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Management of Time Based Taxi Trajectories coupling Departure and Surface Management Systems

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Abstract*— This paper presents concept and results of coupling the surface management system research prototype "TRACC: Taxi Routing for Aircraft: Creation and Controlling" with the departure management system "CADEO: Controller Assistance for Departure Optimisation". TRACC supports Air Traffic Controllers in creating optimized conflict-free taxi trajectories as well as with conflict detection and resolution. TRACC features speed control as new element of surface management and extends the concept of time-based trajectories to the ground. With up-to-date trajectories and therewith accurate taxi time prediction, the cooperation with the runway sequence optimizer prototype CADEO is enhanced. Within this paper both tools are introduced briefly and necessary adaptions of CADEO and TRACC for a combined application are described like push-back management and management of target start-up times. Results of first simulation runs are presented.

Keywords-TRACC, CADEO, time-based trajectories, combination ground and departure management systems, surface management

I. INTRODUCTION

During the last years much effort has been spent in increasing the efficiency and reliability of aircraft movements in airspace. Several support tools for Air Traffic Controllers (ATCOs) like arrival or departure management systems (AMAN/DMAN) have been developed and already deployed at some airports and the focus of research has been laid on e.g. the business trajectory of SESAR [21]. Arrival and (pre-) departure sequences are optimized as well as the whole airspace trajectories and advisories are created to support ATCOs in establishing the planned trajectories and/or sequences. Actually, the planned time-based trajectory starts with departure and ends with landing at the airport runways in spite of incorporating the great importance for the management of departure sequences and the reduction of queues in front of the departure runways. Procedures like the European Airport Collaborative Decision Making (A-CDM) [8] started taking into account the turn-around process (cf [10][25]) and ground traffic demand with a pre-departure sequence and so-called variable taxi time. This could be advanced to get time-based trajectories.

Furthermore, [28] has analyzed the possibilities for increasing accuracy in traffic planning by replacing "First Come, First Served" by more sophisticated planning tools and especially combining arrival, departure and surface planning systems. Hereby a surface management system should implement the necessary level of A-SMGCS. During several test [26] a considerable reduction in fuel consumption when holding aircraft at parking positions was proven. Concerning reductions in fuel burn and emissions the same conclusions were made in [13] were a fuel reduction of 24% per departure was calculated when reducing the taxi time in the movement area. The overall delay was not reduced but shifted to other points of the airfield (spots/gates) [14]. With these former results in mind it seems necessary to combine tools for surface and departure management for a better utilization of departure runways and the taxiway system itself. Thereby, it should be ensured that the number of aircraft on the taxiway system will not come close to a saturation value for this system because this will increase the taxi delay without benefitting the departure runways with a high number of available departures [26]. This will be supported by coupling a departure management system, which create an optimized departure sequence, with a surface management system responsible for calculating appropriate gate release times and optimized taxi trajectories with respect to planned takeoff times.

Such a Surface Management System (SMAN) is described by EUROCONTROL as following: "An ATM tool that determines optimal surface movement plans (such as taxi route plans) involving the calculation and sequencing of movement events and optimizing of resource usage (e.g. de-icing facilities)." [7].

There are already surface management systems existing with very different approaches, pre-assumptions and abilities depending on the intended time frame to start their operations, i.e. industry has other interests as research. This is also true for departure management systems; pre-departure sequence planner as kind of a DMAN are already in use [2], whereas runway sequence optimizer as other kind of DMAN are quite rare and still more academic. An advanced surface and departure management system which is already tested at several airports is the "Spot and Runway Departure Advisor" (SARDA), originally created for the calculation of release times and spots and meanwhile extended to holding aircraft at gates [14] [15]. Nevertheless, it does not create 4D-trajectories nor speed advisories for ADCOs or monitors the taxiing aircraft for deviations. Furthermore, it is a non-modular tool including both functionalities in one tool. Another surface management system is already used at Frankfurt airport [29].

II. MOTIVATION AND GENERAL CONCEPTS

A. Motivation

At the moment several coupling concepts of surface and departure management systems focus on required times of arrival (RTA) at specific points of the movement area and do not create complete taxi trajectories with prescribed times and speeds for the entire route. This means that conflict detection and resolution is carried out ad hoc by pilots and ATCOs while the aircraft is taxiing. This can lead to unexpected RTA adjustments. Subsequently, the departure may not arrive at the planned position (e.g. departure runway) in time, diminishing the improvement of a coupled planning with increasing uncertainty [17].

Our vision of a SMAN is to create conflict-free taxi trajectories in advance which meet specified target take-off times, monitoring these trajectories for spatial and time deviations, carrying out conflict detection and resolution, and finally to adapt the trajectories [20]. This should lead to an increase in safety for surface operations and implements the basis for improving the performance of other tools like departure management systems by providing reliable taxi times. The outcomes of this type of SMAN are more reliable arrival times at specified positions at the airfield (spots / parking positions/runway holding points) by taking other taxiing aircrafts trajectories creation into account and/or taxi target times prescribed by other systems.

The intended usage and investigation goals of each specifically defined surface management system sets the minimum requirements for the corresponding SMAN tool to be developed. This includes requirements depending on the existence of future technologies like e.g. data link, automatic control of aircraft movements and electric taxi.

