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A Concept of Operations for Trajectory-Based Taxi Operations

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A harmonized concept of operations (ConOps) for future surface operations that considers the surface management practices and policies that currently exist in the U.S. and Europe was developed by NASA and DLR. The high-level concept includes a surface traffic scheduling system that generates conflict-free four-dimensional trajectories (4DTs) for all aircraft on the airport surface and on-board or ground-based guidance to enable the flight crew to adhere to the trajectories. This new vision aims to reduce delays caused by disruptions and purely reactive surface guidance and increase efficiency by an optimized use of resources supported by the new concept based on high sophisticated planning means. It further results in reduced environmental impact of the surface operations. This paper identifies and describes the necessary functions of the concept and explains the relationships among them. The concept is supported by results from research conducted to assess the feasibility of this concept. The implementation of this concept poses some challenges that were used as a basis to derive research requirements that will be jointly addressed by NASA and DLR in the future.

Nomenclature

4DT	=	Four-Dimensional Trajectory
A-CDM	=	Airport Collaborative Decision Making
ANSP	=	Air Navigation Service Provider
ATC	=	Air Traffic Control
ATCO	=	Air Traffic Controller
CADEO	=	Controller Assistance for Departure Optimization

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ConOps	=	Concept of Operations
DLR	=	German Aerospace Center
HMI	=	Human Machine Interface
KPA	=	Key Performance Area
NASA	=	National Aeronautics and Space Administration
SARDA	=	Spot and Runway Departure Advisor
TRACC	=	Taxi Routing for Aircraft: Creation and Controlling

I. Introduction

THE airport surface has been recognized as one of the major constraints on capacity and throughput of the entire aviation system. Current-day operations are characterized by inadequate information sharing among air traffic control, ramp/apron control, airlines, and the flight deck, which often results in temporal uncertainty and unpredictability. Together these factors lead to excessive delays, passenger inconveniences and excessive fuel burn and emissions. Using 2009 Aviation Systems Performance Metric data, annual taxi delay was evaluated at major U.S. airports, and calculated a total of 32 million minutes in taxi-out delay and 13 million minutes in taxi-in delay over unimpeded taxi times[1]. At John F. Kennedy International Airport (KJFK) it was found that the average taxi-out time was 56 minutes when the airport was congested and in Instrument Meteorological Conditions compared to the unimpeded taxi-out time of 16 to 19 minutes[1]. Similar trends have been noted in Europe, where it is estimated that aircraft spend 10-30% of their time taxiing, and that a short/medium range Airbus A320 expends as much as 5-10% of its fuel on the ground[2]. This congestion and resulting delays translate directly into excessive fuel burn, resulting in environmental pollution and monetary costs for airlines. Even a 5% reduction in mean taxi-out duration of 13 minutes at a larger airport with 350,000 movements per year would result in a substantial reduction of fuel burn, CO_2 emissions, and cost per annum[3].

To address this airport surface congestion problem, the German Aerospace Center (DLR) and the National Aeronautics and Space Administration (NASA) Ames Research Center (ARC) have collaborated to develop a harmonized concept of operations (ConOps) for surface operations that considers the different surface management practices and policies that currently exist in the U.S. and Europe. The ConOps aims to reduce temporal uncertainty and delays by improving the whole planning chain from gate to runway and vice versa.

First, this paper addresses the challenges of current-day operations. Then, after illustrating the high-level concept vision and the associated objectives of this ConOps, the concept functions will be outlined in more detail. Next, human-in-the-loop and simulation studies are presented and discussed, which demonstrate and promote the feasibility of this ConOps. Finally, the challenges that might be faced when implementing this ConOps are described followed by an outlook of future work.

II. Challenges of Current-Day Operations and Operational Needs

Current-day operations are characterized by inadequate information sharing that results in a great deal of temporal uncertainty and unpredictability, which in turn leads to excessive delays (see Fig. 1).

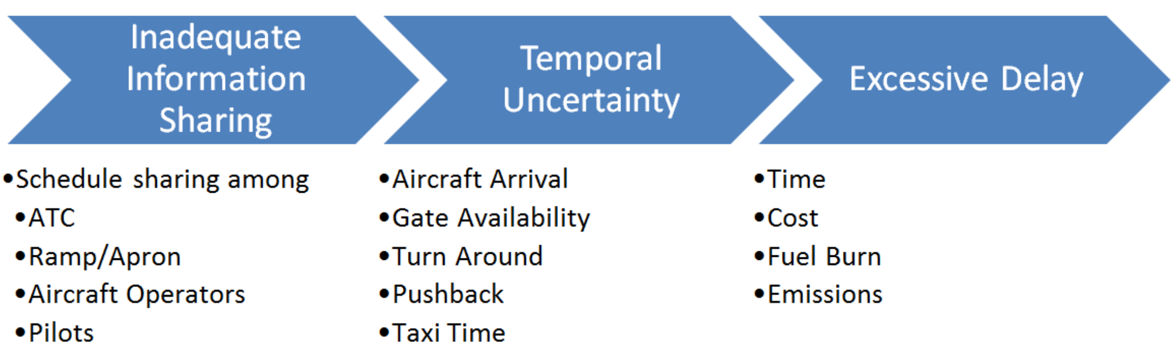

Figure 1. Overview of problems with current-day operations.

For the most part, there are no mechanisms to support the sharing of information between ramp/apron controllers, air traffic control (ATC), and pilots. Tower controllers have difficulty predicting when a departing aircraft will be ready to taxi, and, similarly, ramp/apron controllers have difficulty predicting when an arriving aircraft will require a gate. Because pilots lack information about traffic congestion and taxi time, they tend to push back from the gate as early as possible, which often only yields lengthy delays in departure queues. Likewise, air traffic controllers lack insight into flight deck operations and cannot predict taxi movements such as taxi speed, times to initiate taxi, and requirements to hold in place in the ramp or taxi areas for system troubleshooting, engine start, or other needs.

This inadequate information sharing leads to temporal uncertainty (as shown in Fig. 1). Perhaps one of the largest sources of temporal uncertainty is observed in the prediction of a flight's ready-time given the number of contributing factors that are beyond pilot or apron/ramp controller's control. Another source of uncertainty is variability in the aircraft's taxi time that results because of different reasons such as: individual pilot and aircraft taxi speeds, pilot's time to initiate taxi, and controller's needs to hold or expedite aircraft to facilitate sequencing on the airport surface and at runway crossings. Because of these factors, and the inability to handle these uncertainties in runway scheduling, an aircraft's takeoff time cannot be predicted with certainty, which in turn, propagates to the departure and en-route phases of flight.

The lack of information sharing, and the resulting temporal uncertainty, results in a 'first-come, first-served' rule in which the air traffic controllers handle aircraft traffic reactively, in the sequence in which they arrive, without proactive strategies and efficient schedules. This leads to traffic congestion along the taxiways, stop-and-go movements, and long departure queues. This airport surface congestion is responsible for increased taxi-out times, fuel burn and emissions.

An overhaul of airport surface operations is required to transition from current-day operations that tend to be more reactive towards future operations that are characterized by proactive planning and controlling of airport surface movements. Such future operations must enable efficient scheduling of runway use, optimized pushback management, and precise taxi routing plans that decrease stop-and-go movements and excessive delays. Information sharing that enables broadcasting of the airport surface schedule and the status of each individual aircraft to stakeholders who need the information in a timely manner is a prerequisite for this concept. This concept calls for a transition from predicting when an aircraft will arrive at a destination to enabling pilots to be active participants in meeting time-based constraints.

The problem of inadequate information sharing is being addressed through the introduction of Airport Collaborative Decision Making (A-CDM)[4] in Europe and Surface Collaborative Decision Making (S-CDM)[5] in the U.S. These programs aim to enable airlines, ground handlers, air navigation service providers and airports to work together efficiently to share data, thereby providing all the involved airport partners with the same reliable information on current and planned airport operations. Furthermore, runway scheduler and departure management concepts are being introduced to share the runway resource more efficiently. However, due to temporal uncertainties with outbound traffic arriving at the runway entry points, and landing time uncertainties with inbound traffic, those concepts have not yet been able to realize their full potential benefits[6]. One key element that is still required is the need to address the issue of temporal uncertainty during the taxi phase from touchdown to the parking position, and from the parking position to takeoff. This will be the focus of this paper.

