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Model-Based Analysis of Agents' Incentives in a Distributed Air Traffic Management Process

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Abstract. This work deals with the model-based analysis of agents' incentives in a distributed air traffic management process. The approach is demonstrated on a potential future process for planning arrivals at an airport, in which the scheduling is based on time estimates provided by individual aircraft. The planning process and agent interactions are implemented as a Coloured Petri Net (CPN) Model. State space based methods are used on this model to analyze potential consequences of agents' behavior. The purpose of the analysis is to validate, if the designers' expectations towards aircraft behavior (desired behavior) are compatible with the incentives established by the planning mechanism. Aircraft producing the desired and cooperative behavior should be rewarded for their practice. An example is presented where aircraft react to an operational scenario with a weather-induced event. Potential aircraft choices and reactions are discussed with regard to their compatibility with MaxMax, MaxAverage and MaxMin strategies of rational agents in the scenario context.

1 Introduction

Air Traffic Management (ATM) can be understood as a distributed multi-stakeholder system with a large number of economically and organizationally independent actors. Within the system a wide range of subprocesses are currently being redesigned towards more interactive and cooperative planning processes, often including elements of negotiation between different agents [7, 2, 9]. The redesign follows the aim of reaching better coordination and usage of limited resources and thus a higher global system efficiency. However, if potential new interaction protocols and planning mechanisms are not designed properly, the self-interested behavior of individual agents can also run counter the realization of the global system objective [6]. A suitable modeling of new protocols and their careful formal analysis is a key element for validating that the design objective can actually be reached [11].

The contribution presents a model-based approach to analyze agents' behavioral incentives in a distributed air traffic management process. The approach is demonstrated on the specific example of a new planning process for arrival management [12, 8]. Aim of the new arrival management process is to provide an optimized scheduling of arrival traffic, based on state information and preferences submitted by the various arriving aircraft. In order to reach that goal, a planning system AMAN (Arrival Manager) computes a set of potential candidate sequences (possible schedules), which are evaluated using different rating functions. The objective of the model-based analysis introduced in this work, is to provide a formal argument, if agent's incentives and interest emerging from a certain design variant of the AMAN will or will not be compatible with the behavioral expectations towards the agents as formulated by the system designer (Figure 1).

The core of the approach is based on

- the formalization of the relevant decision context by appropriate modeling tools and
- the application of mathematical solution concepts (decision theoretic criteria) to reason about agents' incentives and possibly predict actors behavior.

After the analysis of rational behavior and incentives within the system, the results are compared to the behavioral expectations of the system designer. These can usually be drawn from a more informal (hermeneutic) actor role analysis of the design documents (e.g. use cases). Where rational behavior and behavioral expectations by design can be shown to contradict, recommendations for the modification of the design should be derived.

2 Arrival Management

The Section introduces the considered application context of arrival management in air traffic control. It starts with a definition of subprocesses and objectives of arrival management in Subsection 2.1 and then outlines expected future developments in the area (Subsection 2.2). These new developments build the background and motivation of this work regarding the application point of view. In Subsection 2.3 the effects on the relation of cooperative and competitive elements in arrival management is pointed out. Subsequently, the scope of the discussion is narrowed down to the specific elements and subprocesses represented in the following model and analysis (Subsection 2.4).

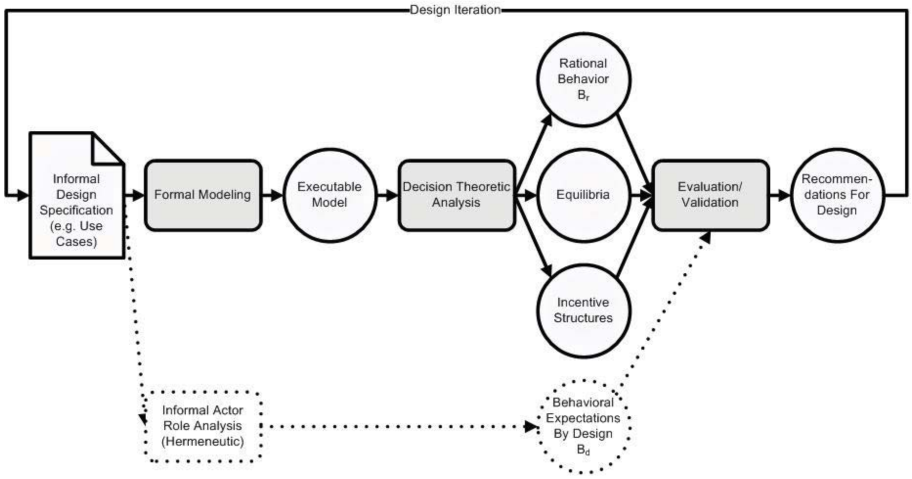

Figure 1: Concept of modeling and validation approach

2.1 Application Context and Subprocesses

Aim of the arrival management process in general is to provide an optimal (safe and efficient) scheduling, guidance and control of arrival traffic to an airport. Independent of the exact procedures applying at a specific airport (which can vary significantly depending on the airport, local regulations and geography), the following four generic subproblems have to be solved by any variant of an arrival management process:

1. *Sequencing*, i.e. establishing a favorable arrival sequence (sequence of aircraft) according to a number of optimization criteria,
2. *Trajectory generation*, which means finding an efficient and conflict free route for each aircraft from its current position to the runway threshold in accordance with the TTO, and also
3. *Metering* that is to determine for each individual aircraft the TTO (Target Times Over) certain points (fixes) of the respective arrival route appropriate for the aircraft's position in the sequence,
4. *Clearance generation*, that is, to decide on the specific clearances which should be given to an aircraft in order to lead it along the route as planned.

