Taxi routing for aircraft: Creation and Controlling

Ground movements with time constraints

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Abstract—**This document describes the ongoing research on a DLR SMAN called TRACC (Taxi Routing for Aircraft: Creation and Controlling). TRACC generates conflict free routes with a maximum of punctuality by creating an advisory list for the taxi route and the appropriate speeds. These routes are created applying techniques from evolutionary algorithms, an area of artificial intelligence. TRACC can be used as stand-alone simulation or within a simulation environment.**

Keywords-automatic taxi routing, controller, simulation, real time, evolutionary algorithms, ground movements

I. Introduction

The idea for the creation of a new surface management tool was born within the DLR project flexiGuide. The objective of this project is to test new traffic management concepts for the extended TMA like trajectory-based arrival management and user-preferred trajectories as well as late merging points on final approach, individual and optimized flight profiles, and time based arrival management.

Today 4-D-trajectories for air traffic are an important part of ATM research but there are not many concepts expanding "4-D" to ground traffic [8]. But when the research goal is to deliver aircraft dependent on time at the glide path it should be guaranteed that the created benefit in punctuality will not get lost during taxi. This is the task the DLR SMAN called TRACC (Taxi Routing for Aircraft: Creation and Controlling, see Figure 1) is developed for. Nevertheless, TRACC does not solely handle arrivals but departures as well. It was designed to be implemented as a research system at the DLR real-time simulator (driven by NARSIM) and will work together with AMAN and DMAN tools. The objective is the creation of conflict-free taxi routes with a complete set of time constraints (specified taxi speeds and time stamps for reaching positions at the airport) which will guarantee a maximum of punctuality (measured in seconds). The optimization is done with respect to different parameters like target time and route length. Therefore, it was necessary to create a strategy for the presentation of the above mentioned time constraints to the controllers without overloading them with additional work. Furthermore, TRACC includes an "automatic" and a "controller in the loop" mode and is able to run as a stand-alone simulation e.g. for testing new taxi strategies or as a part of a simulation system as generator of taxi routes.

II. The TRACC Approach

Today on almost all smaller airports and many Hubs controlling ground traffic is done by controllers without software assistance in the creation of routes and avoidance of conflicts [1]. Most airports use displays to show surveillance data of the airport and interrelate this to the positions of taxiing aircraft. To avoid conflicts and increase the controllability of the traffic some airports use predefined standardized taxi routes (e.g. Frankfurt: Standard Short Cuts) which make it much easier to foresight an upcoming problematic situation. Controller speed advisories are less specific and more of the type "slowing down" than "reduce speed to 20 knots".

Meanwhile the number of tools which are able to control ground movement's and support controllers has increased. Some of them are able to show the traffic, control safety issues by managing restricted areas and partly foresee runway incursions [12]. In difference to TRACC, their focus does not lie additionally on the creation of a "4-D"-trajectory and complete automation but on surveillance and traffic guidance.

A. Objective

Thereby, the main idea for the development of TRACC was to design an SMAN that is suited to cope with "4D-trajectories" on one hand and allow full automation of ground handling for research activities on the other. The objectives of TRACC are:

- To create conflict-free taxi routes for each aircraft from the runway exit to the parking position and vice versa using predefined speed profiles.

