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Final Project Report

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Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU)	
Deutsches Zentrum für Luft-und Raumfahrt e.V. (DLR)	

Abstract

The final report of the RobustATM project provides a publishable summary of the results. In addition it lists all deliverables, dissemination activities, eligible costs, deviations, bills and lessons learned.

Authoring & Approval

Prepared by - *Authors of the document.*		
Name & Company	Position & Title	Date
[redacted] / DLR	Project Leader DLR	17/3/2016
[redacted]	Research Associate	17/3/2016
[redacted] / FAU	Research Associate	14/03/2016
[redacted] / FAU	Project Leader	18/03/2016

Reviewed by - *Reviewers internal to the project.*		
Name & Company	Position & Title	Date

Approved for submission to the SJU by - *Representatives of the company involved in the project.*		
Name & Company	Position & Title	Date
[redacted]	Project Leader	23/03/2013

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Publishable Summary

Mathematical Optimization for Efficient Utilization of Runways and Stable Planning in Disturbed Situations

ATM systems are driven by two competing goals: safety and efficiency. Performance optimization has to consider both aspects, e.g. guaranteeing separation minima between aircraft and minimizing delays. Although for all participating stakeholders (airlines, pilots, airport operators, air traffic control, and more) safety should have first priority, they certainly put different weight and effort on both aspects due to different economic pressure. Anyway, ATM optimization has to take into account the different performance indicators, quantifying e.g. punctuality and safety.

As possibilities of enlarging airport capacities (as important traffic bottleneck) for reducing delays are limited, one has to enhance the utilization of existing capacities to meet the continuous growth of traffic demand. The runway system is the main element that combines airside and groundside of the ATM System. Therefore, it is crucial for the performance of the whole ATM System that the traffic on a runway is planned efficiently. Such planning is one of the main challenges in ATM. Uncertainty, inaccuracy and non-determinism almost always lead to deviations from the actual plan or schedule. A typical strategy to deal with these changes is a regular re-computation or update of the schedule. These adjustments are performed in hindsight, i.e. after the actual change in the data occurred. The challenge is to incorporate uncertainty into the initial computation of the plans so that these plans are robust with respect to changes in the data, leading to a better utilization of resources, more stable plans and a more efficient support for ATM controllers and stakeholders. Incorporating uncertainty into the ATM planning procedures further makes the total ATM System more resilient, because the impact of disturbances and the propagation of this impact through the system is reduced.

Novelty of the RobustATM approach: Optimum robust time-Window assignment leads to Stable Plans in Disturbed Situations

In the project RobustATM, the problem of optimizing runway utilization under uncertainty was investigated. The novelty of the project consisted in applying concepts from mathematical optimization under uncertainty, especially methods from robust optimization. The goal was to incorporate uncertainties into the initial plan in order to retain its feasibility despite changes in the data. The focus was on the pre-tactical planning phase, the actual planning time was assumed to be several hours, or at least 30 minutes, prior to actual arrival times. First, an appropriate mixed integer program (MIP), i.e. a mathematical optimization model was developed for this particular planning phase (described in (1)) that reduces complexity by omitting unnecessary information (without considering uncertainties at this point). Instead of determining arrival times to the minute in this phase yet, *several* aircraft were assigned to the same time window of a given size (e.g. 10 min). The exact orders within those time windows can be decided later in tactical planning. Mathematically, the task is to solve a generalized assignment problem on a bipartite graph. To know how many aircraft can be assigned to one time window, separation requirements were considered for consecutive aircraft types. Then, a discretized time horizon was considered consisting of such time windows and assign each aircraft to one of them.

Afterwards, approaches to incorporate uncertainty directly in the model were developed in order to achieve a stabilization with respect to changes in the data. Therefore, techniques from robust optimization and stochastic optimization were used (described in (2) and (4)).

Robust Optimization for the Best Guaranteed Assignment Even Under Worst-Case Disturbances, Stochastic Optimization for the Best Expected Time-Window Assignment

The stochastic approach optimizes the expected scenario and, therefore, is more likely to remain feasible in the face of disturbances than the nominal approach that ignores them. Thus, on average it provides more stable plans and less necessary replanning. However, the approaches using robust optimization methods provide even more stable solutions. In robust optimization, uncertainty sets are defined against which protection is sought. Then, only time window assignments are considered that can always be realized, as long as the uncertainties manifest themselves within these pre-determined uncertainty sets. Among these so-called robust feasible solutions, the best possible, with respect to pre-defined criteria such as time-efficiency, is chosen. Such an approach goes beyond a sensitivity analysis that determines the stability of a solution ex-post. In contrast, the advantage is that a priori the knowledge about the relevant uncertainties is included in the mathematical models as well as in the solution approaches. Thus, the computed plans are not only feasible under ideal conditions, but remain possible as long as the occurring scenario is within the uncertainty sets that have been pre-defined. In this respect, robust optimization methods protect against worst cases and, therefore, do not need any probability distribution within the uncertainty space. Robust optimal solutions are those with the best (guaranteed) objective function values among all robust feasible solutions. However, the abovementioned guarantee of protecting against the worst case naturally comes at the price that it potentially worsens the objective function value, which is called the price of robustness. Thus, one has to choose uncertainty sets carefully in order to avoid over-conservatism.