Currently, the level of automation and kind of assistance systems used to support the human air traffic controller in his task may vary widely depending on the size of the airport and its technical development. It ranges from virtually no automation (radar display with traffic state information only, controller solves tasks 1-4 without assistance) to working positions with integrated planning systems AMANs (Arrival Management Systems). These may offer sophisticated support for sequencing and metering. The AMAN assistance functions for automated trajectory generation and clearance generation are a topic of ongoing research but are expected to become industrialized in the future.

2.2 Air-Ground Integrated Arrival Management

Future procedures and mechanisms for arrival management are likely to feature a much closer integration of the respective actors and planning systems in the air and on the ground as it is the case today [11].

On a technical level, the closer integration means that a direct coupling and data exchange will be established between the ground-based arrival management system AMAN and the Flight Management System (FMS) on board of the aircraft via a digital datalink. Such a coupling is necessary to make better use of the advanced navigation capabilities of modern aircraft's FMS than is currently the case. Fuel and noise efficient trajectories can be calculated through the FMS but have to be coordinated with, and integrated into, the ground based planning. Nowadays voice radio is still the standard means of communication between air traffic controllers and pilots, making it impossible to exchange greater amounts of (numerical) trajectory data, which is necessary to lead the aircraft along the most preferable route or profile.

From an air traffic control point of view, the most important change may be that the trajectory will in the future no longer be commanded unilaterally to the aircraft by the air traffic controller. Rather the trajectory will be the result of some kind of bidirectional negotiation between air and ground wherein the user (aircraft) preferences and performance data are explicitly taken into account. The negotiation will result in a trajectory contract for a 4D-trajectory. The 4D-contract is an agreement on which trajectory is going to be followed by the aircraft and at which spatial point the aircraft is going to be at a certain point in time.

2.3 Cooperation vs. Competition

The novel control procedures and mechanisms outlined above will move the system towards a more cooperative system. This follows the aim of reaching better coordination and usage of limited resources and thus a higher global system efficiency. However, if the new interaction protocols and planning mechanisms are not designed properly, the self-interested behavior of individual agents (aircraft) can also run counter the realization of the global system objective. To understand that point, it is important to consider that the arrival process to a highly frequented airport inherently also contains a strong competitive element. At least during traffic peaks, different aircraft and airlines are potentially competitors with regard to limited airspace, route and runway resources. A position gain in the sequence for one aircraft will most likely be achieved at the price of some negative effect for one or more other aircraft. No two aircraft can use the same airspace or route segment at the same time. Within legal and operational limits it can be thus be assumed that airlines and aircraft will strive to optimize their strategies in dealing with the planning systems that determine the efficiency and cost of their operation.

2.4 Sequence Planning

The analysis example presented in the remainder of the paper and the CPN model [5] used is focused on a more limited example of the sequence planning (sequencing) aspects of arrival management (see 2.1, step 1). The sequence planning phase is the natural starting point for the modeling of an AMANs behavior, as it precedes the other planning phases (trajectory generation, metering and implementation). All later phases are based on the assumed sequence. Important decisions about the outcome of the overall process (particularly in terms of punctuality, costs and fuel consumption) are made during the sequence planning stage when the position of an aircraft in the sequence is determined.

The mechanism for sequence planning investigated below can be summarized as follows:

When an aircraft reaches a certain area around the airport, it is required to submit its earliest times of arrival (ETA) for a common waypoint WP close the airport where arrival routes are merged. Based on the set of all ETAs received, the AMANs sequence planner establishes a favorable sequence and conflict free target times (TTAs) for this waypoint WP, which are returned to each aircraft. In order to plan the sequence, the AMAN uses different rating functions for sequence evaluation. However, due to weather changes, imprecise predictions of flight performance or other operational incidents, aircraft ETAs may change during the course of the approach (TTAs may become unreachable) and will then have to be updated dynamically. The continuous aim of the sequence planner (AMAN) is to plan for all aircraft a TTA as close to their ETA as possible (i.e. as early as possible). At the same time it is necessary to assure a high degree of stability in the sequence, in order to limit the control effort of air traffic controllers and the need for air-ground communication and renegotiation.

The necessary subprocesses used by the sequence planner to establish the sequence are discussed in Section 3 together with two potential rating/evaluation functions. The rating functions evaluate which sequence is most favorable. The question considered in this investigation and the presented example (see Section 4) is if the assumed planning process and the nature of the evaluation functions encourages aircraft behavior with regard to submitting ETAs compatible with the designers' goals. If this is not the case, the system may set incentives which lead rational actors to behave in a globally undesirable manner. Then the system should be modified.

3 CPN Model

This Section briefly introduces the CPN Tools model [5] developed to analyze the behavior of the cooperative sequence planning process as outlined above. The entire model is presented in more detail in [12].

3.1 Model Architecture

The model consists of 16 pages arranged in 5 hierarchical layers. All 16 pages form a tree structure departing from the toplevel page named *SeqPlanning*. An overview of the structure of the model is depicted in Fig. 2.

A special simulation and analysis approach was developed for the model, which also impacts the model structure. To realize that approach, the pages are organized into three different modules (*M1, M2, M3*) as indicated in Fig. 2. The approach includes alternating and iterative use of state space analysis techniques [4] and simulation for the three different modules in order to cope with the combinatorial problems of planning large sequences. The results of the simulation or analysis phase of one module serve as an initialization for the next phase, realizing a cyclic process [13].