There are several approaches to surface management but most of them are of theoretical nature and not implemented at an airport or even tested in Human-in-the-loop simulations. Often a linearization of a complex solution space is carried out, to allow for an efficient calculation with linear solution behavior (MILP, Mixed Integer Linear Programming). Another possibility is a directed search by combining strategies from different adequate solutions to find an optimum e.g. as it is done by genetic algorithm (see Atkin et al. [3] for example). Sometimes a graph-theoretical approach [16] is used for the creation of a conflict free and parameter restricted route. These algorithms can be divided into two groups where the first one includes all algorithms which will optimize the whole traffic at once and a second group where the optimization is carried out sequentially for each aircraft in dependence of other already optimized aircraft.

As strict conformance to the trajectories might not always happen, we expect an SMAN is required to be adaptive to the implementation of the trajectory by the pilot. On the other hand the acceptance of a surface management system by ATCOs and pilots may depend on the number and kind of changes [6]. Changes on already passed taxi advisories or the usage of an algorithm which optimizes the whole traffic again for each deviation of a single aircraft will most probably lead to acceptance problems. Furthermore, only those aircraft should be penalized by getting a new trajectory (with respect to all already advised trajectories) which has caused the significant deviations, especially for avoiding chain reaction for the other involved aircraft. Also if standard taxi routes are in use at the observed airport they should be taken into account as often as possible. This would reduce the complexity of taxi trajectories for pilots as well as increases the acceptance rate of a SMAN by ATCOs.

DLR already gained experience with research on adaptive planning systems to support ATCOs, e.g. the departure management system prototype CADEO (Controller Assistance for Departure Optimisation) [24]. As CADEO is a DMAN method focusing the runway sequence optimization, it is a good candidate to benefit from a SMAN through the use of more reliable/accurately predicted taxi times. On the other hand CADEO may challenge the SMAN through possible changes of Target Take-off Times and therewith possible sequence changes. This led to investigations of what might be needed when coupling an adaptive SMAN with an adaptive runway sequence optimizer in general [20]. Our approach based on theoretical results and investigates specifically the implemented coupling between CADEO and TRACC (Taxi Routing for Aircraft: Creation and Controlling), the needed adaptations of TRACC before describing the performed tests and the analyses of the results.

Nevertheless, the results found should hold as well for all DMAN and SMAN with similar assumption and principles like pre-departure runway sequencing and 4D-trajectories, also referred to as surface trajectory based operations (STBOs) [15].

B. General Concept of Departure Management System CADEO

CADEO is an adaptive ATCO support tool, which optimizes the departure take-off sequence and calculates Target Take-off Times (TTOTs) [8] for each departure, taking several constraints into account [4]. Without being coupled to a SMAN, CADEO derives the Target Start-up Approval Times (TSATs) for each departure from the TTOTs [23]. This is done using the Variable Taxi Times (VTT) defined within the European Airport Collaborative Decision Making (A-CDM)[8] . The variable taxi time is also used to calculate the earliest possible take-off time for each departure, which is needed as constraint during optimization. Optimization objectives are throughput enhancement, slot compliance improvement, stability of plans, and taxi-out delay reduction [22]. Updating the earliest possible take-off time through updates of the remaining taxi times brings benefit to the departure runway sequence planning (as shown in [23]).

C. General Concept of Surface Management System TRACC

TRACC was developed by DLR as a research prototype to be used for fast-time, real-time and Human-In-The-Loop (HITL) simulations [12] implementing our vision of a SMAN:

create, control and always maintain conflict-free time-based trajectories for all aircraft ground movements. These requirements fulfil those stated in [28]:

Plan => Execute => Measure => Adapt.

Therefore, it was necessary to make some assumption about technical standards of the future like the cockpit's ability to comply with exact speed advisories which are used by TRACC for controlling the aircraft in accordance to their calculated trajectory. Currently, it is very difficult for pilots to follow speed advisories which are more complex than "increase speeds" or "slow down" because the accompanied head down time will increase considerably. This was shown within real time simulation trials testing the ability of pilots to follow speed or time advisories [9] with and without a special support tool integrated into the flight deck. Hence exact commands like "increase speed 15 knots" are unusual, but with upcoming ideas like electric taxi [1] the usage of taxi bots (e.g. ZETO project at University of Darmstadt / Germany) or an additional support tool it would be possible for pilots to keep up with a prescribed taxi speed.

TRACC is designed as a generic tool which can be easily adapted to any airport using a special editor tool for the creation of datasets called ADEN (Airport Data Editor for NARSIM) [11]. The backbone of TRACC is a node-link model where all necessary information is mapped to. This model is used together with flight plan information to create conflict free, optimized and time-based taxi routes ("4D-trajectories") each including an exact speed profile for all aircraft on the investigated airport. For the creation of this speed profile the taxiways are divided into groups like "apron" or "runway exit" with a prescribed standard speed surrounded by an interval for acceptable speeds for each group. Beside the trajectories ATCOs are supported by TRACC with the creation of necessary taxi advisories resulting from the proposed trajectories. In addition, a conformance monitoring (location and time) of each trajectory is carried out and in case of nonconformance the trajectory is adapted to actual position and speed and – if necessary – re-calculated. This requires an automatic conflict detection and resolution (CD&R) part of TRACC. Automatic CD&R will lead to a change in the role and self-concept of the ATCOs from management to more supervising with possibilities to change flight parameter like advised runway, push-back direction or giving route recommendation.