III. High-Level Concept Vision

Whereas emerging concepts like A-CDM/S-CDM and corresponding pre-departure sequencing tools[4] intend to address the prevailing temporal uncertainty by providing more reliable time information about when the aircraft will land, how long the turn-around will last, when the aircraft will be ready again (doors closed) and when the aircraft can use the runway for its departure, this concept aims to address the temporal uncertainty during the taxi phase. This objective will be achieved through the means of temporal and taxi route planning and precise execution. This concept is called trajectory-based taxi operations.

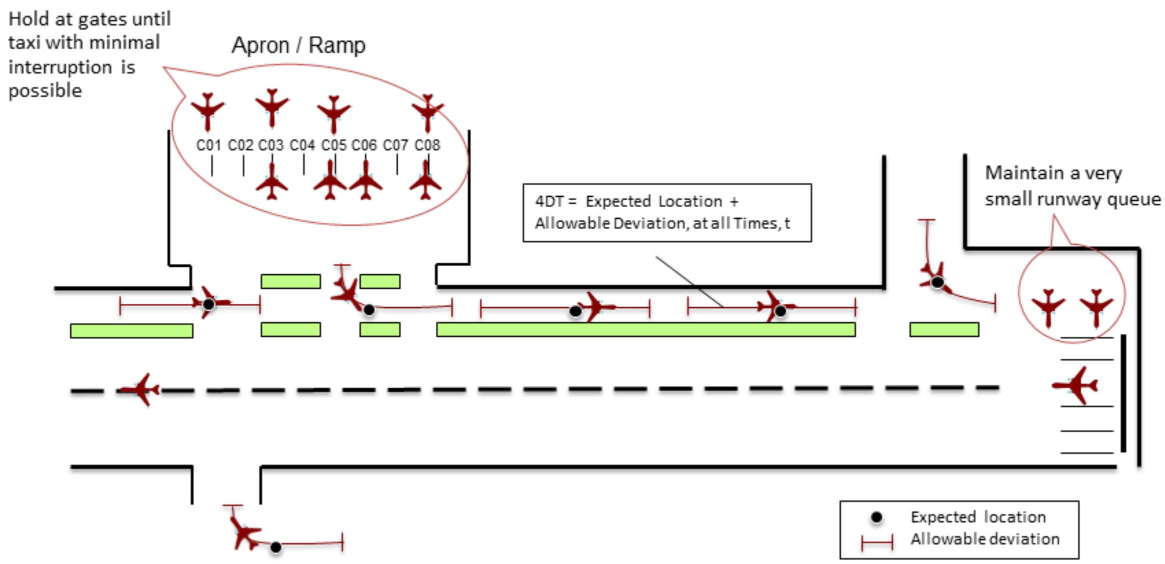

Figure 2. Taxi 4DT for seamless taxiway traffic flow.

Introducing time-based control on surface traffic flow is envisioned to result in a seamless flow of well-separated aircraft executing conflict-free taxiway and runway crossings (shown in Fig. 2). With trajectory-based taxi operations, a four-dimensional trajectory (4DT) is computed for each taxi movement. Every aircraft is assigned a precise 4DT (shown as the black dots in Fig. 2) and an allowable deviation (shown as the red lines in Fig. 2). The aircraft shall stay within that allowable deviation. 4DTs are conflict-free to other taxi trajectories and coordinated such that stop-and-go taxi and holding for other aircraft on the airport surface will be reduced or eliminated. For departures, the goal is to enable the aircraft to reach the departure runway just in time for takeoff, thus saving time and fuel. However, it is expected that a minimal runway queue (e.g., one to three aircraft) will be maintained in order to cope with unpredictable drop-outs and to maximize throughput and capacity usage. For arrivals, the goal is to enable aircraft to land and taxi to the gate without holding at runway or taxiway intersections, and without waiting to access an available gate.

A critical component of this concept is the execution of the 4DT plans by the aircraft, since the planning is only as good as its execution. Each 4DT has a defined error tolerance, but deviations that exceed that tolerance cause replanning resulting in a decrease in the overall system efficiency. Therefore, the pilot must be able to follow a precise taxi route within the temporal and spatial constraints. Such guidance systems can be accomplished via either ground-based or on-board systems.

IV. Objectives

The objectives of this ConOps can be aligned with the Key Performance Areas (KPAs) from ICAO[7]. The relevant KPAs are mentioned along with the specific goals as to how each will be addressed in the proposed ConOps.

The first KPA is Capacity. It refers to meeting the increased needs of airspace user demands at peak times and peak locations while minimizing the restrictions on the traffic flow[7]. In the future, demand is expected to increase due to both an increase in the number of passengers and a general trend to maintain larger fleets with medium-sized aircraft (e.g., B737, A320) rather than smaller fleets of larger-sized aircraft (e.g., B747, A380)[8,9]. Therefore, to support the increased demand, the system of runways, taxiways and the apron/ramp must be used more efficiently and with greater precision. This is expected to be achieved with optimized runway schedules that provide higher throughput and also more accurate and precise taxi route prediction, delivering aircraft to the departure runways in a timely manner.

The second KPA is Efficiency, which refers to both the operational and economic cost-effectiveness of gate-to-gate flight operations from a single-flight perspective. Efficiency refers to “Temporal Efficiency” which is delay-related and “Flight Efficiency” which is trajectory-related[7]. This ConOps aims to address “Temporal Efficiency” by minimizing taxi-out and taxi-in delay[10]. The ConOps supports this objective in two different ways. First, the optimized runway schedule provides takeoff times for every aircraft to minimize runway queue time. Second, the concept aims to provide optimized conflict-free taxi routes to avoid stops while taxiing either for runway crossing or at taxiway intersections.

The third KPA is the Environment, which considers noise, emissions and other environmental issues[7]. This ConOps aims to address this by minimizing waiting time and encouraging delays to be taken at the gate with engines off, rather than on taxiways or at the runway with engines idling.

The fourth KPA, Predictability, refers to the need to provide for consistent and dependable levels of performance for the air navigation service provider and the airspace users. It is vitally important for airspace users because they develop and operate their schedules on that basis[7]. There are two aspects of predictability: global and local predictability. *Global* predictability is related to the adherence of estimated OOOI times (Gate Out, Wheels Off, Wheels On, and Gate In), whereas *local* predictability addresses aspects of taxi between the OOOI times. The objective of this ConOps is to increase predictability in the following ways:

- Generate pushback times and taxi trajectories to meet scheduled takeoff times.
- Coordinate conflict-free trajectories to support taxi with minimal interruption
- Provide better estimates of total taxi time (including queue time)

V. Concept of Operations

A concept for trajectory-based taxi operations is proposed that aims to reduce temporal uncertainty and delays by improving the whole planning chain from gate to runway and vice versa. To accomplish this, a system is proposed that is comprised of the following functions:

a) Runway Scheduling,
b) Time-based Taxi Trajectories,
c) Conflict Detection and Resolution, and
d) Taxi-Trajectory Execution.

Each function in this concept is described in turn. Fig. 3 gives a high-level overview about the relation between the functions.