In Figure 3 the toplevel page *SeqPlanning* within the hierarchy of CPN Model is shown. It features five main substitution transitions and two regular transitions.
The substitution transitions *SequenceGeneration, SequenceEvaluation, SequenceSelection* and the regular transition *SequenceImplementation* together implement the behavior of the automated sequence planning system. The *SequenceGeneration* transition builds the set of candidate sequences by calculating all possible sequence permuta-

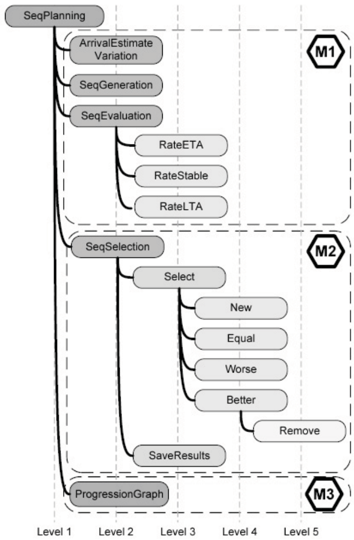

Figure 2: CPN model page hierarchy

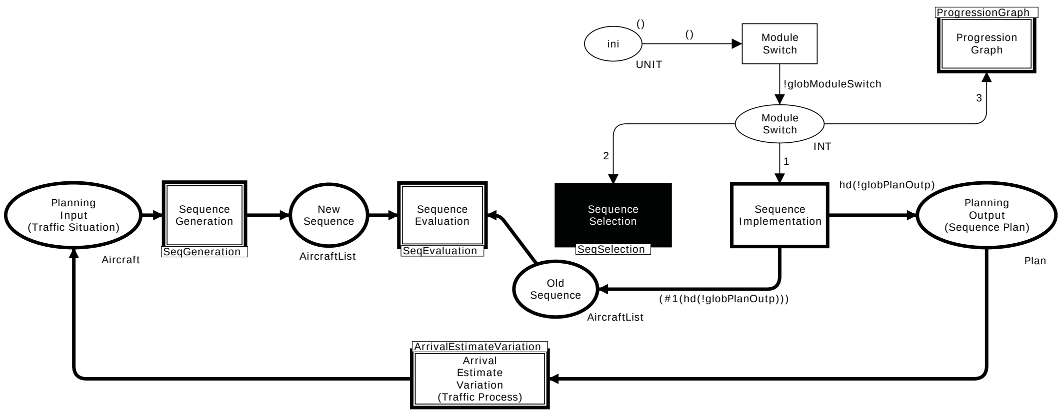

Figure 3: SeqPlanning page of CPN Model

tions and computing the respective target times TTAs. The *SequenceEvaluation* page calculates a quality value for each candidate sequence reflecting the desirability/feasibility according to the different rating functions (presented in the following Subsection 3.2). The *SequenceSelection* page extracts the candidate with the highest quality value, which is implemented by the *SequenceImplementation* transition. Together the four transitions map a perceived traffic situation as planning input to an implemented sequence plan as an output of the planning system.

The substitution transition *ArrivalEstimateVariation* in the lower part of the picture represents the behavior of aircraft. These aircraft may vary their submitted arrival time estimates (ETAs) at certain points of the arrival procedure. Note that these variations are external to the planning system and represent changes of the traffic situation that the planning system has to react to.

The ProgressionGraph page is not a part of the planning process itself and contains a number of analysis functions which are used in the simulations below.

3.2 Rating Functions

This Section introduces two rating functions named *QEarlyETA* and *QStability* [14]. These are assumed to form part of a potential sequence planning system which is investigated in the following experiment. They are implemented on pages *RateETA* and *RateStable* of the page hierarchy in the CPN Model. During each planning cycle these functions are used by the planning system for the evaluation of the set of candidate sequences and lead to the following selection of the most favorable sequence. Each of the rating functions produces a quality value within a range from 0.0 to 1.0 for each candidate sequence. The two individual quality values are combined into a weighted sum to give one total quality value $QTotal$. The candidate with the highest $QTotal$ is selected and implemented.

QEarlyETA:
The function $QEarlyETA$

$$Q_{EarlyEta} = \frac{1}{n}\sum_{ac=1}^{n}\left(\frac{(t_{lim}-(tta_{ac}-eta_{ac}))}{t_{lim}}\right)^{p} \tag{1}$$

with

$$\begin{aligned} p &= 0.5 \\ t_{lim} &= 600\ s \\ n &= numberOfAircraftInSequence \end{aligned}$$

rates how close the assigned TTA of each aircraft ac comes to the submitted ETA of that aircraft.

QStability:
The function $QStability$

$$\begin{aligned} Q_{Stability} &= \prod_{ac=1}^{n} min\left[(1, max(0, -\frac{dtta_{ac}}{t_{sep}}+1)\right] \qquad (2) \\ dtta &= tta_i - tta_{i-1} \\ t_{sep} &= 75\ s\ (minimumSeparation) \end{aligned}$$

rates if the sequence remains stable, that is if target times of aircraft ac in cycle $i+1$ correspond to target times in cycle i. Negative changes in target times (earlier TTA then before) have no negative effect on the quality value. Later target times (delays) are penalized.

QTotal:
The function $QTotal$

$$Q_{Total} = w_e * Q_{EarlyEta} + w_s * Q_{Stability} \tag{3}$$

calculates a single quality value as the weighted sum of $QEarlyETA$ and $QStability$. The corresponding weights w_e and w_s are important parameters which fundamentally determine the planning systems characteristics. They are varied to produce different system behavior in the below experiments.

The following definitions serve to identify within the set of all candidate sequences the sequence candidate with the highest quality values according to $QEarlyETA$ and $QStability$.

