces adverse flow impacts and will be examined in future studies.

Regarding restricted flight counts, NFE-CASA underruns historic values concerning delays below 45 minutes. However, total flight counts and delay minutes exceed historic values by 8% and 25% respectively. We assumed a capacity factor of 1.3, since flight count distributions again featured a best fit. In contrast to 31/07/2012, mean delay exceeded historic val-

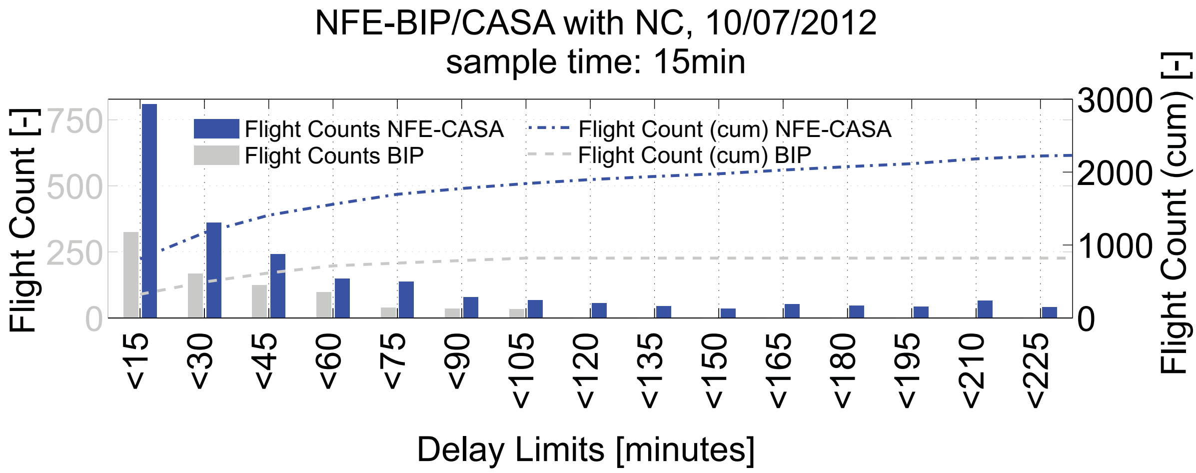

Fig. 12 Delay flight counts of NFE-CASA with (NC) and w/o adapted regulation time periods.

ues significantly. To our conviction, this is attributed to operational flexibility of making short-term decisions in terms of ad-hoc measures like metering or cancellation of flights during the day.

An observable difference between slot allocation results with 60-minute-nowcasting regulation adjustments (NC) to those without is determined. This is not obvious, since convective disturbance not necessarily affects high density airspace in terms of location and time. In total, a delay share of 6.3% is saved in the NC-scenario, accompanied by 5.4% less restricted flights. Especially the sectors of Munich ACC (EDMMALPU & EDMMKPTH), being two of the regulated sectors due to en-route weather, contribute to the results.

The BIP slot allocation of the NC-scenario, provided in tab. 5 and fig. 12, yields optimal results on the objective value $Z(x)$ (total network delay). Compared to NFE‘s heuristic slot allocation results, the gain is extensive. The number of restricted flights and overall delay minutes are reduced by more than a half each considering its total values. This indicates, that our decomposition-based optimization architecture is promising for ATFM problem types. Nevertheless, a high mean delay of 26 minutes at a low number of restricted flights reflects the discrepancy between both solutions, which is FPFS solidity on the one hand and delay minimization on the potential cost of a smaller share of flights on the other.

Table 5 BIP slot allocation results of 10/07/2012 with NC adapted capacity profiles.

Measure	**BIP**
computation time [s]	22.3
$\sum$ constrained flights [-]	820
$\sum$ delay [min] $Z(\mathbf{x})$	10680
$\oslash$ delay [min]	26
max delay [min]	105

5 Conclusion and Outlook

In this paper, a heuristic FPFS slot allocation heuristic algorithm is evaluated against historic slot allocation data. It is part of the Network Flow Environment, which minimizes system-wide tactical ATFM delay. Two different days are evaluated, from which one was impacted by convective activity. Distributions of restricted flight counts within given delay limits highlight an acceptable correlation of $R^2 > 0.8$ to historic delay allocation data for both scenarios. However, total values of restricted flights and delay sums generally exceed historic values by approximately 25%. It was found that a smaller difference of restricted flights and total delay values is at the cost of exceeding mean delays allocated by NFE-CASA in both scenarios. Benefits of an initial integration approach of convective nowcasting information have been observed in terms of delay reduction of around 6% due to an adjustment of temporal regulation scopes. Applied to the extend of the evaluated scenarios, these discrepancies are within acceptable scales. BIP slot allocation extensively improved FPFS slot allocation results, which is due to a possible minimum number of ATFM restricted flights.

Future work will focus on varying model time granularity between 5 and 20 minutes to comprehensively cover realistic time scales for slot allocation. Moreover, capacity scaling and individual nominal capacity adaptation during impact times will be focused in terms of a calibration of the applied capacity models. To reduce the number of restricted flights and corresponding delays, dynamic airspace management functionality as integral part of NFE‘s slot allocation work-flow will be integrated.

The evaluation showed, that NFE-CASA fulfills the requirements to serve as a slot allocation reference in terms of restricted flight count and delay allocation as part of network performance quantification for large-scale ATFM problems. Adequate initial FPFS solutions will be applied for optimization runs as well as relative benefit quantification of sophisticated adverse network impact data sources.

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