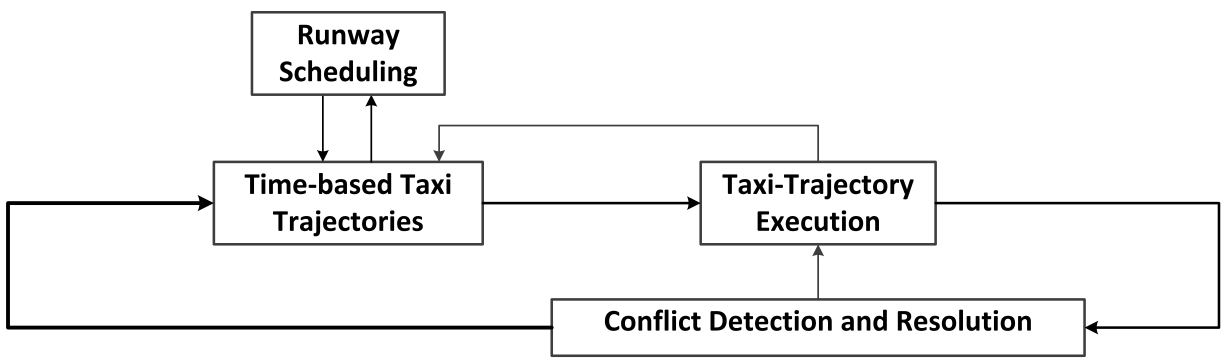

Figure 3. Functional relationship of concept elements.

In the A-CDM concept in Europe, the *Runway Scheduling* function assigns target takeoff times for all departing aircraft based on traffic flow management slots provided by the Network Management Operations Center. In the S-CDM concept in the U.S., target takeoff times and associated target movement area entry times are assigned based on the prediction of demand/capacity imbalance specific to the local airport and traffic management initiatives imposed by both national and local flow management entities. Both the A-CDM and S-CDM concepts envision that this runway schedule is transmitted to Local Control of the Air Navigation Service Provider (ANSP) as well as the flight dispatcher of the airline company to enable negotiations of runway takeoff times or slot swapping, if desired. This could happen up to several hours in advance.

As aircraft are getting close to departure times, the runway schedule is then considered by the *Time-based Taxi Trajectory* function that generates conflict-free 4DTs for all aircraft to ensure that the aircraft meet their runway schedule. If conflict-free routes that fulfill the departure target time cannot be generated, this is communicated to the *Runway Scheduling* function, which adjusts the runway schedule of one or more aircraft accordingly.

The *Time-Based Taxi Trajectory* function transmits the pushback time that often correlates with the engine start-up time to the ANSP Clearance Delivery Controller who issues pre-departure en-route and start-up clearances. The 4DT itself is displayed to the ANSP Ground Controller and the flight deck for the *Taxi-Trajectory Execution* function. Mechanisms are required to enable pilots to communicate technical constraints either before the trajectory creation starts (e.g., request extra time at runway threshold for starting second engine) or during taxi (e.g., request time for troubleshooting a mechanical issue). In this case a new trajectory would be created, which takes the request into account and respects the existing taxi trajectories of other aircraft.

The *Conflict Detection and Resolution* function monitors the execution of the 4DT. If at any time, the aircraft position is outside of the allowable deviation, an impact assessment is conducted and, when warranted, a replan is triggered in the *Time-based Taxi Trajectory* function. This is sent to ANSP Ground Controller and to the flight deck for the *Taxi-Trajectory Execution* function. If the replanning triggers the *Runway Scheduling* function to adapt the runway schedule, the ANSP Local Controller is also informed.

This ConOps is based on several prerequisites. First, the availability of airport and flight information as well as reliable surveillance data is crucial. An information exchange procedure has to be in place that enables the exchange of information between departure and arrival runway management tools. The technological mechanisms to transmit clearance information electronically among the system functions (e.g., Electronic Flight Strips or other mechanism) are required. Also, electronic transmission of the 4D taxi information to the flight deck via datacomm is also required.

The next sections provide detailed description for each concept function whereby important aspects of the functions are emphasized in italics and summarized afterwards.

A. Runway Scheduling

The runway scheduler tool is responsible for scheduling all runway operations, including *departure takeoff, arrival landing, and taxi crossing times* for a single runway or a set of runways that operate in synchronization (e.g., intersecting arrival and departure runways). In essence, the runway scheduler assigns each arriving, departing or taxiing flight a runway time. The goal is to increase runway throughput, balance runway queue size and therefore reduce the aircraft holding time that typically occurs at runway departure and/or crossing queues. To generate a departure runway schedule several constraints have to be taken into account including *takeoff times* assigned by the traffic flow management entities, wake vortex categories of aircraft, the standard instrument departure routes and aircraft departure speeds. The takeoff times assigned by the external flow management entities include the Calculated Takeoff Time (CTOT) in Europe which has a compliance window of -5 /+10 minutes and the Expect Departure Clearance Time (EDCT) in the U.S. which has a compliance window of -5/+5 minutes. These takeoff times are hard constraints and have to be met. It is envisioned that the time buffers around these takeoff times could be reduced if this concept were fully implemented.

B. Time-based Taxi Trajectories

Based on the scheduled takeoff times, surface management tools will generate a taxi plan to deliver the aircraft in a fuel and flow efficient manner to the assigned runway at the right time. This concept adopts a trajectory-based approach in which the taxi plan includes an off-block (pushback) schedule and a conflict-free 4D trajectory (4DT) for every aircraft.

1. *Conflict-free Four-dimensional Trajectory*

A *taxi 4DT* is a time-based taxi route that includes an *expected location (x, y coordinates or latitude, longitude) at all times (t),* with *an allowable deviation from the expected position*. The allowable deviation defines the degree of freedom with which an aircraft can deviate from the expected x, y location at any time and still be considered in conformance with the 4DT. The size of the allowable deviation can depend on factors such as flight type (arriving or departing), speed and airport traffic density. All 4DTs are conflict free at the time of generation if their respective assigned compliance time windows do not overlap. Aircraft will remain conflict-free if they do not deviate spatially or temporally beyond the allowable deviation and the time constraints applied to the creation of the taxi trajectories (e.g., planned pushback, departure or landing time) are valid.

A 4DT *reflects the required times at key locations* of the taxiway system (e.g., gates/spots, runway holding locations), but it also offers increased precision at all times along the taxi route which is necessary to maintain departure sequences and schedules. For example, if an aircraft's goal is only to taxi to its departure runway at a specified time without consideration of conformance along the route, non-conformance (i.e., arriving late or early) can only be identified as the aircraft nears the departure runway, at which time it is too late to adjust the runway schedule. This potentially leads to missed takeoff times, blocked runway holding points for other aircraft and inefficient use of the runway. Furthermore, this aircraft may block the taxiway for another aircraft that is scheduled earlier for takeoff, further reducing runway throughput. It is expected that the biggest benefits will be realized by ensuring on-time arrival at the departure runway for departing aircraft. However, the concept assumes that 4DTs will be generated for arriving aircraft as well. This will be necessary to support close coordination of arriving and departing aircraft at active runway crossings and taxiway intersections, and to support gate management by ensuring gates are available for arriving aircraft without delay, enabling on-time turn around.

2. *Pushback Management*

An important issue for reliable calculation of a 4DT is the *incorporation of pushback management*. In determining the pushback schedule two factors are considered. The first factor is to consider the runway sequence in order to deliver aircraft to the departure runway in the sequence determined by the runway scheduler. The second factor is to minimize excessive fuel burn by holding aircraft as long as possible at the parking positions with the engines off.

Because of these factors, pushback and runway scheduling management need to be considered together. The time-based taxi trajectory tool, which is responsible for the creation of the 4DTs, calculates the earliest possible time when an aircraft with a known "flight readiness time" will be able to leave the position without blocking or being blocked by other traffic (especially in case of single-lane taxiways). Based on this *earliest possible off-block time***,** an earliest arrival time at the departure runway is calculated, either with an assumption about the necessary taxi time (e.g., unimpeded taxi time) or a first optimized conflict-free trajectory for this off-block time, in which case the check for blocked taxiways is mandatory. At the same time, the *latest possible off-block time and the appropriate arrival time at the runway holding point* are calculated. The expected taxi time in reference to the actual traffic should be calculated again. Based on these possible arrival times, the runway scheduler calculates an optimized departure sequence that can be used for the calculation of the best pushback time in combination with a 4DT between pushback and arrival time at the runway. Finally pushback management considers the current traffic situation for every aircraft for the pushback phase.