Definition 3.1 *The sequence candidate s_k with the highest quality value in QEarlyETA is called 'ETA-optimal'.*

Definition 3.2 *The sequence candidate s_l with the highest quality value in QStability is called 'Stability-optimal'.*

4 Application Scenario

This Section describes the operational application scenario under which the sequence planning system shall be tested with regard to the incentives set by the system. The Section starts with a description of the initial traffic scenario, followed by the introduction of a weather-induced scenario event. This leads to a formulation of the resulting aircrafts‘ choices in reaction to this event. It is outlined how the system design expects the aircraft to react. The purpose of the simulation is to validate if these expectations are rational to have for given traffic scenarios and system settings.

4.1 Initial Situation

In Figure 4 a traffic scenario is shown, where a number of aircraft approach a common merging point MP from different directions. The task of the arrival management system is to establish a safe and efficient sequence for these aircraft at the merging point MP. In order to do so, on the one hand a minimal time interval ($t_{sep} = 75\ s$) has to be maintained between the target times of each pair of aircraft over the waypoint MP to ensure a safe separation. In addition to this separation requirement, the planning system constantly seeks to optimize the sequence by selecting the candidate with the highest $QTotal$ as introduced in Subsection 3.2. For the following simulations the considered sequence will consist of a set of four aircraft identified as aircraft A, B, C, D.

4.2 Scenario Event

During the course of the aircrafts' approach, a weather change (or imprecise initial weather forecast) causes the actual wind vector to change from wind direction 1 (North) to wind direction 2 (South)(Figure 4). The aircraft approaching the airport from different directions are delayed or accelerated respectively with regard to their initital planning. This causes a shift of the Earliest Times of Arrival (ETAs) of each aircraft over the Merging Point

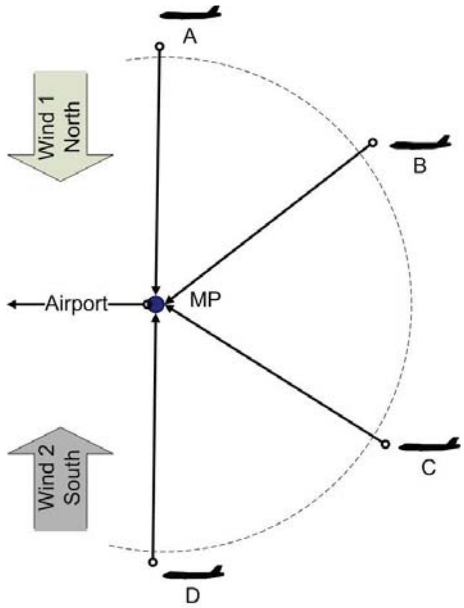

Figure 4: Traffic situation and scenario description

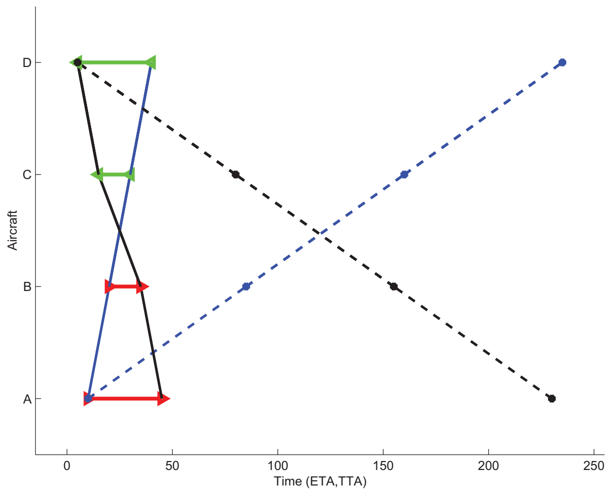

Figure 5: Earliest Times of Arrival (ETAs) and Target Times of Arrival (TTAs) before and after scenario event

MP. Each aircraft will consequently have to correct the Earliest Time of Arrival it submits to the central arrival management system (Figure 5).

In reaction to the modified inputs for ETA as submitted by the agents and the characteristics of the planning system, the planning system AMAN may or may not react with changes to the sequence and modifications of the position and target times of all or individual aircraft in the sequence. This will result in more favorable or less favorable positions for certain aircraft in the new sequence. This in turn may be associated with additional fuel cost and delay with regard to the schedule.

In Figure 5 the assumed earliest times of arrival ETAs and Target Times Of Arrival TTAs (as allocated by the planning system) before and after scenario event are shown. The four positions on the axis of ordinates correspond to the four different aircraft (A, B, C, D). The axis of abscissae indicates time (ETAs and TTAs). The situation before the event is indicated in blue (ETAs are connected by solid blue line, TTAs are connected by dashed blue line), the situation after the event is indicated in black (ETAs are connected by solid black line, TTAs are connected by dashed black line). The arrows running in horizontal direction indicate the shift of the ETA for each aircraft d_{tta}. The Figure distinguishes between delays (red arrow) or accelerations (green arrows).

Note that in Figure 5, through the occurrence of the scenario event, the order of ETAs has been completely reverted (from $ETA_A < ETA_B < ETA_C < ETA_D$ to $ETA_D < ETA_C < ETA_B < ETA_A$). While the ETA-optimal sequence (optimal according to criterium $EarlyETA$ only) before the event was A→B→C→D the ETA-optimal sequence after the event is D→C→B→A. However, the actual result returned by the planning system may differ from the ETA-optimal sequence as will be shown. As defined by $QTotal$, the response of the system will depend on the weighting of the rating functions $QEarlyETa$ and $QStability$ in relation to each other.