For trajectory adaptation two main principles are applied in TRACC for a higher applicability and practicability for controllers and pilots, taking a small restriction in the solution space into account. They are

- "Principle of Lowest Workload", and the
- "Principle of Smallest Modification" and

whereas the principle of smallest modification can be additionally subdivided into

  - "Initiator Pays" and
  - "Highest Similarity".

"Initiator Pays" means that only those aircraft are penalized for deviations from the advised taxi trajectory through the creation of a new one, which have caused the deviation. Furthermore, only one flight has to be newly optimized at the same time. The term "Highest Similarity" stands for the attempt to be as close as possible to a set of predefined standard taxi routes relating to the course of the trajectory if such a set exits at the investigated airport. This and the fact, that only imminent advisories are shown to the ATCO, ensures that the workload for the ATCO will not increase significantly when using a tool like TRACC (see [6][12] for more details). Nevertheless, it is assumed that commands are given via datalink and the position of all aircraft at the airport is always known.

III. COUPLING OF TRACC AND CADEO

As the earliest possible take-off time serves as lower boundary constraint for CADEO's optimization, the quality of the result increases with better quality input [17]. Additionally, one of CADEO's aims is to reduce the queuing and engine running time. This overlaps perfectly as task for a surface management system. A SMAN like TRACC takes the task to calculate und update the earliest possible take-off time, assign an appropriate pushback time and generate a taxi trajectory which delivers the departure on time at the runway regarding the TTOT for maintaining the planned departure sequence and keeping the queues short. This will support CADEO greatly as well as ATCOs and pilots in meeting these prescribed target times.

To achieve this data has to be exchanged between CADEO and TRACC. The most important ones are target times at the runway. As described in [20] TRACC's calculations target the runway holding point, i.e., the point where the line-up clearance will be given. This was reflected in the definitions of "Target Line-up Time" (TLUT) corresponding to the TTOT and "Earliest Line-Up Time" (RLUT, defined by DLR) corresponding to the earliest possible take-off time for the take-off.

The RLUT has to be as early as possible to give room for TTOT improvements. On the other hand, the departure shall not necessarily reach the runway holding point at RLUT to avoid queuing. So SMAN has to come up with a trajectory trying to fit (less or equal) to TLUT as best as possible. The time, SMAN plans to deliver the departure at the runway holding point was defined as "Estimated Line-up Time" (ELUT) [20] and should be close to TLUT. Fig. 1 shows the coupling scheme.

The following triggers are necessary to update the calculations:

- Nothing to do, when RLUT ≤ ELUT ≤ TLUT
- When RLUT ≤ TLUT, but ELUT > TLUT, then SMAN shall adapt the trajectory
- When RLUT > TLUT, then DMAN shall adapt the planned take-off sequence (at least the TTOTs).

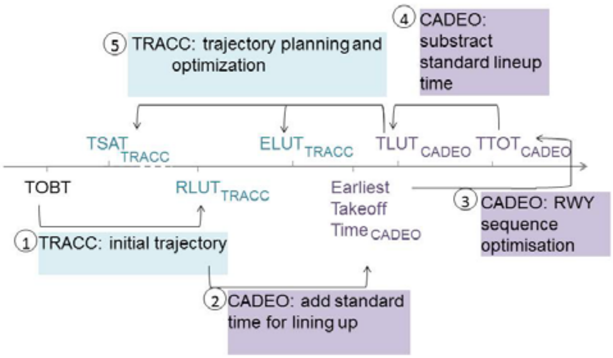

Figure 1. CADEO - TRACC coupling: scheme of actions (1 – 5) with earliest, estimated and target line up times (R/E/TLUT). TSAT is calculated by TRACC according to TTOT and necessary taxi time.

For the coupling of CADEO and TRACC some modifications of the tools were necessary. For CADEO they have been quite simple: do not use VTT anymore but use the RLUT calculated by TRACC.

Several enhancements of TRACC were required as preparation for the coupling with a runway sequence optimizer because of the necessary calculation of an appropriate TSAT for each departure. They are described in the following subsections.

A. Push-Back-Management and Calculation of Lower Bound TSAT

The management of push-backs is an essential part of a SMAN as an appropriate off-block time influences the duration every aircraft is moving on the ground, blocking taxiways for other aircraft and creating environmental impact and costs by burning fuel [26]. Therefore, a sophisticated combination of push-back and TSAT management is implemented in TRACC which calculates the best TSAT for every aircraft taking already taxiing aircraft and TTOTs created by a DMAN into account. The main goal is to hold all departures as long as possible at the parking positions but to reach the departure runway in time.

Fig. 2 shows the flow diagram of the adaption of TSAT due to push-back problems, especially for cases where an in-time push-back would block a taxiway another aircraft is already planned for. This algorithm is passed through at least once for every departure at the first optimization. In this case TSAT is initially set equal to TOBT and CSAT as well (Calculated Start-Up Time: Start-Up Time calculated by optimization algorithm for a conflict free trajectory; serves as TRACC internal intermediate step). Initially the TOBT is checked for problems and, if necessary, the TOBT is postponed (called “TOBT delay” in Fig. 2). The sum of these values creates the lower bound for TSAT and CSAT.