3. *4DT Generation and Optimization*

When 4DTs are generated, many factors are considered, including *compliance to aircraft manufacturers' performance parameters* and *compliance to speed limits in apron/ramp and taxiways*. Other possible optimization parameters could be considered, depending on the specific goals of the airport operations including the desire to minimize the length of taxi route (for reduced fuel consumption), the delay, and the number of speed changes and turns of the route. The optimization parameter could also change throughout the day accounting for changes in the overall airport performance guidance.

The method by which the 4DTs are generated depends on the optimization approach used (e.g., mixed integer linear programming (MILP), or evolutionary algorithms). The results also depend strongly on the implementation of the operational procedures on the airport surface, e.g., allowing only one aircraft at a predefined part of a taxiway to avoid conflicts.

Furthermore, the selected method decides over the type of optimization: global or local. A global optimization approach would take all taxiing aircraft into account and generate a solution with the best value for a given objective function. This often causes a higher computation effort until a level where the computation time cannot keep up with the moving aircraft concerning the execution. Also, a single aircraft trajectory violation could lead to a reassignment of 4DTs for nearly all aircraft on the airport surface and this would unnecessarily increase controller and pilot workload and reduce their situation awareness. On the other hand, a local optimization approach focuses on the creation of a new 4DT for a single aircraft considering the advised 4DTs of all other aircraft as restrictions. This reduces the computation effort, but may lead to non-optimal solutions for a number of aircraft. Local optimization methods are less disruptive for the traffic flow because already taxing aircraft will not get a new 4DT as often as in the case of a global optimization method. Furthermore, it is possible to prioritize an aircraft that is part of a group of conflicting aircraft by re-optimizing others. Taking the requirements and conditions into account, a *local optimization method is recommended* to minimize the number of re-allocations of 4DTs to aircraft that are already taxiing in combination with a good solution for the 4DT itself.

C. Conflict Detection and Resolution

Fig. 4 displays the mechanism of the *Conflict Detection and Resolution function*. This function contains conformance monitoring that detects deviations from the assigned 4DT. If non-conformance is not detected, the 4DT execution will be continued. If at any time, the aircraft position is outside of the allowable deviation, a non-conformance event is triggered and an impact assessment is performed. Based on its predicted impact to the current traffic situation and the airport schedule, different resolutions are activated. Each of these subfunctions (Conformance Monitoring, Impact Assessment, and Resolutions) will be described next.

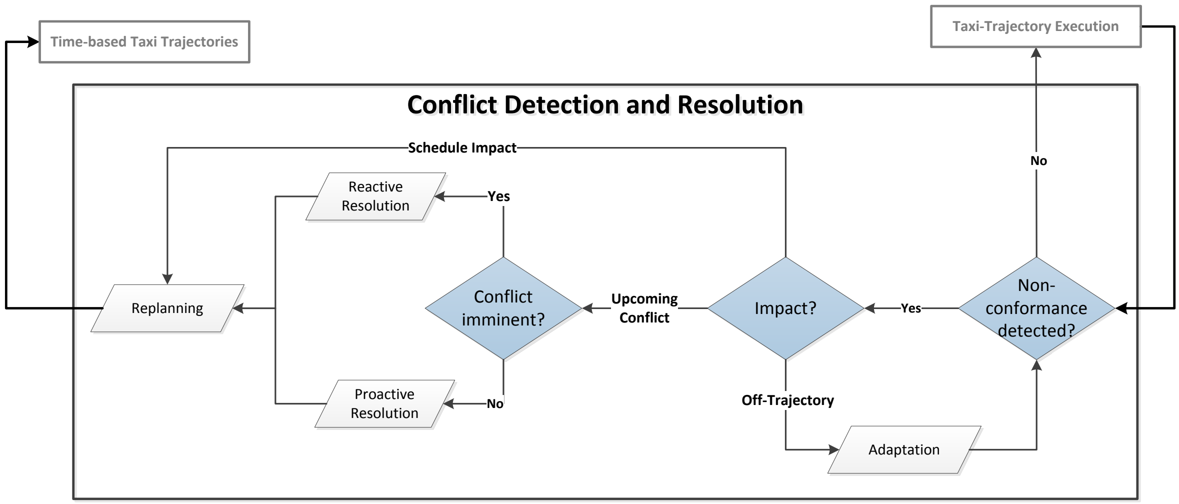

Figure 4. Functionality overview within the concept element *Conflict Detection and Resolution*.

1. *Conformance Monitoring*

Conformance monitoring is critical for maintaining safety in this concept. It prevents potential conflicts, and enables efficient and early replanning when necessary to maintain airport surface throughput and fully realize the benefits of delay reduction. Non-conformance is defined as an aircraft that exceeds the allowable deviation specified by the 4D trajectory. To the extent that aircraft maintain positional (x, y) conformance to the assigned 4DT by staying within their respective allowable deviation, the aircraft will not conflict and will conform to the assigned schedule. If constraints are violated (e.g., an aircraft pushes back late, taxies slower or faster than expected), the trajectory has to be adapted and a conflict check is carried out.

In this concept, there is a need for multiple layers of conformance monitoring – carried out by the pilot, air traffic controller (ATCO), and *Conformance Monitoring automation*. The first layer is performed by the pilot whose responsibility is to ensure the aircraft is in conformance with the 4DT. To support this, pilots require a *flight deck display* showing the allowable range of safe positions at all times. In the event of non-conformance the pilot must either notify ATC or make necessary corrections to the aircraft trajectory.

The second layer is performed by the ATCO ensuring that each aircraft is in conformance with the 4DT. The ATCO also requires *support in the form of a display* that enables the ATCO to view both the expected and actual positions of each aircraft and/or a decision support system to identify non-conforming aircraft.

Finally, the third layer is conducted by the *Conformance Monitoring automation*. Using sensors and surveillance systems, the *Conformance Monitoring automation* continuously compares the actual position of each aircraft to the planned 4DT. At continuous time intervals, the distance between the actual and the planned position is checked to determine if the actual position exceeds the allowable deviation.

2. *Non-Conformance Impact Assessment*

When the Conformance Monitoring automation detects non-conformance, the situation is assessed to determine the potential for either a traffic conflict or a schedule impact. First, instances of non-conformance are assessed for potential traffic conflicts. An upcoming conflict is defined as a situation where there is a risk for collision between aircraft and/or vehicles. The conformance monitoring system must be able to cope with different types of conflicts like lead-follow conflicts, head-on conflicts, taxiway intersection conflicts, conflicts between taxiing and arriving/departing aircraft and pushback conflicts. This impact assessment is carried out by establishing a "safe position" for each aircraft. A safe position is the last position where an aircraft can stop to avoid conflicts with other aircraft. Conflict impact assessment is carried out as a *continuous process of calculating distances between all active (taxiing/pushing back) aircraft* and comparing these values to a set of prescribed minimum distances. The prescribed minimum distances between aircraft can differ depending on the aircraft type, the aircraft state (pushing, holding, taxiing, taking off, landing), the taxiway geometry, and the direction of travel of the aircraft (taxiing behind, or intersecting at right angles). If a potential conflict is found, further parameters, such as the positions of the aircraft on the airport geometry (e.g., parallel) and actual speed of the involved aircraft are taken into account for the concluding assessment and classification. Next, instances of non-conformance are assessed for the likelihood of a schedule impact. A schedule impact is defined as an instance of non-conformance that disrupts the airport surface schedule (e.g., an aircraft does not satisfy a runway crossing time window or a takeoff time window). An aircraft arriving too early can be just as disruptive as an aircraft that arrives too late, so the likelihood of both must be considered in this schedule impact assessment. Finally, if non-conformance is detected, but no conflict or schedule impact is expected, then the aircraft is classified as 'off-trajectory'. The non-conformance impact is summarized in Table 1.

Table 1. Non-conformance Impact Assessment.

