TACTICAL DEPARTURE MANAGEMENT WITH THE EUROCONTROL / DLR DMAN

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Abstract

The paper deals with tactical departure management when using the Eurocontrol/DLR DMAN. It describes characteristics of that operational prototype reflected on objectives and requirements of the DMAN development. The description comprises explanations of the general approach and the embedded algorithms with respect to the used operational- and constraint models, the planning, and timing. The paper also outlines the DMAN architecture. Particular consideration is given to first results from real-time simulation trials RTS1 with DMAN which took place in the framework of the European Gate-to-Gate project at Malmo in 2004. In this context an explanation of the operational concept for departure management with DMAN is given. The paper not only shows and comments first, partly surprising results, but also gives some statements about lessons learnt.

1 Introduction

In the early 90's it was commonly agreed upon among experts that large European airports would become the bottlenecks of the whole ATM system, if in the light of the forecast increase of air transport the operation of air traffic at airports would not be considerably improved This assumption has been verified in the meantime by reality. Arrival and departure management were identified as two key areas which needed to be improved by introducing decision support tools for ATC controllers at airports. Departure management became an important topic of the ATM research in Europe for more than a decade.

Eurocontrol has been fostering such research activities by launching several studies concerning departure management [1-5].

DLR elaborated a concept for tactical departure management and developed functional and operational prototypes [6-10]. One of the first prototypes, named DARTS, was particularly designed for the airport of Zurich. It was extensively tested and evaluated in DLR's tower simulator with Zurich controllers in the loop. The specification of this prototype was then taken as the basis for the industrial development of the first operational departure management tool, which was put in operation at Zurich airport in 2003 [11]. ROPS (Runway Operations Planning System), a more generic variant of this prototype, was developed within the DLR project TARMAC (Taxi and Ramp Management and Control) in 2002.

In 2003 Eurocontrol commissioned DLR to develop an operational prototype of a Departure Manager which should cover a wide range of application areas in respect of both the set of airports for which the DMAN can be configured and the ways the DMAN is operated, i.e. as a stand-alone demonstrator or a tool embedded in a simulated or real ATC/airport environment.

2 Objectives and Requirements of DMAN Development

Although ATM-research is dealing with the development of departure planning systems since the early 90's, basic questions regarding the efficiency of a certain approach, the concept of use and the potential benefits are not sufficiently clarified. There exist neither analytical nor fast time simulation methods to answer these questions seriously. This is due to both the complexity of the planning algorithm itself and the complexity of human machine interactions, or more precisely: the human-in-the-loop-problem.

In the light of these constraints the main objective of the DMAN project was to develop an operational prototype that can be easily adapted to different airports and different purposes. So the DMAN should be applicable for demonstration purposes as a stand-alone system. Moreover, the DMAN should be usable in simulated or real tower ATC environments to enable the verification of the concept of use, to investigate the dynamics of the management process and to study different assessment criteria. A third objective was to create a test and development tool for advanced research into AMAN-DMAN coordination (section 5). And after all, the prototype itself should also provide a solid basis for industrial development of an operational departure management system.

In order to meet all these objectives, a set of requirements could be clearly identified [5], namely:

- The DMAN algorithms must incorporate data-based models for operations and scheduling constraints (adaptability to different airports).
- The prototype must comprise a stochastic event-simulation (stand-alone demonstrator and development tool).
- The DMAN needs a modular architecture, which enables different system configurations. Thus the DMAN should support a varying number of controller working positions (CWP). Furthermore the DMAN planning core should be compatible to already existing or separately developed human machine interfaces (HMI), which are used for guidance and control (section 4).
- Finally an interface module (gateway) must exist to embed the DMAN in a simulated or real ATC environment.

3 Characteristics

3.1 General Approach

The DMAN is a tactical planning tool supporting the departure scheduling of apron and tower controllers. The DMAN optimises the planned departure takeoff time(s) by taking into account several evaluation functions for different aspects of departure management, e.g. capacity and efficiency. At present the tool can handle up to three departure runways, which may mutually interfere with respect to runway operations (landings and/or takeoffs). The runways may be treated in mixed mode operations. From the optimal target departure times the system derives recommendations for timely (engine) start-up and/or push-back clearances.

The DMAN permanently adapts to the progress of all departure procedures, i.e. any clearance given by a controller causes a change of the internal state model and triggers re-planning. With the help of a timer function the tool also recurrently reacts to missing clearances by a recalculation of the earliest (possible) takeoff time. However, to avoid misleading the reader, it should be emphasized, that only in rare cases such planning events may cause a major change of the whole departure sequence.