As Improved Stability Usually comes at the Price of Increased Delay: Considerable Delay Reduction Through Advanced Optimization Approaches under Uncertainty

Recoverable Robustness for Optimum Runway Utilization under Uncertainty leads to Very Stable Plans at only Slightly Increased Delay

A different recent approach to reduce this conservatism is called recoverable robustness (see (4)). The concept of recoverable robustness, which has been developed for timetabling in railways, is to take into account that a solution might become infeasible in some scenario. In that case, it applies a so-called recovery action, i.e. a replanning step that depends on the specific scenario, and makes the assignment feasible again. Thus, a recoverable robust solution can be recovered by limited actions to a feasible one for all occurring scenarios (not necessarily the same feasible solution in each scenario). This potentially necessary recovery is already incorporated in the computation of the initial solution. The task is to determine a solution that is optimum with respect to the original objective, by additionally taking the potential recovery action prices into account. Obviously, this is considerably less conservative than postulating that a solution is (strict) robust, i.e. always feasible as long as one stays within the pre-defined uncertainty sets. Hence, recoverable robustness provides a promising trade-off between little delay (as nominal) and high stability (as strict robust). However, developing appropriate solution methods is a mathematically challenging task. Therefore a simplification suitable for our specific ATM problem was developed. This simplification potentially yields more conservative solutions, i.e. solutions with larger delay, than the general recoverable robustness approach. However, this approach is algorithmically much more tractable. Contrary to the stochastic (and combined) approach, here it is not necessary to know the underlying probability distribution. This fact makes the model applicable whenever the uncertainty characteristics are only known qualitatively.

A New Mixed Robust-Stochastic Model Uses the Advantages from Both Methods and Yields Tuneable Levels of Protection against Disturbances

The combined approach provides a different trade-off between the strict robust and the stochastic approach using the advantages from both methods. It is decided whether a flight is modelled robustly or stochastically dependent on its disturbance distribution.

Thus, for different levels of protection, we developed, implemented and evaluated several optimization models. High protection levels lead to very stable plans, however at the potential price of increased delay. Our computational studies showed that such an incorporation of a priori knowledge on uncertainties has a large positive effect on the resulting solutions. Furthermore, the level of protection can be changed by using either stochastic approaches (usually low level of protection) or robust approaches (high level of protection). Finally, with the developed mixed model the protection level and thus the stability of the resulting plans can be tuned as appropriate.

Validation of the New Optimization Approaches for Runway Utilization under Disturbances Using Real-World Data

In order to be able to test our approaches in a real-world setting, we analyzed real-world data from a large German airport to obtain realistic delay distributions. Practically relevant results were obtained by means of empirical arrival and departure delay statistics and a stochastic delay model for fitting the results of Monte Carlo (MC) computer experiments with 209 flights over 17 and 8 hours time span (low and high traffic scenarios), and 200 repetitions each. It turned out that two-parametric Γ-distributions provide a suitable stochastic departure delay model in order to generate realistic uncertainty sets for the simulations. We then tested our new solution methods within the simulation environment against those realistic disturbances. For each of the 200 repeated runs during an MC-experiment random departure time delays were drawn and added to the planned earliest and (max) latest times. The scheduling performances of the validated MIP-models were quantified with regard to runtime, rescheduling stability and arrival delay statistics (see (2)).

Mathematical Optimization leads to Decreased Delay, when Compared to Baseline Methods and can Determine Globally Optimum Solutions Quickly

The results for the nominal model already showed a significant improvement in terms of stability and delay compared to baseline algorithms First-Come-First-Serve (FCFS) and Take Select (TS8-2), which solve the sequencing problem heuristically with continuous times instead of computing global optimal solutions with our discrete time windows approach. Moreover, runtimes are very low which allows us to solve our realistic instances with about 200 aircraft and 100 or 50 time windows of 10 min (low and high traffic scenarios), respectively, to global optimality within short time.