Non-Conformance Impact	Operational Definition
Imminent Conflict	Safe position is reached in less than the time needed to create and respond to a new trajectory
Upcoming Conflict	Safe position is reached later than the time needed to create and respond to a new trajectory
Schedule Impact	No Safe Node exists (conflict-free) but aircraft is projected to arrive early or late to a scheduled constraint point requiring schedule adjustment
Off-Trajectory	No Safe Node exists (conflict-free), and no schedule impact is identified, but aircraft is taxiing outside of the allowable deviation

3. *Non-conformance Resolution*

There are two possible *resolutions types – reactive and proactive*. Proactive resolutions can further be delineated by adaptations and re-plans. In the event of an imminent collision, reactive resolutions are issued requiring aircraft to hold in position. When a hold is advised it is necessary to check the trajectories of all other aircraft for potential conflicts with this hold as this could lead to trajectory recalculations for a number of aircraft that were not involved in the original conflict. For aircraft with an upcoming (non-imminent) conflict, in which the system determines that a new 4DT can be created before the safe position is reached, a proactive replan is triggered in the *Time-Based Taxi Trajectory* function. When a "Schedule Impact" is detected, an adaptation is first attempted in which adjustments are made to attempt to enable the aircraft to meet the existing runway schedule (e.g., requiring the aircraft to speed up or slow down). If a conflict-free 4DT that complies with the runway schedule cannot be generated, a new runway schedule is developed for the affected aircraft. In the case of "Off-Trajectory" an adaptation is triggered and conformance is re-assessed. Adaptations and Replanning are further described below.

Adaptation

Because the time-cost of computing the new 4DT can be high, it is preferable to give the aircraft an *opportunity to regain conformance* if possible. Therefore, a *two-step approach* is used. The first step would be to send advisories to the flight deck to assist the aircraft in regaining conformance, and then to *adapt the trajectory*. The adaptation has to be carried out stepwise, where in the first step it should verify if the aircraft is on the advised route or not. If this is the case, the actual 4DT is adapted to the current position and speed of the aircraft and rechecked for conflicts. If conflicts are found a *replanning is initiated* (explained in the next section). Otherwise, the adapted trajectory is sent back to the flight deck and the aircraft is required to conform to the revised trajectory. If the aircraft is not on the assigned route (e.g., caused by a wrong turn) the actual position is identified and a new trajectory is created starting from this position.

With this approach the number of replans can be kept low in comparison to smaller adaptations of the trajectory. Instead of creating a complete new trajectory every time a deviation is encountered, a small adaptation to meet the actual taxi parameters is carried out. This is especially important for optimizations that will not only change the speed profile, but the course of the route.

Replanning

When non-conformance that leads to a conflict or the violation of a time constraint is detected, the runway scheduler and the time-based taxi trajectory generator are notified. The use of an algorithm that creates an optimal solution for a selected aircraft gives the user (e.g., the ATCO) the choice to select the affected aircraft in a more direct way using a priority value. This priority value can depend on factors like "departures over arrivals", emergencies, importance, safety, or prioritization based on target times. Therefore, a *prioritization strategy* should be developed and implemented within the optimization tool. For instance, when a conflict occurs, the system must first identify all aircraft involved in the conflict. When only two aircraft are involved, the priority values can be applied directly. But, when more than two aircraft are involved, there may be several possible resolutions. For instance, if aircraft "A" deviates from the taxi route (spatially or temporally) and aircraft "B" and "C" are affected, it should be possible to prioritize aircraft "C" over aircraft "A" that created the conflict. However, the conflict between aircraft "A" and "B" remains unaddressed. The optimization is then carried out for all aircraft that have to be re-planned in the order of the assigned priority.

D. Taxi-Trajectory Execution

High levels of non-conformance will overload the scheduler requiring excessive re-computations and overload the human operators (air traffic controller and pilots) with excessive updates and trajectory modifications. Thus, flight deck support will be required to ensure a high degree of aircraft conformance to the assigned 4DT. A number of different technologies to support aircraft conformance can be envisioned. Fig. 5 shows two possible approaches: Onboard-based guidance and Ground-based guidance.

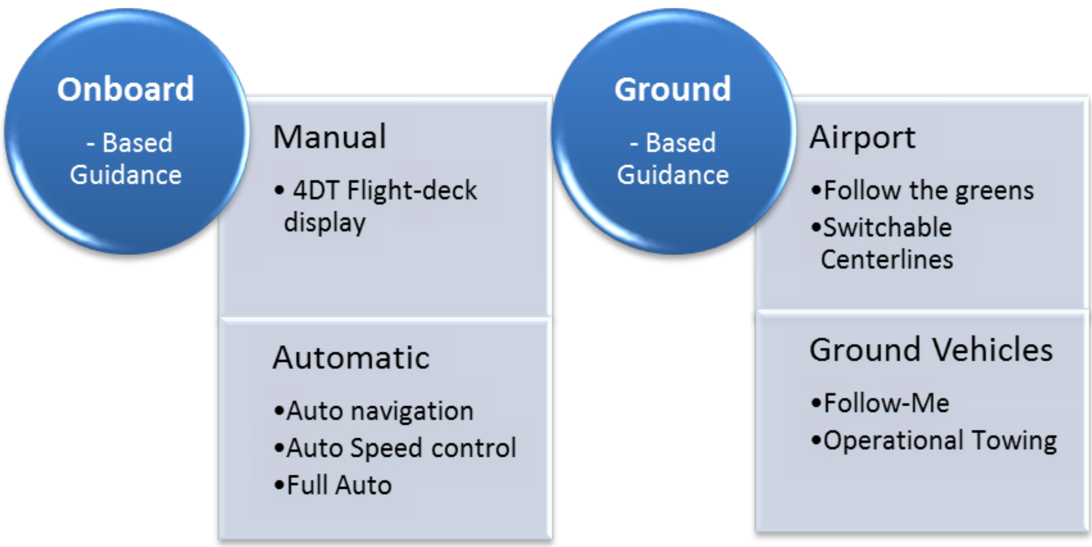

Figure 5. Different guidance means for Taxi-Trajectory Execution.

The onboard-based guidance approach can be further categorized into manual approaches that include avionics and communication tools that support pilots' control of the aircraft while carrying out the 4DT and automated approaches, which include various forms of automation to execute the 4DT. Specifically, advanced technology may be applied to automate the *task of navigation* (nose-wheel control), *speed control* (throttle and brake control), or both (full auto-taxi). In these more automated cases, the *4DT would be electronically transmitted* to the Flight Management System (FMS), for instance, by ground-based augmentation systems (GBAS) and different modes of VHF datalink (VDL). Any of these forms of onboard-based guidance systems would require *new flight deck interfaces* to keep pilots in-the-loop and maintain situation awareness.

Ground-based guidance relies on cues in the environment to provide 4DT guidance. Examples of ground-based guidance may include airport infrastructure upgrades such as switchable centerlines or lighting such as the Follow-the-Greens system which guides the aircraft along the correct taxi path, but also can accelerate and decelerate the aircraft by switching different numbers of lights in front of the aircraft or other vehicles[11]. For instance, when the pilots see three green lights in front of them, their speed is in accordance with the 4DT, two green lights recommends a slower speed, and four green lights would recommend accelerating the taxi speed. Another ground-based solution for effecting 4DT conformance is the use of *ground vehicles* that actively or passively guide the aircraft along its taxi route in conformance with the assigned 4DT. Examples include: Follow-Me Vehicles, which drive in front of the aircraft, but are not connected to it, and Operational Towing, which are tugs connected to the aircraft that tow the aircraft according to the 4DT.

For this concept, a combination of multiple solutions could be feasible. Ground-based solutions generally may have the advantage of enabling faster industry adoption as they do not require aircraft retrofits, but this places the cost burden on the airports. This paper focuses on research in the area of Onboard-based guidance.

E. Important aspects of concept functions

The essential aspects of the concept functions described above are summarized in Table 2. These concept functions are already partly implemented and investigated by NASA and DLR. The next section provides an overview of the preliminary research concerning these aspects.

Table 2. Extract of important aspects of concept functions.