For following optimization runs for the same departure the CSAT could be different from TOBT plus “TOBT-delay” because CSAT is increased in case of problems when creating a conflict free trajectory e.g. after push-back into a single lane taxiway for which opposite traffic is already cleared.

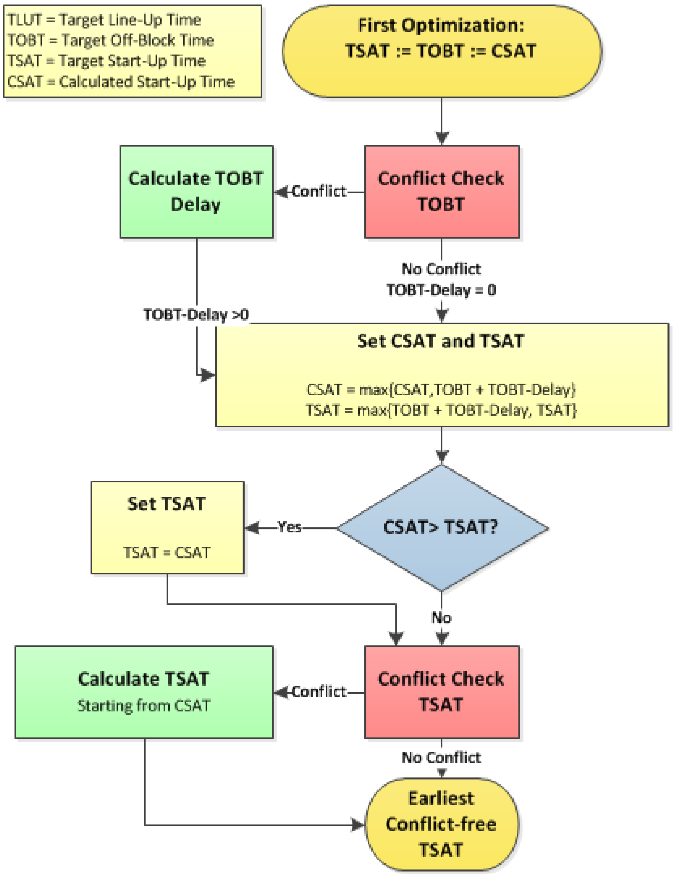

Figure 2. TRACC’s push-back management and calculation of lower bound TSAT where TOBT-Delay means the delay necessary to avoid pushback conflicts and CSAT as lowest time without gridlocks with already planned traffic e.g. on single lane taxiways.

If this leads to a situation where the CSAT exceeds TSAT, the TSAT has to be recalculated and the new TSAT is checked for push-back conflicts afterwards. Otherwise, the new TSAT is higher than CSAT. In both cases it has to be checked again if there is a push-back conflict. If so, the algorithm tries to find the closest conflict-free time starting from CSAT. This is done to avoid artificial delay.

The algorithm for the calculation of an appropriate push-back time is carried out for every update of the TLUT/TTOT send by a departure management system as long as the engines are not started. The resulting TSAT is influenced only by push-back conflicts and is therefore the lowest possible TSAT.

B. TSAT Management in dependence of TTOTs

The push-back management is just one step of the creation process for an appropriate TSAT for a given TLUT. When all departures should reach the runway at their planned TLUT and without unnecessary long taxi time the TSAT should not only reflect solved push-back problems but the TLUTs given by a departure management system as well (Fig. 3).

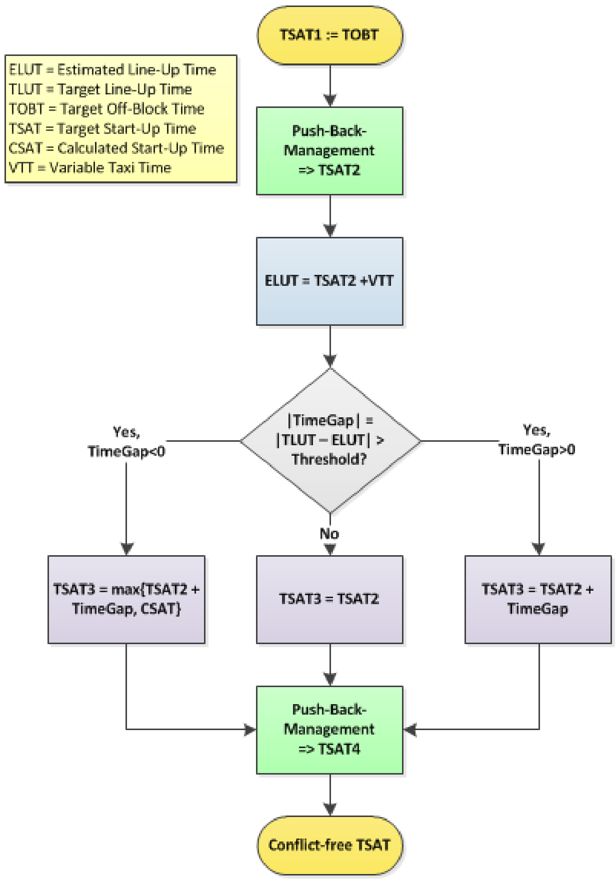

Figure 3. TRACC's TSAT Management: Adapting TSAT to TTOT using expected taxitime VTT and lower bounds created by pushback management algorithm.