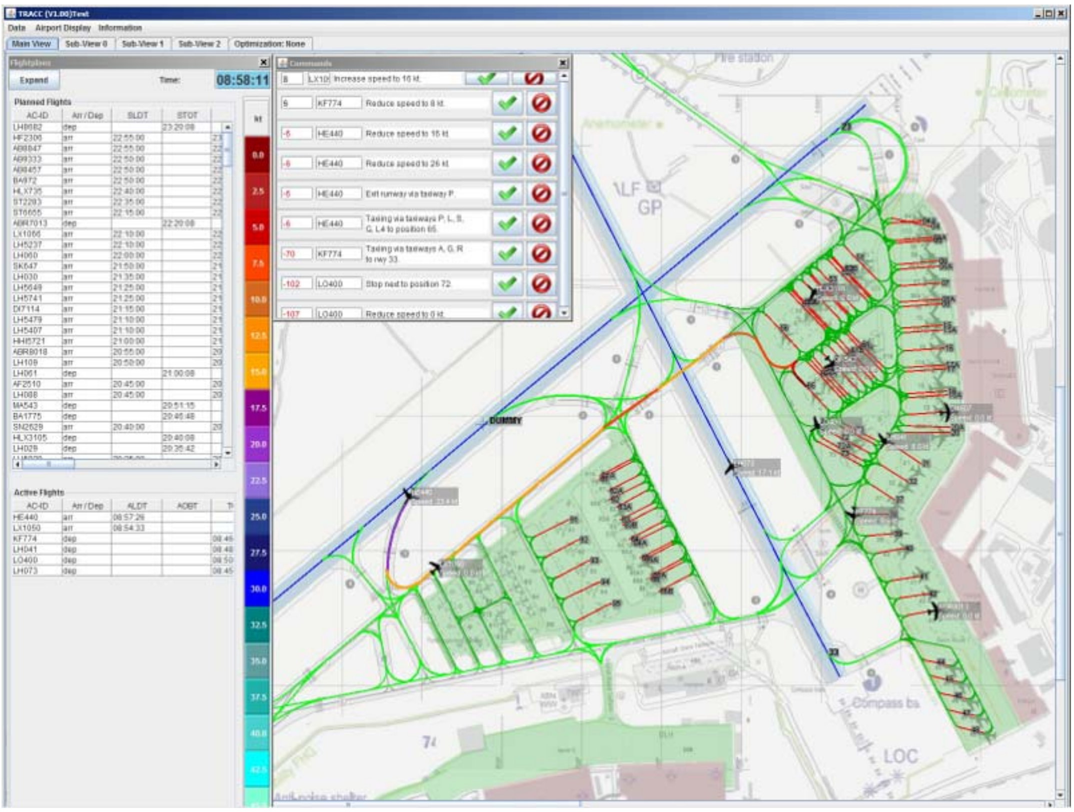

Figure 1. Main screen with view of the airport (map and node-link-system). Three sub screens for detailed views. Aircraft routes as colored lines (color depending on average speed). Expandable Tables with information about planned and active aircraft. Frame with actual controller commands.

- To take into account other requirements like a minimization of delay, route length, or number of stops which should be considered within the route generation process
- To present taxi routes and recommended taxi instructions to the ground controller
- To solve pre-tactical (before arrival or push-back) and tactical conflicts (conflicts between taxiing aircraft caused by constraint violation).

Taxi routes including push-back and line-up are created in advance and allocated to the aircraft before it starts the taxi process. The necessary taxi, push-back, and crossing commands are created automatically from the generated route (list of waypoints) and are presented to the controllers.

The main idea when developing TRACC was to work as close as possible to the standard taxi processes. This includes the assignment of a standard taxi route with standard speeds as start route and automatic identification and solving of push-back problems (pushing back in the route of an already taxiing aircraft). For this, a node-link system representing runways, positions, and taxiways underlie the airport. Nodes are used at taxiway intersections, stop-bars, line-up positions, parking positions and all other points of interest, whilst the links represent the taxiways and are combined with a reference speed as reference value for the optimization. Nevertheless, the used speeds of a route are not limited to the reference speeds, but the minimum speed for all links is five knots. Holding times can only take place at nodes.

B. Principle of smallest modification

In comparison to other approaches [2], [7] the focus of TRACC is on the single aircraft and the usage of the real airport structure for a direct adoption of the created routes. No global optimum for all flights is created, because it must be expected, that several aircraft do not comply with the allocated speed profile and need updated or new routes from time to time also controller may change the route for a selected aircraft without interfering with the other. An important reason for the usage of a single aircraft approach is the complexity of the solution space for this problem. The objective of TRACC is not to find the optimal (global) solution for a group of aircraft, but a good and reliable (local) solution for a single aircraft which complies with the standard rules used for taxi routing and takes the other taxiing aircraft into account. These rules include minimizing the number of speed changes and stops and maintain a speed close to the reference speed as often as applicable under the given circumstances. Calculating a new global optimum every time an aircraft violates the taxi constraints could lead to a higher number of re-routings for aircraft with correct taxi behavior which should be avoided. The optimization is carried out separately for each aircraft depending on the position in the optimization sequence.

TRACC implements the "principle of smallest modification" where the routes should be as close as possible to a set of standard routes and later changes of speeds or waypoints should occur as rarely as possible. Furthermore, only the aircraft which has violated the given taxi constraints should be penalized by a new, perhaps less appropriate route.