Therefore, the DMAN should not be regarded as a pure advisory tool, which for a certain period would allow the controllers to ignore the timing. It is a control system, which has to be operated in closed loop.

Although, the tool can gain a much better "situation awareness" by using surveillance data (section 5), the availability of any surveillance system is no prerequisite for the introduction of a planning tool supported departure management (section 4). In fact, the DMAN can be introduced without any major change of the ATM environment.

3.2 Algorithms

3.2.1 Operational- and Constraint Models

Operational departure procedures[1] seem to be similar for all departures at all airports, at first glance. However considering these procedures in more detail, it becomes obvious, that depending on various conditions, the set of necessary clearances and the responsibilities for controlling and issuing clearances may differ. For instance, for a certain subset of parking positions, no push-back is required as the aircraft park nose-in-nose-out. Since, as already mentioned, given clearances cause a change of the aircraft state, e.g. an aircraft "is taxiing", "is pushing-back", "is ready for takeoff" etc. the DMAN needs specific models, which can cope with all possible variations of departure procedures. Moreover, all information concerning the structure and the areas of validity of these models must be expressible in form of external data sets.

A similar situation exists if one considers the constraints of a departure sequence (a sequence of departure takeoff times). Although ICAO regulations (standards) exist for minimum wake vortex separations, there are additional constraints a DMAN must take into account when calculating an optimal departure sequence. One group of such constraints, but not the only one, is caused by defined minimum separations[2] (in terms of Nautical Miles) between two consecutive aircraft along the Standard Instrument Departure Routes (SID).

3.2.1.1 Operational Models

Operational Models are used for two purposes, namely to control the human machine interactions and to derive planning constraints. On the basis of the selected operational model the next clearance for a certain departure, which needs be given to start the

[1] With the term "departure procedure" all actions (of a pilot) shall be denoted which need a clearance by a controller.

[2] Sometimes denoted as Miles in Trail or Minutes in Trail Separations

following operational step, is determined and displayed on the dedicated electronic flight strip(s). As the operational model also indicates the next responsible controller working position (CWP), DMAN uses the operational models to control the movement of the flight strips between different CWPs. For instance, a flight strip may move from Clearance Delivery (CLD) via Ground West (GND-W) and Ground North (GND-N) to Runway Control (RWY), whilst another one may move from CLD via GND-N to RWY, depending on the parking position and the consequential taxi path through different areas of responsibility.

The operational models provide information about the expected overall time for all remaining operational steps, which enables a calculation of a planning constraint, the so called earliest (possible) takeoff time (ETOT). The calculation is triggered by the event of a given (controller input) or a missing clearance, usually caused by a delay of the current operational step. The planning process (section 3.3.2.2) considers ETOT as hard constraints, i.e. in no case a planned takeoff time will be earlier than the corresponding ETOT of that flight.

The following example may illustrate the "modelling language" of such rules. **IF** *stand* belongs to a (user-defined) group of stands named STANDS1 **AND** *aircraft type* does **NOT** belong to a (user-defined) group of types named LARGE1 **THEN** model name is MODEL1. The terms *stand* and *aircraft type* are variables (according to the first order logic) for the particular flight plan- and aircraft data.

3.2.1.2 Constraint Models

The constraint models comprise three categories of constraints, namely wake vortex separations, SID separations and runway occupancy separations.

Wake vortex separations are standardised by ICAO regulations for a single runway, but are much more complex in case of mutually interfering, e.g. crossing runways. In such cases, not only the weight categories of the aircraft have to be considered but also the combination of runways used by leader and follower.

The DMAN allows modelling complex situations by a hierarchy of constraint matrices. The SID separation models are structured in a similar way. Compliance with a required distance between two consecutive departures along a common path of the two SID can be ensured by a required minimum time span between the start of the takeoff runs of these flights. Of course, the necessary time span depends on both the speed (classes) of these flights and the geometry, and especially the length, of the common part of the SID of the leader and the SID of the follower. These coherences obviously require a four-dimensional matrix of times, but can also be expressed in a hierarchy of two two-dimensional matrices. At the top-layered SID matrix only the SID of leader and follower are used as indices. However, the elements of this SID-matrix are not times, but references to second layered matrices. The elements of these matrices, indexed by the speed classes of leader and follower, contain the values for the required time spans.