Therefore, a given TSAT is handed over to the push-back management process (see section "push-back management", compare Fig. 2) and the expected taxi time when using the planned trajectory is added afterwards (referred to as VTT as well). The resulting estimated line-up time (ELUT) is calculated and compared to the TLUT. If the difference between them is too high (configurable value; currently set to 30 seconds after several parameter tests) the TSAT is adapted according to the type of difference (cf. Fig. 3). The threshold value was introduced for ensuring a more stable TSAT without changes of only a few seconds because every TSAT change will initiate a new optimization run resulting in a new trajectory with new RLUT and ELUT times for the departure management system.

If the TSAT is decreased the CSAT is used as the lower bound. The CSAT is a value given by the optimization part of TRACC after unsuccessful attempts to create a conflict-free trajectory for a special time (e.g. caused by opposite traffic).

A second run of the push-back management algorithm is carried out for this TSAT potentially leading to a new one (see section III A). With the resulting TSAT, a new trajectory has to be calculated.

This approach cannot guarantee an ELUT below the TLUT value given by CADEO because it is always possible that the runway holding point cannot be reached in time because of other traffic.

C. *Calculation of RLUT*

The up-to-date RLUT is essential for CADEO because it provides a lower bound for the calculation of a TLUT. Before the RLUT can be calculated, push-back management has to be carried out and the first conflict-free trajectory has to be created by the optimization algorithm. Based on this trajectory the RLUT calculation is conducted in two different ways:

- Increasing speeds of the optimized trajectory by a certain percentage as long as they do not exceed an allowed maximum value.
- Optimize the actual trajectory again but with taxi time as most important evaluation parameter.

Due to the high effort in calculation time for the second variant the first one is carried out at the beginning and the resulting trajectory is tested for conflicts afterwards. In case of conflicts the second way is used afterwards. Then, the resulting RLUT is send to CADEO. This process is executed each time a new trajectory is created. Furthermore, to prevent situations where the necessary off-block time for meeting the RLUT has already exceeded (e.g. when the actual time is higher than the CSAT used for the RLUT creation but below TSAT) the RLUT has to be adapted, too.

D. *Conflict Detection and Resolution (CD&R)*

Although, CD&R is a functionality of TRACC it is the backbone of coupling DMAN and SMAN as monitoring aircraft movements for trajectory deviations takes place. As stated in [17] uncertainty is the main reason for reducing the benefit created using a departure management system. Therefore, reducing uncertainty in arrival times at the departure runway should be one of the most important tasks for a surface management system like TRACC. This can be done by monitoring all aircraft movements, adapting the given trajectories to the actual situation and creating new in case of conflicts or missed arrival times at the departure runway. If it is not possible to reach the runway in time due to other traffic a message must be send to DMAN informing about the new earliest possible line-up time. In this case the DMAN can recalculate the sequence and send a new TLUT so the SMAN can create an appropriate new trajectory.

In general, there are three main different strategies for CD&R. Two of them create and maintain conflict-free taxi trajectories. The first one compares the complete taxi trajectory at once with the taxi trajectories of all other moving aircraft for conflict-detection. The second approach blocks the occupied parts of taxiways, so for the time they are used by other aircraft overlapping occupancy intervals indicate conflicts. The third approach does not even create conflict-free trajectories but applies a short term conflict detection using safety areas around each aircraft, e.g. [18]. Every aircraft is surrounded by such an area so intersections whilst taxiing indicate an imminent conflict. In the context of safety, these areas could be divided into incidence and consequence areas.

Within TRACC the approach of comparing the new trajectory to all already existing ones is implemented. To maintain conflict-freeness, TRACC's conflict detection and resolution functionality consists of the following parts:

1. Identification of deviations from planned trajectory.
2. Adaption of the planned trajectory to the deviations in position and speed.
3. Test of the adapted trajectory for conflicts.
4. In case of conflicts or significant deviations from the given time constraints: creation of a new conflict-free trajectory with respect to current position, time and – for departures – TLUT/TTOT.

For the identification of deviations a two-step approach is used. First, the distance between the planned and the actual position is calculated. If the resulting distance is too high, a second step follows: it is checked whether the actual position belongs to the planned trajectory or if the aircraft has even left the planned route. If the aircraft is still on the planned route, only position and speed are adapted before conflict probing the modified trajectory. Only in case of conflicts or unmatched time constraints, the creation and optimization of a new trajectory is triggered.

An important prerequisite for conflict detection is the allowed minimum distance between two taxiing aircraft. In the literature values between 60 and 200 meters are defined [3]. These distances are either a fixed value for all aircraft combinations or depend on the size of the aircraft, the area of the airport they move or the speed they have. TRACC uses a minimum distance combined of the wake vortex class and half the maximum of aircraft length and wingspan to reflect the different blasts of aircraft engines of different wake vortex classes and the size of the aircraft.