POS1	Aircraft	ETA1	TTA1	ETA-Shift	ETA2
1	A	10	10	35	5
2	B	20	85	15	80
3	C	30	160	-15	155
4	D	40	235	-35	230

Table 1: Initial state of example sequence and ETA-Shift

4.3 Agents' Choice

The agents' choice in the scenario is as follows: The correction of ETA in general cannot finally be avoided by the aircraft, but it is assumed the aircraft will in practice have considerable choice in the timing of the submission to the planning system. The update may be submitted as soon as it is detected. Alternatively, it may also be delayed for a certain time interval. The choice of timing determines the chance of an aircraft to be the first, second, third or fourth aircraft to submit the modification. Thus it influences (although not generally deterministically) the submission order. If an update was submitted as soon as possible and appropriate under the given circumstances it is in practice very difficult to control for an external observer. Important knowledge about the operational situation is encapsulated by the aircraft. This makes it difficult to just impose an early submission as a mandatory rule. Such a rule could hardly be enforced in practice.

4.4 Designers' expectations

The expectation of the system designer is that the aircraft should correct the time prediction ETA as soon as the change is discovered (that is, as soon as practically feasible for the flightcrew). This behavior is necessary in order to keep the planning system up to date and guarantee that all plans produced by the systems are practically feasible and efficient. Since this behavior is difficult to enforce by regulation, it is desirable that behavior be in a selfish agents own best interest, so he will try to act in the desired way where this is possible.

4.5 Validation objective

The purpose of the simulation is to validate if the designers expectation are compatible with the incentives structures established by the planning system dynamic behavior and protocol. Specifically, the analysis serves to decide

1. if the available choice (timing of submission) impacts the outcome, or if the outcome is generally independent of agents' choice,
2. if it is actually in the (rational) interest of each agent to announce necessary modifications of the Earliest Time of Arrival as soon as possible,
3. if the behavior expected by the designer (early submission) will also be rewarded by the planning system and will be experienced as favorable by the agent, and
4. if it is possible to systematically influence or manipulate the response of the planning system in a strategic manner.

4.6 Simulation Setting

In Table 1 the numerical values characterizing the traffic scenario used in the following simulations are stated. The columns 1-3 list the Earliest Times of Arrival (ETAs), Target Times of Arrival (TTAs) and aircraft Sequence Position (POS) before the scenario event. The columns 4-5 contain the shifts in ETA triggered by the scenario event, together with the resulting absolute ETAs after the occurrence of the event.

5 Simulation results for a single simulation run

Figure 6 exemplifies the kind of outcome achieved by one single simulation run. The tree shows potential responses of the planning system to the submission of the modified Earliest Times of Arrival (ETAs). The root node (left side) of the tree represents the inital state of the planning process before any modification of ETA are submitted. The sequence planned by the system in this initial state is A→B→C→D. Traversing the arcs from the root node to the different leaf nodes of the tree, each branch represents a different order of receiving the modified ETAs by the different aircraft. For the case of four aircraft, 24 combinations (and thus 24 leafs) are computed. The respective ETA-shift between each pair of nodes is annotated in the arc label. In the labeling of each node the resulting sequence planned by the system for the dynamic state can be seen.

Besides the specifity of this singular result, looking at the set of leaf nodes in the tree allows one first conclusion: The outcomes of the sequence in this simulation scenario are in fact impacted by the order of submissions as submitted by the agents. The behavior of the agents affects the resulting utility of the solution for them. Thus the choice of an agent to submit a correction early or late does matter. In this Figure, red arcs are used to indicate where an agent's position has directly deteriorated after his own action. Benefits for individual agents under this setting always occur trough a combination of several actions and can thus here not be attributed to a single action in the same manner.