Only the planned route (e.g. "taxi via taxiway a, b, c to position A1...") and the advisories for the next two waypoints are shown to the controllers (see Figure 2). Actual speed commands and clearances are published just in time (1 minute before activation). This way it is possible to avoid sending redundant, confusing, or conflicting advisories.

C. Optimization Sequence

The optimization sequence list for all aircraft starts with a sequence on "First Come, First Served" order in reference to the TTOT (Target Take-off Time) and can be changed by a controller or automatically if an aircraft needs to be re-routed. The planned speed and position of every active aircraft on the airfield is known from NARSIM (NLR Air Traffic Control Research Simulator [10]) and is compared to the real position. In case of deviations a conflict test is executed and if conflicts occur with the adapted route a new route for the observed aircraft is developed. For this, the routes of all other already planned aircraft are taken into account, but are not subject to change. The most important problem is to guarantee safety under real time circumstances.

Figure 2. Controller Command Panel. For each aircraft the time in seconds until activation, aircraft-ID, command and accept and reject buttons are shown.

D. Test Environment

For the implementation a basic data set of NARSIM was used. Therefore, TRACC works on the same node-link system as the DLR real time simulator. Afterwards, data needed by TRACC concerning the runway system (exits), taxi speeds, and push-back operations was added via ADEN (Airport Data Editor for NARSIM, [6]). As test case the structure of Hamburg Airport was used together with an appropriate flight schedule including scheduled and target times, used runway and position, and aircraft type. Nevertheless, TRACC is a complete generic tool and does not depend on the selected airport. Runway operations are privileged over taxi operations, which are privileged over gate operations (Push-back, roll-through).

The optimization process for each aircraft starts depending on the position of the aircraft in the optimization list not later than 5 minutes before landing / push-back / roll-through. In case of push-backs, a check for conflicts with already moving aircraft is carried out and e.g. the push-back is delayed if necessary to solve the conflict. The following optimization process can contain two different optimization algorithms (speed and route optimization) depending on number and complexity of conflicts. After completion of the route creation process, the found technical route (list of way points) is translated into a sequence of controller commands with time stamps (advisory list) for the publishing time (see Figure 2). In accordance to the used node-link system only nodes can be used as waiting points and speed changes are calculated as a linear change between two succeeding nodes. With the activation of the aircraft the corresponding flight stripe is moved from the table of the planned flights to the table for active flights. Afterwards, the next planned position of this aircraft is calculated for each time step and can be compared to the actual position when working together with the real time simulation environments.

E. Fields of Application

TRACC is designed to fulfill several different tasks in the field of fast-time and real time simulations. As fully automatic stand-alone simulation tool it can be used for testing new taxi strategies (e.g. electric taxiing) or the possible influence of new taxiways. The same can be carried out with controllers in the loop. Furthermore, it can be used as a functional complement on the ground for projects with 4D-trajectory objectives or just as a generator of taxi commands or ground traffic including arrival runway exit selection, push-back, and line-up.

III. METHODOLOGY

A. Optimization Algorithms

TRACC has two different optimization algorithms in use, both from the field of evolutionary algorithms. This type of algorithm was selected because of the good experiences in the past when applying it to the creation of flight routes in the TMA [3] or within a first approach to taxi planning [5]. The modular design of TRACC supports an easy exchange of the optimization strategy.

The typical principles of evolutionary algorithms [4], [9] are the closeness to the biological counterpart of normal evolution. In nature, a group of individuals mix their genetic material, especially the information coded in chromosomes, to get better chances to survive in a hostile environment by a higher degree of adaptation. For an evolutionary algorithm, a population of solutions for an artificial problem is coded as sequence of parameters (chromosomes) describing the problem. Within TRACC the chromosomes consist of a sequence of succeeding waypoints (nodes) together with speed advisories.

As in nature, solutions can be mixed (so called cross-over, exchange of speed information or waypoints) or mutated (speed change or introduction of a new waypoint). To guarantee the "Survival of the fittest" an evaluation function is created which calculates an evaluation value for each solution based on how the parameter set fulfilled the given task. Currently, this function takes the number of conflicts, distance to target time, length of taxi route, number of speed changes and holdings into account but the observed parameters can be exchanged easily. For the next generation only the fittest solutions are selected and undergo the evolutionary operator's crossover and mutation again until an appropriate solution is found.