Within TRACC's conflict detection each link of a trajectory is considered as a vector in space with first way point $\vec{a}$, direction $\vec{b}$, speed v, speed change Δv, time t and factor λ:

$$\vec{a} + (v + \Delta vt)t\lambda\vec{b} \qquad (1)$$

So it is possible to calculate the minimum distance between two links for almost all cases. Some special cases like parallel links, same speeds etc. are verified separately. Furthermore, several situations where aircraft are waiting or using the same link or counter link can be calculated very easily in advance.

IV. Experiment Description and Results of TRACC – CADEO Coupling:

For the experiments of testing the coupling of TRACC and CADEO a generic airport based on Munich was simulated, using two independent runways and one apron in between.

This airport was selected because of the runway configuration with two parallel runways which can be found often in Europe (London-Heathrow, Athen-Eleftherios, Oslo-Gardermoen, Berlin-Brandenburg) and because Munich is an A-CDM airport with a high number of available information [27].

As traffic scenario a flight schedule containing 17 departures using one runway and 33 arrivals using both runways within one hour was selected. The simulation was conducted in the ATS360 simulator of DLR [6]. Three simulation runs with the same setup and traffic were evaluated. As traffic simulator the NARSIM simulation tool [19] was used, fed with taxi and speed commands given by TRACC itself according to the advised trajectories.

Due to a realistic behavior implementation of NARSIM given commands to an aircraft (esp. braking and accelerating) results in delayed pilot reactions. Therefore, CD&R algorithm of TRACC was invoked often for adjusting actual and planned positions and speeds as it would have been using Human-in-the-loop simulation, too. Furthermore, TRACC possess a nondeterministic behavior, which leads to pseudo realistic progress. Consequently, this has resulted in different ground movement situations and different results for the three runs using the same input setup, as it can be seen at TABLE II).

TABLE I shows exemplary the actions taken by TRACC when receiving a TLUT, which triggered the creation of a new trajectory. The left column shows the output written by TRACC, the right column the explanation. The numbers in brackets show time differences in seconds, in which the TLUT value shows the difference to the actual ELUT of the aircraft trajectory and the TTOT value the difference to the last TTOT.

TABLE I. Example for one line of TRACC output (actions carried out for the creation of a new conflict-free trajectory): Run1_20141112, departure callsign AFR3234

Code	**Reason**
TLUT adapted (73)	TLUT adapted by 73 seconds compared to last ELUT
TTOT adapted (99)	TTOT adapted by 99 seconds in comparison to last TTOT
TOBT Push-back conflict (55)	Push-back conflict at planned push-back time. Adding 55 sec. to avoid conflict.
TSAT adapted (72.0)	Adapt TSAT by 72 sec. for avoiding idle times on airfield (slow taxi, queues)
TOA	Carry out "Time Optimization Algorithm" [12]
TLUT adapted (-98)	TLUT adapted whilst optimizing
TTOT adapted (-99)	TTOT adapted whilst optimizing
(Break)	Stop optimization and start again with new values.
TOBT Push-back conflict (55)	Push-back conflict is still the same
TSAT adapted (-72.0)	Adapt TSAT to changed TLUT but not below TOBT
TOA	Carry out "Time Optimization Algorithm"
RLUT Calculation (small)	Carry out RLUT-Calculation with speed increase as far as possible

Fig. 4 shows the progress of TSAT, ELUT, RLUT and TLUT exemplarily for flight DLH1069 of the 1st run. All adaptations of the trajectory were caused by CADEO. If the difference between new TLUT and current ELUT is more than 30 seconds, this triggers the creation of a new trajectory (12:34:00 in Fig. 4). The new trajectory potentially influences TSAT and ELUT. Using this tolerance interval avoided many unnecessary trajectory adaptations as the figure shows (e.g. 12:28:02-12:33:32). Every time a new TSAT is calculated this triggers a check for the RLUT because in the meantime the trajectory used for RLUT calculation might be influenced by the trajectory adaptions of other flights.