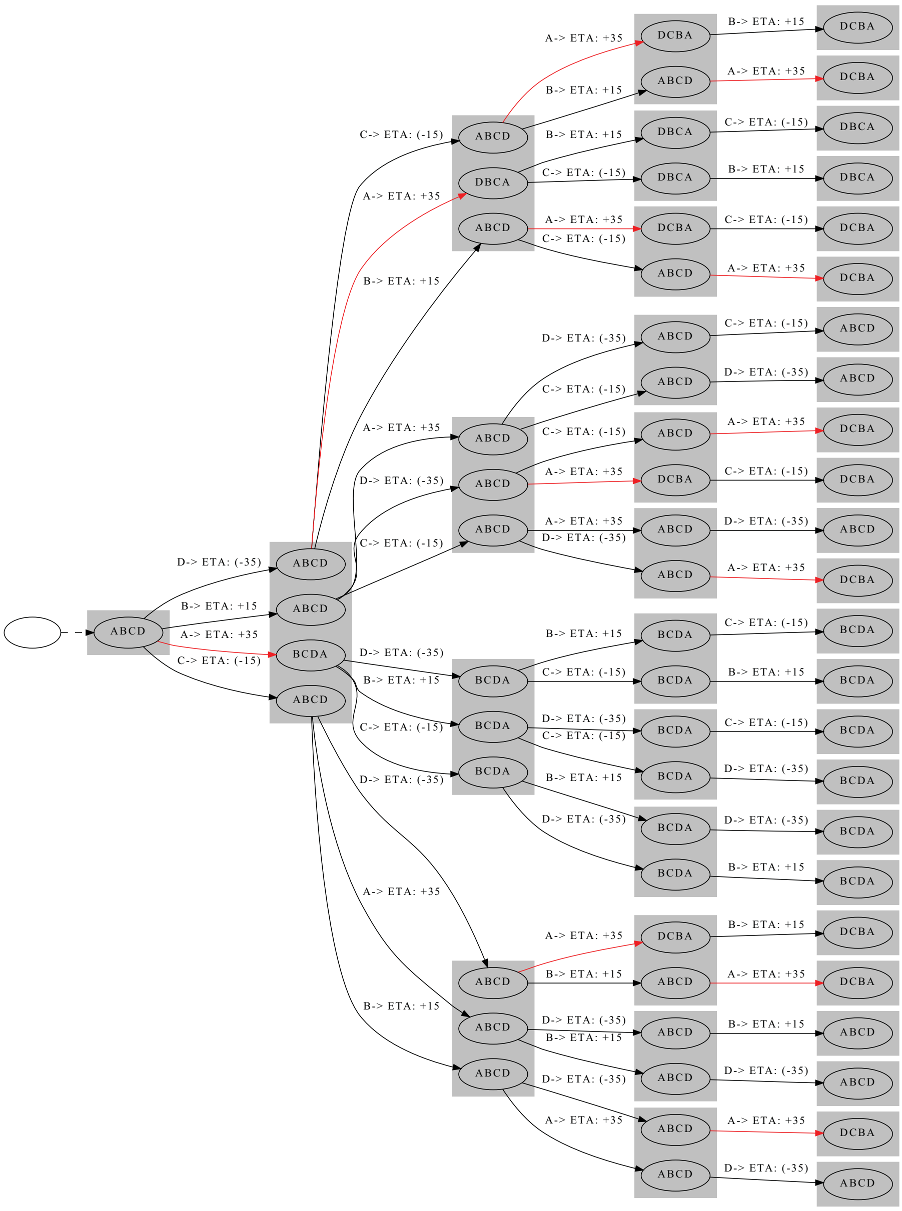

Figure 6: Sequence results as a function of aircraft submitting ETA-shifts in different orders

6 Aggregated results for a set of simulation runs

As shown in the following, the actual results depend critically on the ratio of the two weighting factors w_e and w_s. For the example illustrated in Figure 6 a medium ratio of $r = w_s/w_e$ was chosen. This stabilized the sequence to some extent, but allowed optimizations of the sequence due to sufficiently large changes in aircrafts ETAs. To further investigate this influence, aggregated results will be presented below, obtained from a set of simulation runs of the above kind. In this set of simulations, a systematic variation is performed of the planning system characteristics in terms of relative weighting of rating functions $QEarlyETA$ vs. $QStability$. This variation presents different trade-offs between flexible optimization for changing traffic situations on the one hand and stabilization of the sequence on the other hand. The aim is to draw more general conclusions about the characteristics of the hypothesized planning system and its consequences on behavioral incentives for the agents. In particular, the simulation series seeks to answer the question which strategies are favorable for the individual agents for different settings of the system.

6.1 Maximum, minimum, and average outcomes as a function of timing

In the considered set of simulations a constant value $w_e = 1000.0$ is used, while w_s is incremented in 13 equally distributed steps from $w_s = 0.0$ to $w_s = 600.0$. In terms of $r = w_s/w_e$, this means r was gradually increased from $r_{lower} = 0.0$ to a value r_{upper} =0.6. For r_{lower} the weighting of stability is zero, and the final sequence result is always the ETA-optimal sequence, regardless of agents' timing of submission. For r_{upper} the weighting of stability is sufficiently high to prevent any changes in sequence whatsoever, thus the final sequence is always identical with the initial sequence. The actual range of interest for r lies between r_{lower} and r_{upper}. There, the final result may vary depending on the order of submission by the agents. For each step of r in this range, the results for all different orders of submission are calculated in the same manner as for the decision tree in Figure 6.

In Figure 7 the results of the simulation are shown. The four subplots correspond to the perspectives of the four different Aircraft A, B, C, D. For each aircraft the respective subplot characterizes the possible outcomes for the sequence as a function of

- order of submission (1st, 2nd, 3rd or 4th aircraft to submit) on the X-axis,
- ratio $r = w_s/w_e$ on the Y-axis.

The resulting Z-values of the colored bars represent outcomes in terms of aircraft position in the sequence:

- maximum (best possible) outcome, considering all possible choices of other actors (green bar),
- average (expected) outcome, assuming non-strategic, random choices of other actors (blue bar),
- minimum (worst possible) outcome, considering all possible choices of other actors (red bar).

Note that low sequence positions have a high utility (earlier arrival time) and are thus more desirable than high sequence positions.

From Figure 7 it can be concluded that

1. the outcome depends on the timing of the submission (difference of up to 3 positions), the aircraft can influence its chances by a favorable timing of the submission,
2. the outcome depends on the setting of the planning system (difference of up to 3 positions), the ratio r determines the range of achievable results,
3. both statements 1) and 2) are true for maximum, average, and minimum possible outcome,
4. the outcome also depends on the choices of other aircraft (which cannot be influenced directly). This dependence is manifested in the differences between maximum, average, and minimum outcome for equal own timing and equal setting of parameter r.

6.2 MaxMax, MaxMin, and MaxAverage Strategies

In Figure 8 the focus changes from the descriptive results in Figure 7 towards a strategic perspective and decision theoretic view. Again the four subplots represent the perspectives of the four different aircraft, X-axis denotes order of submission, Y-axis denotes parameter r of the planning system.

The subplot for each aircraft highlights the choices (order of submission) which are compatible with

- a MaxMax strategy (risk taking), seeking to achieve the optimum of all possible outcomes (compatible choices marked in green),
- a MaxAverage strategy (risk neutral), seeking to maximize average/expected outcome (compatible choices marked in blue),
- a MaxMin strategy (risk aversive/conservative), seeking to maximize the minimum outcome (compatible choices marked in red).