The two algorithms used for TRACC differ in the scope of modification (genetic operators) and the evaluation function which is applied to the same type of chromosomes.

The first one (TOA: Time Optimization Algorithm) works only on the speed part of the chromosomes and therefore is much faster as the other algorithm which changes the routes themselves (ROA: Route Optimization Algorithm). ROA has to be aware of the problem to maintain the usability of a route undergoing evolutionary operators. TOA is used for all aircraft as a first approach whilst ROA is used in more complex cases, where TOA was not able to create a conflict-free route or when a conflict is caused by opposite traffic and therefore the route has to be changed completely. For the optimization process for each algorithm a different predefined number of generations is carried out in automatic mode.

B. Conflict Detection

Three different types of conflict search are carried out, depending on the status of the flights. These types are:

- Conflicts between arriving / departing and taxiing aircraft.
- Conflicts between taxiing aircraft and
- Conflicts between aircraft pushing back and taxiing aircraft.

As is the rule in ATM, TRACC privileges runway operations over taxi operations, which are privileged over Push-back-operations.

1) Conflicts between arriving / departing aircraft and taxiing aircraft:

For aircraft on the runway system no conflict search with other arriving, departing, or taxiing aircraft is carried out. Instead the corresponding runway blocking times are compared to the considered runway crossing times of all other taxiing aircraft, which in case of conflicts have to wait in front of the runways until the runway can be crossed. The necessary waiting time ends when an aircraft has passed the stop-position of the aircraft or an arrival has left the runway.

2) Conflicts between taxiing aircraft:

Aircraft movements are described as time dependent movements on a vector in a 2-dimensional space. For the conflict search for taxiing aircraft all links between succeeding waypoints of the observed routes are regarded as vectors in space. Then the position p of each aircraft can be described by the following formula:

$$p = w_i + \lambda_i \cdot (v_i + \Delta v_i \cdot t) \cdot t \cdot (w_{(i+1)} - w_i) \qquad (1)$$

with w_i = waypoint i, v_i = Speed $[m/s]$ at waypoint i, Δv_i = Speed change per time unit $[m/s^2]$ at waypoint i , t = time unit $[s]$ and λ = the reciprocal of the length of the link (directional vector) $[1/m]$.

With this formula it is possible to calculate the minimum distance between two straight lines by solving a set of equations. Curves are approximated by a sequence of lines. The boundary points where the aircraft leaves the link have to be taken into account.

Furthermore, because the calculation of the minimum distance for all combinations of route links between an observed aircraft and all other planned aircraft is very time-consuming, a distinction of cases is done in advance. Special cases are e.g. no time overlapping, one or both aircraft wait. Figure 3 shows two aircraft on their corresponding vectors with the used part of the link between succeeding waypoints colored in green and blue. The minimum distance between both aircraft on this link combination will take place at t_{min2}, the last position of the blue aircraft on this link.

A conflict between an observed aircraft and another aircraft is not counted as one conflict but the number of link combinations of both routes where conflicts occur are calculated. This approach gives the algorithms the possibility to change stepwise to a conflict free route by reducing the number of conflicting link combinations step by step.

3) Conflicts between aircraft pushing back and taxiing aircraft:

Taking into account the priority of taxiing over pushing aircraft for each departure which tries to leave its position, the same type of conflict search algorithm is used to calculate conflicts in the push-back phase. In case of a conflict, the pushing aircraft is delayed as long as necessary to avoid blocking the taxiway for all other aircraft. For test cases,

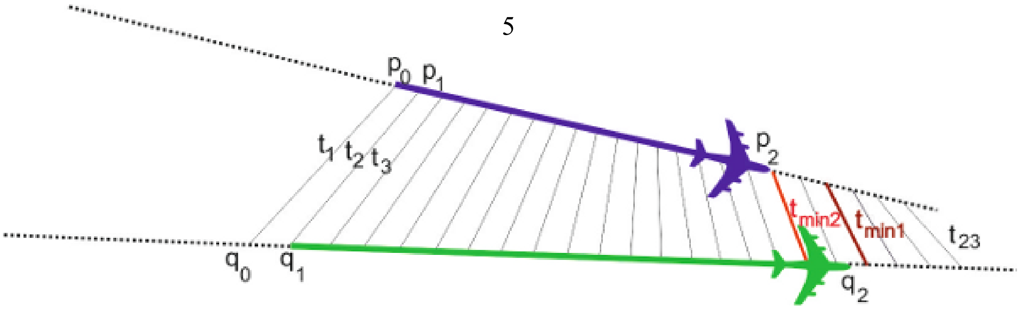

Figure 3. Time dependent minimum distance between two aircraft moving on vectors in space.