Robust and Stochastic Methods Determine Solutions Quickly and Lead to Stable Plans. Robust Methods are the Most Stable, however at the Price of Increased Delay

Compared with baseline scheduling (FCFS, TS8-2 and nominal MIP) the robust and stochastic models exhibit the predicted significantly reduced runtime and rescheduling. Using the (strict) robust approach, there are less than 30% of the reschedulings compared to the nominal approach. Hence, a substantial stabilization of the plans is achieved, which is exactly the goal as well as the promise of robust optimization. However, even the robust model produces (very small) rescheduling-values, due to the fact that some of the randomly drawn disturbances exceeded the range that were chosen for protection. Naturally, this advantage regarding the number of reschedulings is paid for by slightly larger delay. However, in the robust version, the increase in delay barely amounts to the width of about one time window, which in the time window assignment approach, is the smallest possible increase that is possible. Thus, the price of robustness is relatively low. On the other hand, robust optimization enabled the project to compute very stable plans which remain feasible for all scenarios within the pre-determined uncertainty set. The stochastic model showed 60% of the reschedulings compared to the nominal approach. Regarding the average delay value, a slight increase compared to the nominal approach was observed, but only about 25% compared to the robust one.

Advanced Robust as well as Mixed Robust-Stochastic Models Lead to Very Stable Plans and can be Computed Quickly, at Low Increase in Delay Only

The combined model exhibited smaller delays than the robust model and less rescheduling than the stochastic model (both about 50% reduction). This of course depended on the distribution of robustly and stochastically modelled flights. The validation results, where varying this distribution, showed exactly what was the goal to achieve by combining the robust and stochastic approaches: By setting the degree of robustness one can gradually choose the preference regarding the advantages of the expected scenario approach (less delay) and the strict robust approach (higher stability). The (simplified) recoverable robustness approach remains quite stable while producing less delay than the strict robust approach.

As expected, the FCFS heuristic without optimization provided the shortest runtime but rather instable planning. Such straight-forward approach has obvious disadvantages when it comes to dense traffic scenarios. Then, the number of replannings is drastically larger than an optimized schedule can achieve. Furthermore and more importantly, the runtimes of the validated MIP-models are also very low, namely about 20 s / MC-run (note, that one MC-run contains around 150 simulation steps). These runtimes were significantly smaller than the continuous time TS8-2 baseline (> 200 s). Further, in the considered disturbance scenarios, the robust optimization approach needs almost no rescheduling. Thus, it is by far the most stable approach.

Our results show that it is indeed possible to stabilize pre-tactical planning by mathematical optimization approaches that include knowledge about the uncertainties already in the modelling and optimization phase. The corresponding optimization tasks can be solved fast in practice. Thus, we succeeded in computing stable plans with a high probability to remain feasible despite changes in the input data.

Potential Future ATM Topics That Could be Studied after RobustATM:

Include Viability Theory for Optimal Control in X-Events

In the following, we briefly point out potential future work that went beyond the research in the project RobustATM. The validation was based on MC-simulations using average disturbance statistics with removal of extreme delays (partly originating from disruptive or X-events like autumn storms, leading to airport closure). This procedure appeared justified for the comparison between different scheduling models and optimizer strategies. Towards the end of the project, however, initial investigations into the specific effect of X-events were started. One specific approach is based on Viability theory which provides an optimal control and resilience framework for the management of complex ecological and sociotechnical systems such as ATM. We developed an initial macroscopic nonlinear dynamics performance model (described in (3)) for simulating on a generic basis suitable management actions for reducing or even preventing disruptive effects, even for outlier (X-)events. Preliminary results in fact indicate the usability of our strongly simplified model as a basis for the application of Viability theory. The latter would provide for a discretized state space optimal control trajectories in terms of minimum cost (= maximum resilience). In the recent FP-6 project “PATRES” an efficient SVM (support vector machine) classification algorithm was developed for determining the viable sub-statespace. We propose the integration of MIP based optimal scheduling technique (microscopic level, addressing single flights) into a Viability theory based generic (macroscopic level of order and control parameters) ATM-resilience framework as a medium term goal.

Make Larger instances Solvable by Investing More Research into the Optimization Approaches

Some of the optimization models developed in the project (e.g. general recoverable robustness) are mathematically very challenging and, therefore, provide the possibility of future investigations. In order to develop and enhance solution methods which are able to handle appropriate instance sizes for these models, intensive research in mathematical optimization will be required. This includes a comprehensive theoretical analysis, the development of new algorithmic concepts as well as their implementation and evaluation.

Extension of the Methods and Results from RobustATM to Tactical Planning. Develop an Integrated Framework that Optimizes Pre-Tactical as well as Tactical Planning

Within RobustATM, the focus was on pre-tactical planning. In principle, the methods can be adjusted to the tactical phase as well. Especially, it is relevant to develop algorithms for a “transition” between the pre-tactical and the tactical planning phase. Within the simulation, one has to switch from the discrete time window approach to a continuous time approach for each aircraft that enters the tactical phase. The result would be an integrated and optimized planning tool for the pre-tactical as well as the tactical phase that is protected against uncertainties.