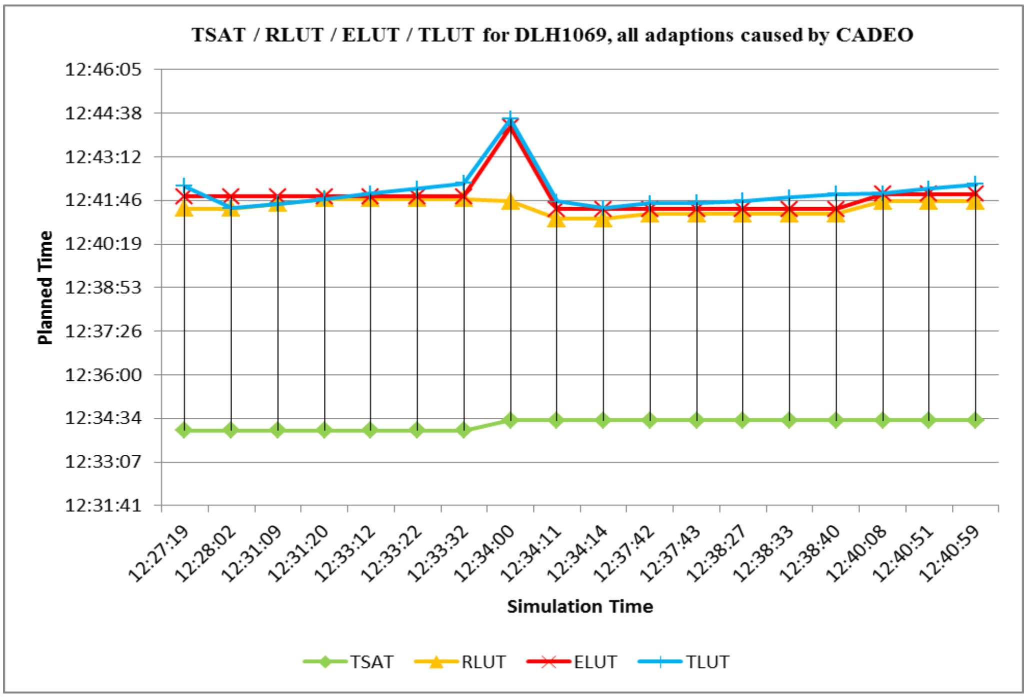

Figure 4. Example for the influence of a TLUT change on ELUT and TSAT, Run1_20141112. Every change of TLUT by CADEO results in a feasability test of ELUT by TRACC and leads to an adaption of TSAT and a recalculation of the trajectory if “ new TLUT-ELUT” > threshold value (cf 12:34:00).

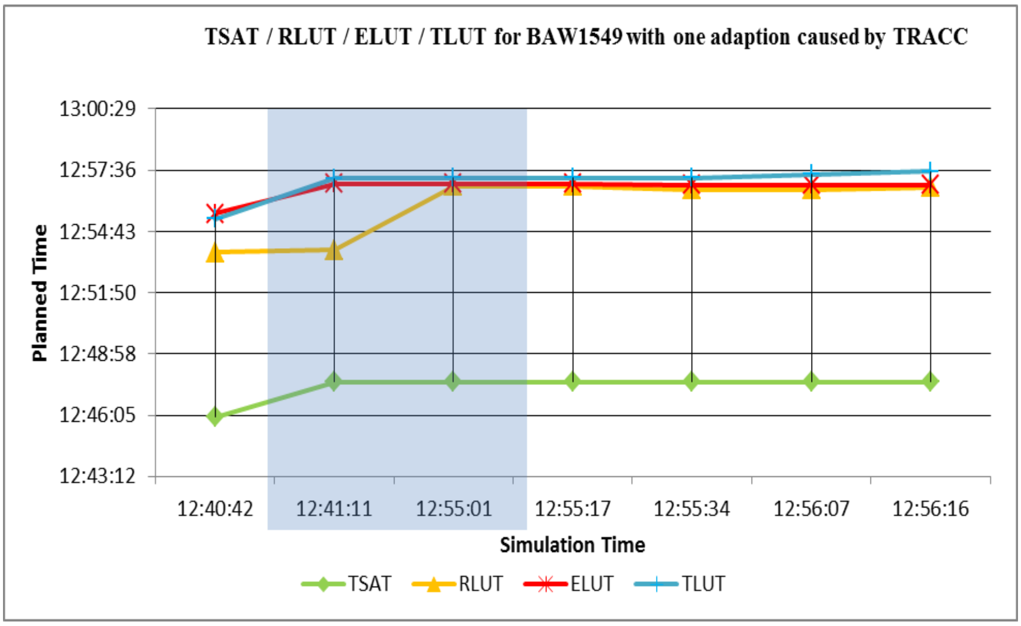

Figure 5. Example for the influence of an ELUT change on TLUT and TSAT, BAW1549, Run1_20141112. Adaption was triggered by TRACC caused by a diverting speed profile and led to an increase of the RLUT

The next figure (Fig. 5) shows an example for the same values for a situation where TRACC has triggered an adaption of TLUT caused by an adaption of the trajectory to a diverting speed profile in reality (data points in grey area). It can be seen that the RLUT was increased in reaction to the TSAT adaption at 12:41:11.

TABLE II shows total number and type of reasons for TSAT adaptions. A TSAT change is often triggered by a preceding TLUT change. TSAT adaption could lead to push-back conflicts which are solved by approaching the new TSAT from the first possible TSAT based on TOBT.

This increases the probability that the aircraft will not push too late for the given TLUT because a delayed push-back restricts the earliest time an aircraft can reach the departure runway holding point (RLUT). Fig. 4 shows as an example at 12:34:00 a situation where the difference between succeeding TSATs is considerably less than between the related ELUTs and this indicates a new push-back conflict at the best TSAT belonging to the ELUT. Furthermore, this table shows that TRACC consists of a nondeterministic behavior. All runs have different numbers for the occurrence of the different adaption reasons.

When looking at TABLE III and bearing in mind the reasons for the adaptions (see TABLE II) it is clearly shown that CADEO's runway scheduling which results in TLUTs and TRACC's trajectory management has taken intensive action for expanding the dense traffic to a more smooth flow.

Furthermore, the taxi time decreased in comparison to the variable taxi time (VTT) proving that this combination has not created holdings or taxi phases with lower taxi speeds but instead has adapted TSAT, speeds and the route itself in an appropriate way.