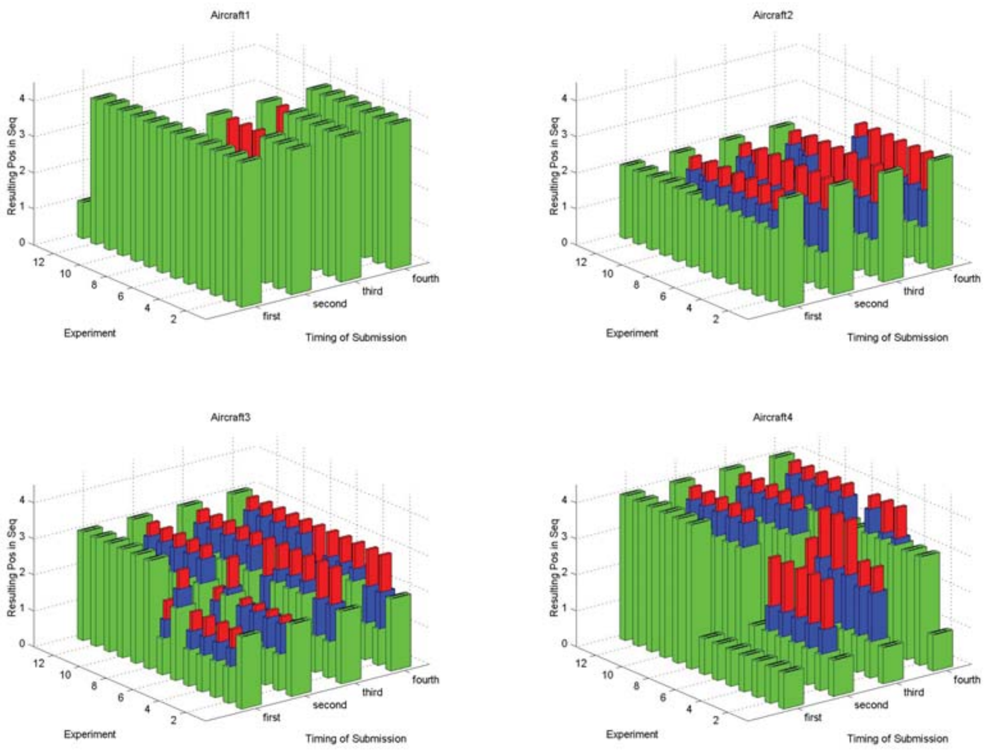

Figure 7: Best case (maximum), average and worst case (minimum) sequence outcome for each aircraft

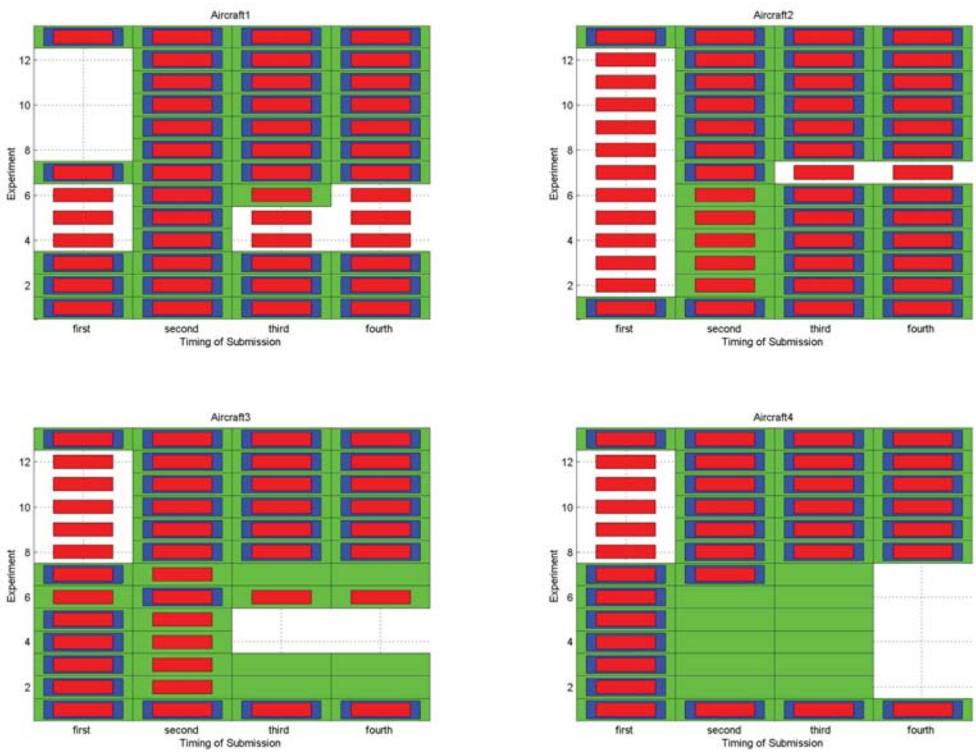

Figure 8: Timing of submission compatible with MaxMax, MaxMin, and MaxAverage strategy (per aircraft)