Make Approaches More Realistic by More Advanced Parameter Tuning

Furthermore, transitions of different kinds need to be explored in more detail. The real world ATM has to deal with many changes that take place over time and have to be included in the simulation as well as the optimization approaches. For example, there is no constant level of traffic at an airport, thus the transition between high traffic load and low traffic load can be considered. On the other hand, further investigation of different uncertainty parameters (μ, σ) would be interesting as well as varying the chosen degree of protection.

Increase the Relevance of the Results by Including Departure Delays as Well

Due to their dominating influence on arrival delays, in the present validation and simulations concerning disturbance we restricted to departure delays. In order to increase the relevance for real life situations in future simulations also en-route disturbance and disruptive events during the final flight phase (approaching the destination airport) will be included. Because empirical data were available only for the destination airport (our data source) departure delays for our relative comparison between different optimization strategies were derived from these data. For improvement of future simulations it would be good to have departure airport data available.

Extend the Approaches for Several Runways

Moreover, the methods developed here can be generalized to the situation of airports with several runways. The assignment of runway time could also be considered for groups of flights (e.g. different airlines), in order to figure out which groups cause much delay on certain airports and find appropriate solutions for them. Lastly, questions in the field of capacity planning as well as runway operation questions could be studied using optimization under uncertainty. In particular, one could study questions such as whether more runways need to be added or when they should be opened, respectively, in order to reduce delays.

Mathematical Optimization under Uncertainty for ATM Applications where Disturbances Play a Role

Finally, mathematical optimization methods under uncertainty could be developed and used in the ATM system for many different applications as well, for example for gate assignment, for taxiing, for determining stable trajectories, etc.

In summary, building upon the outcome of RobustATM, many further interesting questions could be studied in the future whose answer would increase the stability of the plans for realistic traffic situations.

Publications:

(1) Fürstenau, N., Heidt, A., Helmke, H., Kapolke, M., Liers, F. (2014). Pre-Tactical Time Window Assignment: Runway Utilization and the Impact of Uncertainties. In: Schaefer, Dirk (Editor) Proceedings of the SESAR Innovation Days (2014) EUROCONTROL. ISBN 978-2-87497-077-1.

(2) Fürstenau, N., Heidt, A., Kapolke, M., Liers, F., Mittendorf, M., Weiß, C. (2015). Pre-tactical Planning of Runway Utilization Under Uncertainty: Optimization and Validation. In: Schaefer, Dirk (Editor) Proceedings of the SESAR Innovation Days (2015) EUROCONTROL. ISSN 0770-1268.

(3) Fürstenau, N., Mittendorf, M., Kamo, S. (2016). Nonlinear Dynamics Approach for Modelling of Air Traffic Disruption and Recovery. ICRAT7, Philadelphia/PA, submitted

(4) Kapolke, M., Fürstenau, N., Heidt, A., Liers, F., Mittendorf, M., Weiß, C. (2016). Pre-tactical optimization of runway utilization under uncertainty. J. of Air Transport Management (2016), DOI: 10.1016/j.jairtraman.2016.02.004

1 Introduction

1.1 Purpose of the document

The purpose of this document is to:

- Summarise the technical results and conclusions of the project (Publishable Summary);
- Provide a complete overview of all deliverables;
- Provide a complete overview of all dissemination activities (past and in progress). Where appropriate, provide feedback from presentations. Describe exploitation plans.
- Provide a complete overview of the billing status, eligible costs, planned and actual effort (incl. an explanation of the discrepancies).
- Analyse the lessons learnt at project level.

1.2 Intended readership

This deliverable is addressed to the ATM community, participating stakeholders as well as mathematicians who are interested in runway scheduling approaches focussing on the pre-tactical planning phase.

1.3 Inputs from other projects

NA

1.4 Glossary of terms

NA

2 Technical Project Deliverables

Management deliverables such as progress reports, gate report or this final report need not be included.