Concept Elements			
Runway Scheduling	**Time-Based Taxi Trajectories**	**Conflict Detection and Resolution**	**Taxi-Trajectory Execution**
- Integrated departure and arrival manager - Assigned take-off times	- 4D Taxi Trajectory, expected location at all times along the route - Allowable deviation - Conflict-free taxi 4DTs - Reflect required times at special points - Pushback management considers earliest / latest possible off-block times - Local optimization - Complies with aircraft performance parameters - Complies with speed guidelines in apron/ramp and taxiways	- Continuous conformance monitoring by flight deck, ATCO, and automation - Impact assessment based on calculation of safe position - Four impact types: Imminent Conflict, Upcoming Conflict, Schedule Impact, Off-trajectory - Two-step approach: First, enable aircraft to regain conformance / second, adapt trajectory - Reactive and proactive resolutions - Prioritization strategy for replanning	- On-board based approaches: Automatic control, manual control - Ground-based approaches: External vehicles, airport lighting - Flight deck interfaces to enable 4DT execution and/or monitoring - 4DT electronically transmitted via datacomm

VI. Preliminary research related to concept functions

Both DLR and NASA have conducted preliminary research that has contributed to the formation of the proposed 4D Taxi ConOps and assessed its feasibility. To support this research, several prototype tools have been developed that address the intended functions of the concept, including *Runway Scheduling* (CADEO and SARDA), pushback management as part of *Time-based Taxi Trajectories* (TRACC and SARDA), *Time-based Taxi Trajectories* (TRACC), Conformance Monitoring as part of *Conflict Detection and Resolution* (TRACC and flight deck displays), and *Taxi-Trajectory Execution* (4DT Flight Deck Displays). Each prototype tool will be reviewed next.

A. Research Prototypes Developed in Support of the 4DT Taxi ConOps

1. *Controller Assistance for Departure Optimization (DLR, Institute of Flight Guidance)*

Controller Assistance for Departure Optimization (CADEO) is a prototype departure management system that optimizes the departure sequence at the runway while considering arrivals on the same or dependent runway(s). It provides support for A-CDM by calculating Target Takeoff Times (TTOT) and Target Start-Up Times (TSAT). CADEO suggests clearances for engine start-up, pushback, taxi, and also takeoff at the right time to maintain runway throughput and minimize taxi time on the airport surface. CADEO considers estimated times for taxi-in and taxi-out, as well as time separations for using the active runways dependent on Standard Instrument Departure (SID) routes, and wake vortex classes and dependencies with other active (parallel/crossing/converging) runways[12].

2. *Spot and Runway Departure Advisor (NASA)*

The Spot and Runway Departure Advisor (SARDA) is a decision support tool that provides guidance to ATC Tower controllers and airline ramp controllers to improve efficiency, predictability, and throughput of airport surface traffic[13,14]. SARDA provides advisories for sequencing and scheduling of departure pushback from the gate to the ramp controller. SARDA also provides advisories for release of aircraft from spots and sequencing of runway operations (i.e., takeoff and crossing) to the Ground and Local controllers, respectively. Schedule for departure pushback, which is derived from SARDA's optimal runway schedule, is provided to the ramp controller as advisories. The pushback advisories are displayed on the ramp controller display in either gate-hold time in minutes or notification of immediate pushback. The pushback advisories are updated as the traffic situation changes, so that the overall objective of surface management is maintained.

The SARDA runway scheduling algorithm takes as input the current snapshot of the airport surface traffic, separation criteria, scheduled pushback times, and estimated landing times of arrivals in the next 15 minutes. The scheduling algorithm also incorporates operational constraints, including wake vortex separation, traffic management initiatives (e.g., Expect Departure Clearance Time), and airline priority. These inputs and constraints are passed to the runway scheduler that calculates the best runway occupancy schedule for both arrivals and departures with corresponding takeoff times for departures. The runway-scheduling problem can be solved for multiple objectives, including throughput (runway occupancy time for the last aircraft) and system delay (total delay for all aircraft).

3. *Taxi Routing for Aircraft: Creation and Controlling (DLR, Institute of Flight Guidance)*

Taxi Routing for Aircraft: Creation and Controlling (TRACC) is a prototype surface management system that generates conflict-free 4D trajectories from gate to runway and vice versa to meet Target Takeoff Times with a minimum of speed changes during the taxi process. The 4DTs are created by applying techniques from evolutionary algorithms, an area of artificial intelligence. TRACC provides guidance instructions (speed and route) for the air traffic controller via the corresponding human-machine interface (HMI), which can be seen in Fig. 6[16].

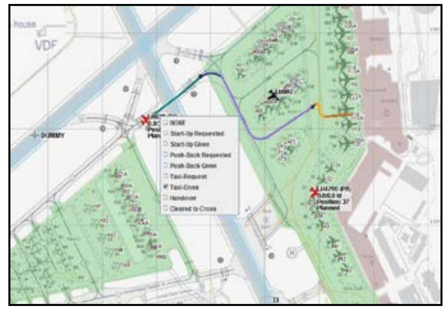

Figure 6. Air Traffic Controller HMI of TRACC[15]. *The taxi trajectory is displayed with different colors that represent different speeds.*

4. *4DT Flight Deck Displays (NASA)*

The 4DT taxi flight deck display (see Fig. 7) includes an Airport Moving Map (AMM) that depicts the cleared taxi route shown in magenta with a highlighted band representing the 4DT. The marked center point of the highlighted band represents the precise 4DT location, and the front and back edges of the band depict the allowable deviation (shown as +/- 15 seconds in Fig. 7). By keeping the aircraft's position (white chevron) on the highlighted area (light magenta area in Fig. 7), the pilot is ensured to be in conformance with the assigned 4DT. The display enables the pilots to determine their conformance status 'at-a-glance', without spending excessive eyes-in time[17].

Figure 7. 4DT Flight Deck Display[17].

B. Preliminary Feasibility Assessments

The prototype tools discussed above have been created to enable research, which in turn has informed the development of the ConOps. In the following sections, specific research results that have directly informed the ConOps are reviewed. They are organized based on the concept functions. In the first part, research associated with a single concept function is described. Then, research associated with the combination of these functions is described.

1. *Runway Scheduling Research (DLR)*

Different optimization strategies for runway scheduling have been investigated at DLR. Two frequently used optimization strategies were implemented in CADEO: 1) minimizing system delay, and 2) maximizing throughput. Minimizing system delay alone provides benefits in throughput as well. The multi-objective approach[18] considered throughput, taxi-out delay, compliance to slots (coming from the European Network Management Operations Center) and planning stability. It was found that throughput and slot adherence is not the critical issue compared to the decrease of taxi-out delay, which corresponds to the queue length. Results from human-in-the-loop simulations showed that the output of CADEO supported the controllers' work[19] and the stop times while taxiing could be reduced by 26% thus reducing taxi time and avoiding lengthy queues[12].

2. *Runway Scheduling Research (NASA)*

Human-in-the-loop simulations were conducted in NASA's Future Flight Central ATC simulator to evaluate performance of SARDA's runway scheduling algorithm for Dallas/Fort Worth International Airport[13,20] and human factors metrics, such as workload, situation awareness, and usability of the SARDA tool. The ATC Tower controllers were provided advisories for releasing aircraft from spots and sequencing for runway operations (i.e., takeoffs and crossings). The results from the simulations with SARDA advisories showed significant reductions in taxi delay (45-60%) and fuel savings (23-33%) compared with non-advisory cases. The results also showed a reduction in controllers' workload and an increase in their perceived spare attention. The workload and attention levels were also shown to be less sensitive to the effects of increases in traffic density.

3. *Pushback Management Research (NASA)*

A series of human-in-the-loop experiments was conducted for Charlotte-Douglas International Airport (KCLT) in 2014, to evaluate the concept and performance of SARDA's ramp controller pushback-management decision support tool[14]. The results showed that the tool helped reduce taxi time and fuel consumption without reducing runway throughput or increasing the ramp controllers' workload.