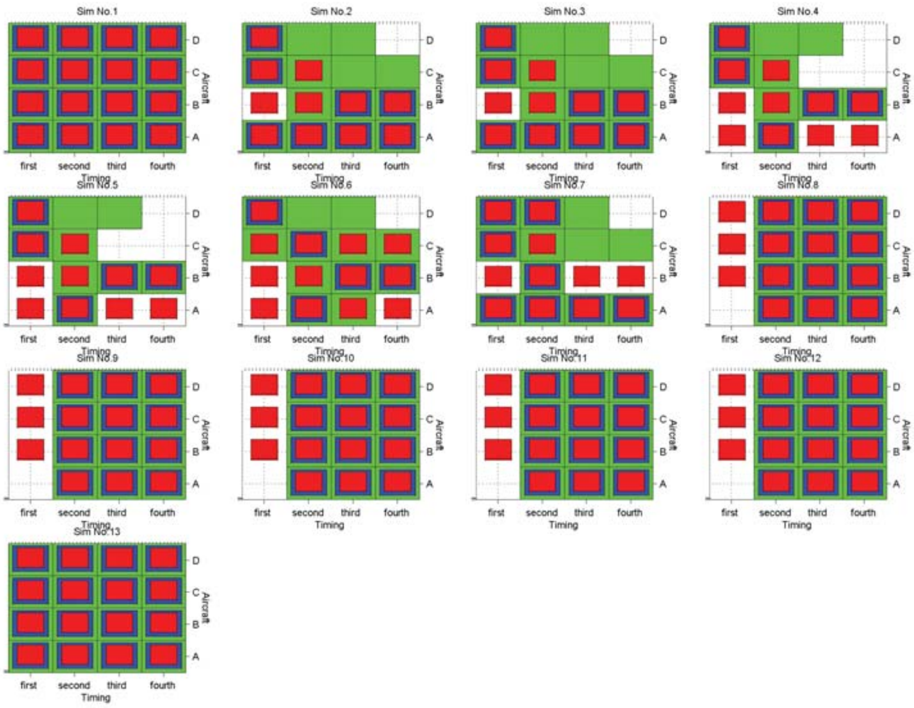

Figure 9: Timing of submission compatible with MaxMax, MaxMin, and MaxAverage strategy (per simulation run)

In Figure 9 the identical result for MaxMax,MaxAverage, MaxMin Strategy are reorganized in a different scheme. Each subplot now represents one simulation trial (one defined setting of the planning system). This visually opposes the perspectives of all four aircraft for one setting of the r value.

The results obtained from the model allow the following conclusions: First, for the extreme bounds of $r = r_{lower}$ (experiment 1) and $r = r_{upper}$ (experiment 13), choices and order of submission do not matter and all choices are thus compatible with all strategies. All cells in the matrix are thus marked with green, blue, and red rectangles. For all other tested values of r within the range of interest (experiments 2-12), order of submission does matter and some or all actors may benefit from certain strategic choices. Some choices are compatible with several strategies (cell marked with more than one color) and some strategies may cover several different choices. However, notably a number of choices exist, which are not compatible with any of the three mentioned strategies at all. This is the case where the cell is empty, indicating that the corresponding choice optimizes neither the best case nor the average case nor the worst case outcome for the actor. On the basis of the result, to have this order of submission is thus undesirable in the sense of any of these three strategies for the actor. It should probably be avoided by a rational agent.

When looking at the distribution and meaning of strategy-compatible and incompatible choices over the different experiments (especially experiment 2-7) the following observation can be made: For aircraft A and B it is particularly the timing of submission as 1st or 2nd aircraft which fail to be compatible with some or all of the strategies. On the other hand, for aircraft C and D it is particularly the submission as 3rd of 4th aircraft which fail to be compatible with some or all of the strategies. If this result can also be reproduced for a wider range of simulation scenarios (e.g. varying initial situations, larger sequence), it appears that the system establishes incentives which favor a different strategy of submission depending on the fact if the direction of the ETA-shift is positive or negative. For aircraft for which the new ETA is earlier than the old ETA (aircraft is accelerated as for C and D) the system rewards an early submission of updates. For aircraft for which the new ETA is later than the old ETA (aircraft is delayed as for A and B) the system rewards a late submission of updates. As far as can be seen from current results this tendency holds for MaxMax, MaxAverage, and MaxMin strategy.

In terms of the validation objective (compare Section 4.5) the second part of the result contradicts the designers expectation that all aircraft should submit their updates as soon as possible. Ihe agent may profit from acting in contrast to the designers expectation and global system requirements. If the system rewards that submissions of later ETAs are delayed by the aircraft, then a timely submission should not be expected in practice. Future work will deal with the more detailed investigation of this effect and potential cures should be discussed. These could consist in a combination with further rating functions in order to adjust the incentives of the system to be compatible with designers' behavioral expectations.

7 Conclusions

Within the Air Traffic Management system, many different processes are currently redesigned into more interactive and cooperative planning processes as a part of a large initiative to establish Collaborative Decision Making (CDM) [1]. The presented Arrival Management process is one example of such a process where in the future user data and preferences may be collected from several agents to establish a more favorable and globally efficient planning. However, if potential mechanisms of such systems are not designed properly, agents might use the new interaction possibilities and available choices to realize further their own interest. This might cause behavior which is unexpected and undesirable from the designers point of view. In this case the initial objective of the redesign (usually performance and capacity gains) might not be reached. A suitable modeling of potential new protocols and their careful formal analysis before their introduction can be a key element for validating if incentives set by the system are compatible with the designers' expectations. If possible, it should be assured that the desired behavior is also in the agents' own best interest.

The presented work discusses elements of a potential future mechanism for arrival planning which was implemented as a Coloured Petri Net (CPN) model presented in [12]. The model supports the formal analysis of the mechanism by calculating state spaces with the reactions of the planning system to all possible combinations of behavior of the aircraft. In this paper, the model is used to investigate an operational traffic scenario where aircraft have to adapt their submitted time estimates ETAs for a common merging point as a reaction to a change in wind. The system designers' behavioral expectation would be that all aircraft submit their corrected estimates to the planning system as soon as possible. However, the analysis shows that this behavior is not always profitable for the aircraft. Particularly aircraft which are slowed down might generally profit from delaying the update of the ETA. The desired instant update might be irrational in terms of MaxMax, MaxMin, and MaxAverage strategies. The result will have to be examined on a more varied set of scenarios in the future and the effects of potential modifications to the mechanism to cure this problem will be further discussed.

8 References

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