Number	Title	Short Description	Approval status
As per latest schedule	*As per latest schedule*		*Submitted, approved or rejected*
D1.1	Report on selected ATM application	Report on selected ATM application with description of impact of disturbances	Approved
D2.1	Report on appropriate techniques	Report on appropriate techniques for the solution of the ATM problem	Approved
D4.1A	Validation Plan	Validation Plan for validation exercise described in D4.1	Approved
D4.1	Validation report for stochastic and for robust models	Validation Report	Approved
D3.1A	Draft Report on the concept of a robust, stochastic model for ATM applications	Draft of D3.1	Approved
D3.1	Report on the concept of a robust, stochastic model for ATM applications	Report on the concept of a robust, stochastic model for ATM applications, including the model, theoretical aspects, description and computational efforts	Approved
D4.2	Validation report for combined models	Validation Report	Approved
D5.1	Report on analysis of nominal, robust, stochastic and combined approach	Technical Report	Approved
D5.2	Report describing generalized model	Technical Report	Submitted

Table 1 - List of Project Deliverables

3 Dissemination Activities

3.1 Presentations/publications at ATM conferences/journals

SESAR Innovation Days 2013, 26/11/2013 – 28/11/2013, Stockholm: We presented a poster entitled *"RobustATM - Robust Optimization of ATM Planning Processes by Modelling of Uncertainty Impact"*, which outlines the different solution approaches for pre-tactical planning problems considered in the project and their benefits for the ATM system.

SESAR Innovation Days 2014, 25/11/2014 – 27/11/2014, Madrid: We presented a paper entitled *"Pre-Tactical Time Window Assignment: Runway Utilization and the Impact of Uncertainties"* [1], in which we set up a mixed integer program (MIP) for the pre-tactical optimization of runway utilization. Afterwards, the impact of disturbances on the deterministic solutions was investigated. The results showed that it is crucial to enrich the optimization approach by protection against uncertainties, in order to produce less necessary replanning.

The paper above was further selected to be published in a special issue of the **Journal of Air Transport Management (2016).** Therefore it was extended and eventually published under the title *"Pre-tactical optimization of runway utilization under uncertainty"* [5]. The extension included the incorporation of uncertainties directly into the model by using techniques from robust and stochastic optimization.

SESAR Innovation Days 2014, 25/11/2014 – 27/11/2014, Madrid: We presented a second paper at the SIDs entitled *"Robust Runway Scheduling Using a Time-indexed Model"* [4]. Two mathematical models for tactical runway scheduling were developed and evaluated in different traffic scenarios. Furthermore, the model that performed better in practice was extended to a strict robust model.

This paper was also selected for the special issue of the **Journal of Air Transport Management (2016).** It was also extended and published under the title *"Robust Runway Scheduling Under Uncertain Conditions"* [6]. The extension included a light robustness model which was presented and validated in a simulation procedure.

SESAR Innovation Days 2015, 01/12/2015 – 03/12/2015, Bologna: We presented a paper entitled *"Pre-Tactical Time Window Assignment: Runway Utilization and the Impact of Uncertainties"* [2], in which we analyzed real-world data from a large German airport to obtain realistic delay distributions, which turn out to be two-parametric Γ-distributions. We described a simulation environment and tested our new robust and stochastic solution methods against standard algorithms (e.g., First-Come-First-Serve). The encouraging results showed that our approaches significantly reduce the number of necessary replannings.

ICRAT 2016, 20/06/2016 – 24/06/2016, Philadelphia: The empirical airport traffic data analysis from the DLR test platform at a large German airport (2013 – 14) that was used for the generation of realistic traffic scenarios and delay statistics yielded also some extreme weather events (X-events) with traffic disruption and complete airport closing. Average delay statistics as used in our simulations include these as outliers (e.g. delays > 2 h) which usually are eliminated before being fed into Monte Carlo simulations. That is why we started initial research in integrating also these real world events into the optimized scheduling. This work is performed at DLR under the resilience and viability headline and we have submitted a first paper, "entitled *Nonlinear Dynamics Approach for Modeling of Air Traffic Performance Disruption and Recovery"* [3], with initial results to the FAA – Eurocontrol ICRAT conference /Philadelphia. An outline is included in Deliverable 5.2.

Related Doctoral thesis at FAU (currently ongoing):

- Development of optimization methods that are protected against uncertainties, with a focus on the pre-tactical planning phase
- Development of robust optimization methods for the tactical planning phase
- Mathematical optimization for the tactical planning phase taking further side constraints such as precedence constraints into account

Related Master theses at FAU:

- *[M1] Robuste Optimierung in der Flugplanung: Entwicklung eines statischen sowie eines zeitexpandierten Modells zur robusten Zeitfenster-Zuordnung in der prätaktischen Phase* (engl.: Robust optimization in ATM: A static and a time expanded model for robust time window assignment in the pre-tactical planning phase)
Adviser: Frauke Liers
- *[M2] Optimierung von Flugbahnen: Ein gemischt-ganzzahliges Modell zur Berechnung von Trajektorien-Netzwerken* (engl.: Trajectory Optimization: A Mixed-Integer Model for Determining Trajectory Networks)
Adviser: Frauke Liers

Related Bachelor theses at FAU:

- *[B1] Leichte Robustheit bei der Planung von landenden Flugzeugen* (engl.: Light robustness for arrival planning)
Adviser: Frauke Liers, Manu Kapolke
- *[B2] Online Scheduling für Anflugprobleme* (engl.: Online scheduling for arrival planning problems)
Adviser: Frauke Liers, Andreas Heidt
- *[B3] Vergleich zweier Modellierungsansätze für das wiederherstellbar robuste Zuordnungsproblem* (engl.: Comparing two modeling approaches for the recoverable robust assignment problem)
Adviser: Frauke Liers, Andreas Bärmann, Lena Hupp

3.2 Presentations/publications at other conferences/journals

Workshop "Operations Research in den Ingenieurwissenschaften" (engl.: operations research in engineering), 03/03/2014, Asselheim: We gave a talk on *"Robust Optimization in ATM and telecommunication"* in which we presented several mathematical optimization tasks together with methods yielding protection against uncertainties, as developed in RobustATM. Audience: German engineering scientists as well as mathematicians.

MPI Noon Seminar, 16/04/2015, Max Planck Institute Saarbrücken: We gave a talk on *"Exact Approaches for Air Traffic Management Problems" where we presented the optimization tasks developed in RobustATM. We focused on presenting results about structural investigations of the underlying mathematical problems*. Audience: Computer science scientists.

ISMP 2015 (International Symposium on Mathematical Programming), 14/07/2015, Pittsburgh: We gave a talk on *"Robust Time-Window Assignment for Runway Utilization"* where we presented the models and solution concepts developed in RobustATM. The three-annual ISMP conference is one of the most important meetings in the field of mathematical optimization Audience: mathematicians, computer scientists, operations research scientists.

OR 2015 (International Conference on Operations Research), 04/09/2015, Vienna: We gave a talk on *"Pre-Tactical Planning of Runway Utilization using Robust and Stochastic Optimization"*. We presented the problem statement and several solution approaches investigated in RobustATM. The annual Operations Research Conferences are very important for our field. Audience: mathematicians, operations research scientists, practitioners.

OR 2015 (International Conference on Operations Research), 04/09/2015, Vienna: We also gave a talk on *"Light and Recoverable Robustness for Runway Schedules in Air Traffic Management"* in which we presented some robust optimization models for tactical runway scheduling. Audience: mathematicians, operations research scientists, practitioners.

3.3 Web presence

The following web site contains a brief introduction of the project:

http://www.mso.math.fau.de/edom/projects/robustatm-robust-optimization-of-atm-planning-processes-by-modelling-of-uncertainty-impact

The project wiki contains information about the consortium, the project deliverables, publications, slides from presentations and minutes from project meetings:

https://edom.mi.uni-erlangen.de/dokuwikis/robust-atm/doku.php

Other web links to publications and presentations:

- SID 2013 posters:

  http://www.sesarinnovationdays.eu/2013/posters

- SID 2014 papers and presentations:

  http://www.sesarinnovationdays.eu/2014/papersandpresentations

- SID 2015 papers and presentations:

  http://www.sesarinnovationdays.eu/2015/papersandpresentations

- Papers in Journal of Air Transport Management (2016):

  http://dx.doi.org/10.1016/j.jairtraman.2016.02.004

  http://dx.doi.org/10.1016/j.jairtraman.2016.02.009

3.4 Demonstrations

Provide one paragraph per demonstration (excluding demonstrations part of validation exercises or acceptance tests), explaining what was demonstrated and to whom. Provide an additional paragraph on the feedback.

3.5 Exploitation plans

Invest Further Mathematical Optimization Approaches – Rise Interest for ATM Applications in the Optimization Community

Within RobustATM, it was possible to model the pre-tactical planning phase by several different assignment problems with additional side constraints and a quadratic objective function. Subsequently, they were protected against uncertainties using robust and stochastic optimization as well as a mixed model. The fact that the underlying problem structure is that of an assignment problem has many advantages. Assignments with a linear objective function are very well understood both from a theoretical as well as a practical point of view. The fact that in our case the objective is quadratic instead of linear due to fairness issues, changes this picture dramatically. In fact, the corresponding quadratic assignment problems (QAP) belong to the most challenging optimization tasks in combinatorial optimization. The QAP occurring in RobustATM – although being difficult - are usually less computationally demanding in practice. This fact is interesting in its own right and makes the study of the specific QAP instances from RobustATM interesting. (FAU)

Study Different Optimization Problems Under Uncertainty, Similar to how it was done in RobustATM