4. *Time-based Taxi Trajectories Research (DLR)*

During the development of TRACC, several important implementation types such as local or global optimization were considered, but early analyses revealed that a global optimization approach would lead to excessive replanning. In case of a conflict between two aircraft, a local optimization needs to replan only one aircraft while a global optimization always needs to replan more than one aircraft. Because the number of replannings is a factor in increasing controller workload, the local optimization method was selected as the better choice.

Another important point was the creation of a procedure for handling non-conformance in a timely manner. Tests using a fast-time environment have proven that in the event of non-conformance, TRACC's first attempt should be to adapt the 4DT to match the aircraft's current state and to replan only in cases that a conflict will occur when using this adapted 4DT. This reduces the necessity for time-consuming replannings. With this approach we found that TRACC could adapt 4DTs in a timely manner.

The 4DT conformance monitoring interface for air traffic controllers was tested in a human-in-the-loop simulation conducted at DLR with air traffic controllers from different airports[15]. It demonstrated that the concept of 4D taxi trajectories was supported in general based on ATCO-rated measures of acceptance, usability, and situation awareness when using the proposed traffic situation display. However, there is still some future work required to improve and to balance stability and adaptation of the plan. In this research, route changes were issued verbally to pilots who responded with a verbal readback. This resulted in increased ATCO workload and heavy use of the radio frequency. As a result, the need to transmit clearances electronically via datalink was identified[15]. As a result of these simulation runs several features for the ATCO-Display were adapted or added to meet the requirements of the controllers.

5. *Taxi-Trajectory Execution Research (NASA)*

Past research has shown that adequate pilot conformance will not be attained without flight deck support to meet both navigation and schedule conformance. In current-day operations, non-conformance in the form of navigation errors has been shown to occur on approximately 17% of low-visibility and night simulation trials[21]. This level of non-conformance is unacceptably high for the proposed closely coordinated 4D trajectory-based operations. An assumption is that aircraft will be equipped with airport moving maps either integrated into the navigation display or on electronic flight bags to support airport navigation requirements.

With regard to schedule conformance, early pilot-in-the-loop flight deck simulator research[22] has shown that simple procedural approaches in which the ATCO provides a verbal time and/or speed guidance via radio yield inadequate time precision and excessive pilot head-down time. A series of piloted simulations assessed whether pilots could meet required time of arrival (RTA) for taxi routes when ATC provided a required taxi speed as part of the taxi clearance. It was found that the average error to reach the final RTA location was +/- 30 seconds depending on the required speed. A second experiment required the pilot to attempt to conform to the required speed in the taxi clearance within a tight bound of +/-2 kts of the commanded speed. Final average RTA error was reduced to +/- 6 seconds, but with increased head-down time, pilots reported that "bounding" the aircraft's speed was "unsafe". In a subsequent study[22], it was found that when taxi clearances included a required taxi speed, RTA error at the departure runway was between 20 and 30 seconds; however, along the taxi route, the aircraft was out of conformance (more than +/- 30 seconds) 28% of the time. These simulations show that procedural solutions (i.e., incorporating a speed requirement into a taxi clearance) do not provide adequate 4DT conformance, and demonstrate the need for 4DT flight deck displays.

To demonstrate the feasibility of 4DT displays, NASA has conducted two 4DT taxi simulations with two different types of displays designed to support pilot conformance to a 4DT. NASA Ames Research Center performed a proof-of-concept, pilot-in-the-loop study[17] of the spatial display concept for 4D taxi described previously and shown in Fig. 7. In this study, the 4DT was sent via datalink to an Airport Moving Map (AMM) located in the flight deck Navigation Display. The display depicted the precise 4DT and the allowable deviation of either +/- 15 seconds or +/- 30 seconds. The data indicated that such a system afforded more than 99% conformance to the 4DT across the entire route with significantly reduced time of arrival (TOA) error at the runway endpoint. Pilot ratings indicated that it was safe with acceptable "eyes-in" (looking at the display) times. A separate concept to support 4D taxi was tested at NASA Langley Research Center[23]. In this simulation, the AMM provided textual displays of required time of arrival (RTA), estimated time of arrival (ETA) and the difference. One version of the AMM showed a graphical prediction of the aircraft's predicted and required location in 30 seconds. Pilots were able to maintain conformance along the route within 15 seconds of the required speed/location profile. Pilots reported that the required "eyes-in" time and overall safety ratings were acceptable. These preliminary studies have demonstrated the feasibility of on-board guidance to support precise conformance to 4DTs.

6. *Taxi-Trajectory Execution research (DLR)*

DLR has conducted research to assess the feasibility of automated-taxi for executing the 4DT. Automated 4DT execution relies on several prerequisites such as reliable surveillance information to support the pilots with the knowledge of their exact positions. This will not only be used for input for an integrated flight deck display, but also provide necessary support for surveillance systems for the ATCO. For that purpose the Ground Based Augmentation System (GBAS) Differentially Corrected Positioning Service (DCPS) was investigated to enable enhanced services such as guidance of aircraft during taxiing.

Beside the positioning service, GBAS is able to provide additional service to support reliable navigation. In extension to the provision of different approach tracks, a GBAS-based definition of ground paths (TAP - terminal area path) between the runway and the parking stands at the airport is possible. With such a system, existing navigation avionics and ground installations are usable on both sides, on ground as well as on-board. The successful usage of GBAS transmitted routes for the ground was shown by DLR[24]. These ground paths consist of different waypoints as used for the area navigation and will be directly used for a taxi-FMS for automatic 4D taxi trajectory generation and guidance.

Both simulation runs and taxi tests conducted on the surface of the Braunschweig-Wolfsburg airport showed the feasibility of GBAS for future applications of airport surface movement[25,26]. Within these tests, the quality of the DCPS was proven, as was the ability to transmit GBAS messages for taxiing. A taxi-FMS with autopilot was demonstrated in the flight deck simulator, in which the aircraft autopilot controlled the nosewheel, throttle and brakes to follow the 4DT. Later in this year, all systems will be integrated in an experimental aircraft where the aircraft will be piloted manually based on a specific guidance symbology given by the FMS. This will be the first step toward full implementation of auto-taxi in an operational setting.

7. *Integrated Runway Scheduling / Time-based Taxi Trajectories research (DLR)*

The aforementioned human-in-the-loop simulation (paragraph VI-B-4) was also used for a first test of the coordination between the DLR departure management systems CADEO and the DLR surface management system TRACC, revealing the necessity of more sophisticated combined simulations. These tests represent the combination of the functions *Runway Scheduling* and *Time-based Taxi Trajectories* of the DLR tools for the first time. The coordination concept was introduced in 2013[27] whereby both systems focus on different geographical areas. TRACC calculates the trajectory based on the Target Off-Block Time (TOBT) until the runway holding point before line-up is performed and passes the earliest possible line-up time (RLUT) to CADEO. CADEO considers the aircraft for the optimal runway sequence and sends the optimized time for performing line-up - the Target Line-Up Time (TLUT) - back to TRACC. After that, TRACC calculates again to deliver the aircraft close to the TLUT issued by CADEO. The improvement against the current variable taxi time from Airport Collaborative Decision Making (A-CDM) is that the RLUT has to be kept up-to-date. TRACC needs to take into account different optimization strategies to keep RLUT: a) route adaptation b) speed adaptation on the same route, and c) dynamic change of weighting of optimization parameters. In case that RLUT is greater than the Target Takeoff Time, CADEO needs to re-optimize. This coordination concept is an advancement compared to a simpler coordination strategy in the human-in-the-loop simulation.[15]

This concept was taken and the TRACC tool was advanced compared to the human-in-the-loop studies[15] by conducting simulation runs[28]. In particular, the calculation procedure for the best pushback time was improved and a sophisticated method for calculating the TSAT was added. TRACC performs the Pushback-Management function first to calculate the earliest possible Target Off-block Time (TOBT) and then calculates the Target Start-up Time (TSAT) based on this TOBT. The resulting TSAT is used to calculate the earliest line-up time needed by CADEO. When CADEO sends back a Target Line-Up Time (TLUT) the final TSAT is calculated to meet the target time. Every time CADEO adapts the runway schedule, TRACC starts a series of recalculations. Likewise, whenever TRACC’s conflict detection and resolution algorithm detects a deviation and adapts or replans the 4DT, the expected time when the aircraft will reach the runway is sent to CADEO. Because TRACC’s optimization algorithm focuses on meeting the CADEO target times this will not trigger a recalculation of the runway sequence very often.