TRACC possesses a second strategy where the push-backs start normally and the already moving aircraft are re-routed using TOA and ROA.

C. *Safe Node Concepts*

One of the most important tasks when managing taxy operations is to solve suddenly evolving conflicts. There are several situations where one has to be aware of them. An example is, when departures reach the runway earlier than expected, because this leads to changed runway blocking times and has therefore side effects on other aircraft which try to cross this runway. Furthermore, changed routes for other aircraft can lead to new conflicts. Another potential conflict situation arises if an aircraft doesn't follow the instructions and needs a new route whilst already taxiing. Therefore; two questions are evolving:

1. How much time do I have to solve the problem?
2. Where should/can I start my optimization process?

Each optimization algorithm needs a special amount of time for the optimization task. So a value must be found which guarantees an appropriate solution. In case of TRACC, a value of 30 seconds is selected for unplanned situations. If the conflict occurs within the next 30 seconds calculated from actual time, an emergency stop is conducted and the aircraft has to wait at a node before the conflict occurs until the other aircraft has passed by. This additional stop can lead to conflicts with other aircraft, where again a reaction is necessary.

Naturally, as stop node the waypoint before the position of the first conflict is calculated, but unfortunately, there are situations where this is not enough. If two aircraft taxi in opposite direction, the last node where they share the taxiway and the minimum separation is maintained has to be identified. The preceding node is then called "safe node" for the observed aircraft. And this "safe node" is the last possible starting point of a new optimization process because it can be guaranteed that no conflict with the other aircraft takes place. As a start node for the optimization the first waypoint before the safe node is selected, which is more than 30 seconds away from the actual position.

The safe node is calculated not only in conflict situations but for all chromosomes of the population within the optimization process. It is used for a problem dependent creation of holding points in more complex traffic situations, where the aircraft has to wait to avoid conflicts. When the safe node is identified the part of the old route before the safe node is retained and a new route is created from the safe node to the destination whilst the aircraft is moving on the remaining fixed part of the route.

IV. RESULTS

Because this tool is subject to ongoing research there is no comparison between real and simulation data available so far. Nevertheless, first test runs have been carried out to get an impression of the quality of the optimization results for both used Algorithms. As reference data for the traffic of a selected flight plan the values for conflicts, route length, target time, and delays without optimization process but based on standard routes are calculated and compared to the results when using both optimization algorithms. As standard routes the shortest connections between start- and destination were used. These routes use different standard speeds for taxi-area, apron, runway exits, and positions and the only stops within these routes are situations where aircraft have to wait to cross an active runway.

The used flight plan consists of 33 flights over a period of one hour with five minutes start-up phase for the simulation. It includes several types of routing problems like "Crossing of runways when another aircraft starts its take-off on this runway", "Push-back conflicts", and "Taxi conflicts (passing / opposite traffic)". Five flights have conflicts when no optimization is used and three flights undergo a revision of the push-back time because of conflicts. Crossing of runways does not lead to conflicts because they are solved before the optimization process. For analyzing the results it is obvious, that the possible results of each single optimization task for an aircraft depend on the routes created for the previous flights. The optimization is carried out with a population size of 40 chromosomes (solutions) and a number of 500 populations for TOA and ROA. Nevertheless, the goal for this simulation runs was not to find a global solution for all aircraft but to prove the ability of TRACC to create conflict free, short, and punctual routes which can be easily followed by pilots.

TABLE I shows the conflict data of the used flight plan with five conflict situations. Each problematic aircraft has only conflicts with one other aircraft, but for a higher number of links. This results in a lack of separation of 282.7 meters for all link combinations.

TABLE II shows the differences between TOA and ROA. Whilst TOA has the same route length and only the speeds are subject to change the route length for ROA increases a little bit when avoiding conflicts, but in return the punctuality increases. Nevertheless both algorithms create routes which are more accurate than using the standard route.