When it comes to uncertainty protection, we could develop models and solution approaches for QAP under uncertainty. Here, we developed advanced robustness concepts such as recoverable and light robustness methods that are modern in robust optimization. However, according to our knowledge, they have not yet been applied and studied for (quadratic) assignment problems. This might be due to the lack of knowledge of an application where they occur naturally. From a mathematical point of view, our results are relevant for the field of optimization under uncertainty as we could show that they can be solved effectively and that they indeed generate solutions that are protected against uncertainties. Furthermore, several researchers started getting interested in our application, among them colleagues from TU Dortmund and a colleague from the ETH Zurich. Of course, at this point many research questions remain open, and the results obtained here are only first steps towards being protected against uncertainties in mathematical optimization. (FAU)

More Detailed Research in Modeling the Real-World Delay Distributions

For the validation we developed a new stochastic delay model (Gamma process) extending the basic Poisson queuing theory and related to the PSRA model (pre-scheduled random arrivals). However, there is a certain amount of previous research publications addressing the time series analysis of traffic statistics (e.g. the mixing of seasonal effects, trends, stochastic components) which should be addressed and considered in more detail than was possible with the given resources. Further improvement of delay modeling would be a research topic on its own. (DLR)

More Detailed Analysis of Advanced Robust and Stochastic Concepts in Order to Make them Even more Applicable in the ATM Context

The same is true for further mathematical analysis of advanced robust and stochastic optimization models. They have already been developed within the project (D3.1), but an appropriate evaluation in order to make them applicable in practice was beyond the scope of RobustATM and would also be a research topic on its own. (FAU)

Benefits from RobustATM for the ATM Domain and Further ATM Applications with Disturbances

Further, the promising project results obtained with the new discrete models for optimized scheduling suggests several directions of further ATM research and generalization of the present approach.

First of all, air traffic management will benefit from the utilization of a new paradigm instead of FCFS for real-time rescheduling of disturbed plans and assigning new target times that takes into account the previous delay statistics. It helps to prevent or/and to compensate changes caused by a disturbance. (DLR/FAU)

The methods and results from RobustATM could be extended to the case of several runways, it could be integrated together with gate assignment or taxiing, just to name a few, with the goal of determining better and more stable plans effectively. Finally, stable trajectories in simplified model could be obtained, such as it has been proposed in the 2015 Horizon 2020 call “STARNET” that has received good evaluation, however did not get funding due to a large number of applications. Nevertheless, the first promising steps into this direction have been obtained in the recent Masters’ Thesis [M2] at FAU which would be a good starting point for continued research. Many further questions need to be addressed in order to be able to calculate stable trajectory networks.

Extending the RobustATM Results for the Pre-Tactical Phase also to Tactical Planning

Secondly, an extension of the pre-tactical optimization into the tactical range and development of an extended arrival manager, e.g. by transfer of the pre-tactical plan at $\approx$ 30 minutes before planned landing to a continuous optimizer for the final approach, can result in a new air traffic management supporting tool. (DLR/FAU). Many further algorithmic questions need to be addressed in order to develop such an integrated tool.

Extending the RobustATM Results to Dynamical Model for Recovery after Disruption

Next, a combination with an advanced dynamical model for optimal performance stabilization or recovery after disruption under (anticipated) strong disturbance is of the great value. A corresponding

WP-E funding application ("Antifragility") achieved a sufficient qualification 2015, however did not receive a grant due to a very large number of applications. Nevertheless this research was continued with DLR-internal resources and the initial results [3] provide a good starting point for a new application within the upcoming WP-E call.

Extending the RobustATM Results for an Improved Optimization-Based Arrival Manager

We presented initial concepts and preliminary results to illustrate the potential of these extensions and generalizations of the high-potential results of MIP-optimizer based models for realization of an extended arrival manager. It is expected that this kind of advanced assistance tool will lead to improved efficiency and resilience of the ATM traffic management. We believe that the inclusion of the discrete optimization and robustification of plans through inclusion of uncertainties can be integrated into the promising and well documented formal framework of Viability theory that has the potential for a mathematical basis of ATM resilience. Initial steps were successfully demonstrated with the modelling and simulation of disruption and recovery of traffic under extreme weather conditions [3]. (DLR)

4 Total Eligible Costs

This section is based on the Project Costs Breakdown Forms of the eligible costs incurred by project participants.