TABLE II. FREQUENCY OF REASONS FOR ADAPTION OF TSAT TIMES (PBC: PUSH-BACK CONFLICT, TLUT: ADAPTION OF TSAT TO TLUT, TLUT/PBC: TSAT ADAPTION TO TLUT LED TO PUSH-BACK CONFLICT, WHICH TRIGGERED AGAIN TSAT CALCULATION).

Run	**Reason**		
	PBC	**TLUT**	**PBC / TLUT**
1	7	11	5
2	8	13	7
3	7	10	9

As mentioned before for the creation of trajectories the speed is limited to an interval around the prescribed standard speed for the different taxiway types. Therefore, the reduction in taxi time is not caused by using inadequate high taxi speeds.

Fig. 4 gives an example for the decreasing taxi time at 12:34:11 where the TSAT stayed the same in spite of a decreased TLUT. For this case TRACC was able to create a new trajectory which has fulfilled the TLUT time constraint..

TABLE IV gives an overview over the reasons and the amount of trajectory adaptions. The first column characterizes the type of the adaption; the second diverts the results in reasons for the creation of a new trajectory (second group of rows) or the type of action taken. The following two columns show the average amount of occurrence of each reason per simulation run and per aircraft. The first group of rows shows the number of adaptions of trajectories carried out by the CD&R part of TRACC, which is caused by differences between the planned and the actual speed profile or the usage of a wrong taxi route.

The second group of rows breaks down the case "new trajectory" of the first group and analyses the causes for the creation of new trajectories. The numbers are all very low because we assumed the ATCO behavior is very TRACC-compliant. Nevertheless, the main reasons for new trajectories triggered by CD&R were upcoming conflicts as a result of trajectory deviation (see TABLE IV). The last row shows the number of TLUT changes that led to the necessity to create a new trajectory or did not initiate a new optimization and therewith a new trajectory.

TABLE V shows the difference between TLUT and ELUT for all occurrences of a TLUT change (middle column) and restricted to the last appearance of an adaption of this type (right column). The higher values in the right column are caused by the mechanism of avoiding a new trajectory creation as long as |TLUT-ELUT| < 30s as it can be seen in Fig. 4. Nevertheless, the combination of average value and variance shows that most departures will arrive at the runway a short time before the line-up clearance will be given. This proves the ability of TRACC to stay close to the given TLUT time and to support the CADEO in maintaining a defined departure sequence, if necessary by delaying the aircraft at the position (see TABLE III).

TABLE III. AVERAGE DIFFERENCE BETWEEN TSAT AND TOBT FOR ALL OCCURRED ADAPTIONS (COLUMN 4), AVERAGE DIFFERENCE FOR THE LAST ADAPTION FOR ALL AFFECTED DEPARTURES (COLUMN 5) AND AVERAGE DIFFERENCE OF LAST TSAT FOR ALL DEPARTURES (COLUMN 6) AND DIFFERENCE BETWEEN VTT AND ACTUAL TAXI TIME (COLUMN 7).

Run	**Number affected AC**	**Number Adaptions**	**Avg. Delay TSAT / All Adapt. [s]**	**Avg. Delay last TSAT / Affect. Dep.[s]**	**Avg. Delay last TSAT / All Dep.[s]**	**Taxi Time Difference to VTT [s]**
1	13	23	144.6	136.6	104.5	-55
2	15	28	119.8	122.7	108.3	-63
3	13	26	140.3	141	107.8	-61

TABLE IV. REASONS FOR NEW OR ADAPTING TRAJECTORIES

Change Group	**Type**	**Avg. Nr. / Run**	**Avg. Nr. / AC**
CD&R adaption all flights	New trajectory	13.7	0.3
	Adapted trajectory	119.7	2.4
CD&R-reasons for creating new trajectories	Route or speed deviation leading to conflicts	9	0.2
	Route deviation (no conflict)	1	0.0
	Deviation speed profile (no conflict), missed target time	3.7	0.1
TLUT-change (departures only)	New trajectory	63.3	3.7
	Unchanged trajectory	30.3	1.8

TABLE V. DIFFERENCE BETWEEN TLUT AND ELUT, ALL ADAPTIONS FOR ALL RUNS.

TLUT – ELUT	**All Adaptions (281) [s]**	**Last entry for affect.AC (51) [s]**
Average	8.5	11.8
Variance	17.4	24.3
Minimum	0	0
Maximum	150	150

Furthermore, the simulation runs have shown that the length of the queue at the departure runway did never exceed the value of one aircraft, but there were always several aircraft on their way to the runway.

V. CONCLUSIONS AND OUTLOOK

The tests with a combination of CADEO and TRACC have shown the feasibility of the coupling concept of departure and surface management. This confirms a significant potential for implementing the next part of the SESAR Business Trajectory for ground traffic. Nevertheless, some questions are still open, e.g., if CADEO should take the ELUT into account. Currently, CADEO assumes that an aircraft is able to reach the runway holding point at every time behind RLUT which is not always possible because of other traffic. Furthermore, a more sophisticated and situation dependent minimum distance between taxiing aircraft could be investigated for increasing the degree of utilization of the taxiway system. As the currently investigated airport has a clear ground structure without bottlenecks e.g., within the terminals, one next step will investigate the coupling using a much more complex airport structure and an increased traffic demand. The preparations to use Charlotte Airport (US) have already been started and are part of the DLR-NASA cooperation.

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