Based on these advancements, computerized simulation runs were conducted with no human-in-the-loop. It was shown for the Munich airport design that the concept to combine TRACC and CADEO is feasible in that it reduced the runway delay (mean 8.5 seconds) in favor of the gate hold delay (mean 134.2 seconds) and the queue length at the runway to at most one aircraft[28]. Further work in the area of minimum distances for conflict detection and the optimization space for CADEO could be performed to prepare this tool combination for subsequent human-in-the-loop simulations.

More simulation runs were conducted for Charlotte-Douglas International Airport (KCLT) with the support of NASA researchers. These runs have emphasized the necessity of a fast trajectory-planning tool. The reason is that there were situations where a late aircraft caused a replanning of CADEO resulting in a changed departure sequence with a higher number of new TLUTs for several aircraft. In these cases, TRACC had to create new trajectories for each of these aircraft. TRACC was able to do this, but it showed that the calculation time is crucial for a taxi trajectory-planning tool.

8. *Integrated Taxi-Trajectory Execution/Runway Scheduling /Pushback Management research (NASA)*

An integrated flight deck and ATC human-in-the-loop taxi-out operations simulation was conducted in the Dallas/Fort Worth International Airport (KDFW) environment[29]. In this integrated Pilot-ATCO simulation, ATC Ground and Local Controllers used the SARDA decision support tool to plan and issue spot-release clearances and departure clearances. The Airport and Terminal Area Simulator (ATAS), a simulated B737NG, was integrated into the realistic simulated traffic environment. Ten commercial transport pilots piloted the ATAS and taxied from gate to runway following ATC clearances. The results of this integrated Controller- and Pilot-in-the-loop simulation demonstrated that the SARDA algorithms were able to accurately monitor aircraft taxi conformance and adapt to the range of typical pilot/aircraft taxi performance. Additionally, in one off-nominal scenario, the ATAS-piloted aircraft stopped for more than one minute simulating a passenger problem. SARDA was able to detect and recalculate the takeoff time with revised estimates as accurate as those for nominal taxiing-out aircraft. To be adopted, SARDA advisories for traffic sequencing and scheduling must be robust to the pilot/aircraft performance variations similar to those observed in this simulation (e.g., variation in taxi speeds, and variability in the time required to initiate taxi, line-up-and-wait, and takeoff after receiving clearances). Simulation results indicated that with these observed pilot/aircraft performance variations, the SARDA system yielded controller advisories that were: **Supportive** of time-based operations; **Compatible** with controllers' expectations; **Predictive** of actual takeoff times; and, **Adaptable** to off-nominal events.

C. Conclusion

In summary, the development of the ConOps has been supported by an extensive range of research efforts that have included system prototype development efforts for each concept function, separate and integrated pilot-in-the-loop and ATCO-in-the-loop assessments, and fast-time modeling. These research efforts are summarized in Table 3 and Table 4 whereby conducted research is marked with an "X". These assessments have served to demonstrate the feasibility of the concept.

Table 3. Implementation of single concept functions by research systems from DLR and NASA.

Concept Functions	Research System			
	CADEO	**TRACC**	**SARDA**	**4DT Flight Deck Display**
Runway Scheduling	X		X	
Time-Based Taxi Trajectories		X	X*	
Conflict Detection and Resolution		X		X**
Taxi-Trajectory Execution				X

* SARDA supports pushback management and off-block scheduling aspects of time-based taxi trajectories
** 4DT flight deck display supports pilot conformance monitoring

Table 4. Implementation of combined concept functions by research systems from DLR and NASA.

<table>
<tr><th rowspan="2">Concept Functions</th><th colspan="4">Research system</th></tr>
<tr><th>CADEO</th><th>TRACC</th><th>SARDA</th><th>4DT Flight Deck Display</th></tr>
<tr><td>Runway Scheduling</td><td colspan="2" rowspan="3">X</td><td colspan="2">X</td></tr>
<tr><td>Time-Based Taxi Trajectories</td><td></td><td></td></tr>
<tr><td>Conflict Detection and Resolution</td><td></td><td></td></tr>
<tr><td>Taxi-Trajectory Execution</td><td></td><td></td><td colspan="2">X</td></tr>
</table>

VII. Concept Challenges

This 4D taxi ConOps promises efficiency benefits for future airport operations, but also poses significant challenges regarding perspectives, operational procedures, policies, implementation, and the status of current technology. The following areas require further research before this concept can be realized and relevant technologies are fielded:

- Technology Research and Development
- Changes to Operational Procedures
- Ensure System Robustness and Resilience
- Define Roles and Responsibilities

Technology Research Requirements. While the prototype tools developed at DLR and NASA have demonstrated feasibility, further work is required in the areas of runway-schedule optimization and conflict detection and resolution algorithms. Likewise, the development of tools, technologies, and interfaces to support all operators (pilots, ATC, Ramp/Apron controllers) and to facilitate communication among operators is required.

Changes to Operational Procedures. The operational procedures that are in use today require modification in order for this concept to be fully implemented. Most notably, this trajectory-based taxi concept requires tighter coordination between tower ATCO and Ramp/Apron Controllers in order to exchange information about the 4D taxi trajectory, takeoff/landing times and in- and off-block times among all stakeholders. The mechanism for the coordination, and the ramifications of these operational changes, require further investigation.

Ensure System Robustness and Resilience. System Robustness refers to the ability of a system to experience no stress when facing a disturbance whereas Resilience is defined as the ability of a system to recover from a disturbance in a given time interval[30]. In order to ensure system robustness and resilience, research is required to ensure that the system that is developed and fielded considers aircraft, pilot and air traffic controllers' constraints and capabilities, and environmental conditions such as weather, and that the system can accommodate and adapt to uncertainty / off-nominal situations.

Define Roles and Responsibilities. The inherent increase in complexity associated with 4DTs necessitates the introduction of new forms of automation. However, it is critical that each task is evaluated and the role of the human and automation in carrying out the task is carefully considered. This is a multifaceted problem that must aim to balance system performance (efficiency and safety), operator performance (workload, situation awareness, and complacency), and user acceptance.

VIII. Summary and Next Steps

The ConOps for trajectory-based taxi operations was introduced that consists of four concept functions: Runway Scheduling, Time-based Taxi Trajectories, Conflict Detection and Resolution, and Taxi-Trajectory Execution.

The initial feasibility assessments have shown that the proposed concept addresses the KPA objectives in the following manner. Our initial research showed that the trajectory-based taxi concept significantly reduced taxi delay, taxi times and time spent stopped on the airport surface, while benefitting runway throughput, thus addressing the Efficiency and Capacity KPAs. Our research also showed that reducing the runway delay in favor of a gate hold delay, where the aircraft wait with engines off, yielded a reduction in fuel consumption that supports the Environment KPA. Finally, generating pushback times and conflict-free taxi routes that were coordinated with the runway schedule resulted in better estimates of taxi times, which supported both local and global Predictability. However, the extent to which these KPA objectives are met in actual operations will depend greatly on the ability of the aircraft to execute the 4DTs as planned. Our simulation research showed that given onboard guidance in the form of a spatial 4DT taxi flight deck display, pilots could manually execute the 4DT with +/-15 seconds precision. Likewise, evidence of the feasibility of auto-taxi through a taxi FMS based on GBAS was provided.

NASA and DLR are continuing this collaborative research effort with a focus on concept verification and validation, which will be an iterative process designed to support concept refinement and further demonstrate and quantify the expected benefits.

Acknowledgments

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