TABLE III looks into the taxi times in more detail. The average taxi times show combined values for arrivals and departures and the taxi times are close together for all algorithms. The resulting value for the difference to the standard route is divided into arrival and departure taxi time differences and is shown in the last two columns. It can be seen that the highest difference takes place for the arrivals, for which the routes are longer and which have to cross the departure runway 28 after landing on runway 32. The TRACC algorithms are able to change the speeds in such a way, that the runway crossing delay (see TABLE IV) is shifted partly to the taxi delay and the number of speed changes is considerably reduced in comparison to the standard route. Furthermore, the results for the ROA algorithm are closer to the target time than TOA, but this is bought by an increase for the number of speed changes. An important result of these comparative simulation runs is that the TRACC algorithms are able to create short, conflict free, and punctual routes, which are better than the set of standard routes with standard speeds used for comparison.

TABLE I. DATA FOR THE CONFLICTS OF THE USED FLIGHT PLAN.

	Avg. number of conflicting link combinations	Avg. number of conflicting aircraft	Avg. summarized lack of separation [m]
Standard Route	7.16	1	-282.7

TABLE II. DIFFERENCES IN MEETING THE TARGET TIME AND THE ROUTE LENGTH WHEN USING TOA AND ROA IN COMPARISON TO THE STANDARD ROUTE.

	Difference to target time [s]		Taxi route length [m]		
	Standard Route	**TRACC**	**Standard Route**	**TRACC**	**Differ-ence**
TOA	10.4	7.9	2103.3	2103.3	0
ROA	10.5	6.9	2103.3	2104.6	-1.3

TABLE III. AVERAGE TAXI TIMES WHEN USING TOA AND ROA.

	Average taxi times [s]			Average taxi times difference [s]	
	Standard Route	**TRACC**	**Differ-ence**	**Arrival**	**Depart-ure**
TOA	212.6	210.0	2.6	4.3	0.4
ROA	212.8	209.1	3.7	6.5	-0.2

TABLE IV. DIFFERENCES BETWEEN THE RESULTS WHEN USING THE STANDARD ROUTE IN COMPARISON TO THE ALGORITHMS OF TRACC (STANDARD ROUTE – TRACC).

	Difference between standard route and TRACC (standard – TRACC)			
	Stops	**Taxi Delay [s]**	**Crossing Delay [s]**	**Speed Changes**
TOA	0.05	-0.2	2.0	1.8
ROA	-0.03	-5.8	6.7	0.9

The results for ROA and TOA show significant differences which reflect the different approaches. The degree of freedom for route creation is much higher for ROA caused by the possibility to change the route in addition to the speeds as in case of TOA. Because for both algorithms the same simulation parameters were used (number of generations, chromosomes), it was much harder for ROA to create good results, but they were comparable (pareto-optimal) to the results of TOA.

V. OPERATIONAL CONTEXT

As mentioned before, TRACC is part of the DLR project flexiGuide, where it will be connected to AMAN and DMAN. This project has a timeframe until the end of the year 2013. The development of TRACC should be seen as a research project which will create the basis for further investigation and developments in this area. Within the SESAR context [11] it is established in the key feature “Airport Integration and Throughput” from “Deployment Baseline” to the 4D-concept of “Step 2”. Nevertheless, it will consider aspects of automation support tools for the airport as well. As important prerequisite for 4D-taxiing, a better ability of the aircraft to maintain a prescribed taxi-speed is identified, e.g. by electric taxi.

VI. FUTURE WORK

The most important step for the development of TRACC will be the implementation of a control system which compares planned and actual positions of taxiing aircraft and decides how to cope with identified problems. The decision depends on the possible detection of conflicts as a result of constraint violations and leads to the creation of a new route for the observed aircraft. Commonly, an algorithm has to be created which is able to cope with unexpected situations like usage of wrong speeds, wrong taxiway, or wrong exit or a non-cooperative aircraft.

Furthermore, TRACC will become fully integrated inside the DLR real time simulation environment where it will work as stand-alone SMAN or in co-operation with other DLR tools like AMAN and DMAN. Besides the possibility to test diverse procedures for ground movements or estimate the impact of new pavements for taxiways, parking positions, or runway exits, TRACC provides a reliable management of ground movements that allows a better testing of the capabilities of DMAN and AMAN. Benefits created by those tools will not be influenced by avoidable ground conflicts and delay.

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