Date	Deliverables on Bill	Contribution for Effort	Contribution for Other Costs (specify)	Status
Date of invoice	*List of deliverable numbers*	*Requested contribution for effort*	*Requested contribution for travel, licences, logistics etc.*	*Billed or paid*
04.12.2014	D0.1, D6.1, D0.2, D1.1, D2.1, D4.1A	115.618,27 €	4.592,42 € (travel costs)	paid
05.08.2015	D0.4, D6.2, D4.1, D0.6, D3.1A	171.203,79 €	0,00 €	paid
22.10.2015	D0.8, D3.1, D6.3	75.173,92 €	1.903,99 € (travel costs)	paid
	D0.10, D4.2, D5.1, D5.2, D0.11	192.510,08 €	5.801,00 € (travel costs) Plus additional travel costs due to travel to ICRAT (Fürstenau) and to the close-out (Liers)	To be billed after the close-out meeting
GRAND TOTAL		554.506,06 €	12.297,41 + x € (travel costs, travel cost for ICRAT and close-out to come)	

Table 2 Overview of Billing

Company	Planned man-days	Actual man-days	Total Cost	Total Contribution	Reason for Deviation
FAU	802	802	291.448,55 €	291.448,55 €	
DLR	626	626	367.139,89 €	275.354,92 €	
GRAND TOTAL	1.428	1.428	658.588,44 €	566.803,47 + x €	(travel costs for close-out + ICRAT to come)

Table 3 Overview of Effort and Costs per project participant

5 Project Lessons Learnt

What worked well?
The consortium collaborated very closely and very intensively...DLR invested its expert knowledge about the ATM application and its expertise about validation. FAU invested its expert knowledge about mathematical optimization and mathematical optimization under uncertainty. This joint work was a lot of fun, for both sites.
In contrast to many other (international) collaborative projects only little administrative effort was involved so that more than usual resources could be focused on generation of scientific content.
Very competent and constructive supervision was experienced by Eurocontrol (Dirk Schäfer) and the SJU (Olivia Nunez).
From our point of view, several interesting and relevant results could be obtained during RobustATM. As is always the case in a challenging project, many interesting problems remain open, and further questions emerged during our work.
What should be improved?
There was not enough empirical data concerning the considered set of flights to evaluate the values of ET, LT and maxLT realistically. Therefore, these values have been approximated. For the more realistic evaluation, empirical data should be available. It was more difficult than expected to get sufficient empirical traffic data from airport operators. It was a lucky incident that DLR happens to have access to airport data sources (testplatform, 2013-14, and ongoing) from a previous cooperation. Nevertheless even these data are not sufficient because departure data from origin airports of the typically 150 – 250 arrivals/day are incomplete.
Data cleaning and pre-processing is important however very time consuming, so that it is difficult to get reliable statistics. In future projects, the empirical data part as prerequisite for reliable validation of any significance for real life requires at least the same amount of resources as the theoretical / methodological part.
Developing new mathematical methods, developing solution algorithms as well as implementing the corresponding computer programs is a non-trivial and time-consuming process. The project duration of RobustATM of 2.5 years was very short in order to accomplish this. Usually, with institutions such as the DFG, BMBF etc., funding for a research project is granted for 3 years. Thus, it would be highly desirable to extend the duration of the research projects to 3 years.
Less written deliverables (reduction of template based formal reporting) would leave more resources for research, generating results and producing peer review journal papers with impact factor qualification.

Table 4 - Project Lessons Learnt

6 References

Reference to main documentation including a full list of the project's external publications. Project deliverables should not be included here.

[1] Fürstenau, N., Heidt, A., Helmke, H., Kapolke, M., Liers, F. (2014). *Pre-Tactical Time Window Assignment: Runway Utilization and the Impact of Uncertainties.* In: Schaefer, Dirk (Editor) Proceedings of the SESAR Innovation Days (2014) EUROCONTROL. ISBN 978-2-87497-077-1.

[2] Fürstenau, N., Heidt, A., Kapolke, M., Liers, F., Mittendorf, M., Weiß, C. (2015). *Pre-tactical Planning of Runway Utilization Under Uncertainty: Optimization and Validation*. In: Schaefer, Dirk (Editor) Proceedings of the SESAR Innovation Days (2015) EUROCONTROL. ISSN 0770-1268.

[3] Fürstenau, N., Mittendorf, M., Kamo, S. (2016). *Nonlinear Dynamics Approach for Modelling of Air Traffic Disruption and Recovery*. ICRAT7, Philadelphia/PA, submitted

[4] Heidt, A., Helmke, H., Liers, F., Martin, A. (2014). *Robust Runway Scheduling Using a Time-indexed Model*. In: Schaefer, Dirk (Editor) Proceedings of the SESAR Innovation Days (2014) EUROCONTROL. ISBN 978-2-87497-077-1.

[5] Kapolke, M., Fürstenau, N., Heidt, A., Liers, F., Mittendorf, M., Weiß, C. (2016). *Pre-tactical optimization of runway utilization under uncertainty.* J. of Air Transport Management (2016), DOI: 10.1016/j.jairtraman.2016.02.004

[6] Heidt, A., Helmke, H., Kapolke, M., Liers, F., Martin, A. (2016)*. Robust Runway Scheduling Under Uncertain Conditions.* J. of Air Transport Management (2016) , DOI: 10.1016/j.jairtraman.2016.02.009