The third category considers necessary separations between arrivals and departures[1], since a landing or a takeoff is blocking the runway for other operations. If an airport uses crossing runways the models must distinguish whether the successive operations take place on the same or on different runways. This is again done by a table hierarchy as described above.

3.2.2 Planning

3.2.2.1 Algorithm

The planning of the departure takeoff times is put down to an optimisation task with multiple, mutually contradictive objective functions, which can be formally expressed by

$$\mathbf{t}^* = \arg\min_{\mathbf{t}\in T(C)} \{Q(\mathbf{a},\mathbf{q}(\mathbf{b},\mathbf{t}))\} \tag{1}$$

where:

t* is the vector containing the optimal takeoff times,

$$Q(\mathbf{a},\mathbf{q}(\mathbf{b},\mathbf{t})) = \mathbf{a}^T\mathbf{q}(\mathbf{b},\mathbf{t})$$

is the scalar optimisation function for the vector optimisation problem,

$$\mathbf{a}^T = [a_1 \quad a_2 \quad \ldots \quad a_p], \quad a_i \geq 0\ \forall i, \quad \|\mathbf{a}\| > 0$$

is a weight vector for the p objective functions

$$\mathbf{q}(\mathbf{b},\mathbf{t}) = [q_1(\mathbf{b},\mathbf{t}) \quad q_2(\mathbf{b},\mathbf{t}) \quad \ldots \quad q_p(\mathbf{b},\mathbf{t})]^T$$

is the vector of objective functions, and

$$q_i(\mathbf{b},\mathbf{t}) = \sum_{j\in D} b_j q_i(t_j)$$

$$\mathbf{b} = [b_1 \quad b_2 \quad \ldots], \quad b_j > 0\ \forall j \in D$$

is a particular objective function, which sums up the portions resulting from the evaluation of the

[1] Here the models must distinguish between the cases A-D, D-D, and D-A, where for example A-D symbolises that a departure follows an arrival (takeoff after landing).

particular takeoff-time t_j of a departure j from the departure set D.

As the system uses only monotonous objective functions q with respect to t_j, the optimisation of all takeoff times does not need to be done by a search in the solution space $T(C)$[1], but can be performed more easily by investigating all possible, minimum staggered takeoff sequences. So planning is now reduced to a tree-search problem.

However, since this a NP-hard problem, for larger sets of departures a more sophisticated search algorithm is required to solve the problem in due time. The planner uses an A*-algorithm, which on average reduces the calculation time by about 40 percent. Furthermore, some heuristics are applied, which however cannot guarantee to find the global optimum solution. In particular, a so-called take-select strategy was implemented, which optimises the takeoff sequences for a subset of *D* several times, by sliding a "selection-window" over a pre-sorted sequence [3].

3.2.2.2 Objective Functions

The departure manager actually takes into account four objective functions $\mathbf{q}(\mathbf{b},\mathbf{t})$ when planning the departure sequence. These functions are measures for

- throughput (capacity)
- taxi-out delay
- CFMU slot compliance
- planning stability

All objective functions are defined as monotonous functions penalising too less throughput, too much taxi-out delay, violation of CFMU-slots, and finally, variations of the solution in comparison to the previous solution. As there is naturally no strong match between the optimisation aspects and corresponding mathematical measurement functions, the design of such functions needs some appreciation for adequacy. Without going into detailed explanations the measurement function $q_1(\mathbf{b},\mathbf{t})$ for throughput may illustrate this.

$$q_1(\mathbf{b},\mathbf{t}) = \sum_{j \in D} b_j \left(t_j - t_0\right)^p, \quad p \geq 1$$

where t_0 denotes the actual time, and p is a parameter. The freedom in defining structure and parameters of the objective functions leads on the one hand to a great flexibility of the algorithm but requires on the other hand a skilful tuning of the large parameter set, whereas the latter one can be done best in a simulation environment.

3.2.2.3 Hard- and Soft Constraints

DMAN distinguishes between hard and soft constraints. By definition hard constraints must not be violated by any solution whilst a soft constraint may be violated, but the greater the violation the worse the evaluation of the solution.

All separation constraints explained in section 3.2.1.2, which ensure safe operations, belong to the group of hard constraints. Additionally, the earliest takeoff times (ETOT) of the departures, which are calculated with the help of the operational models (section 3.2.1.1), are treated as hard constraints, even there is a certain probability that the current operational step will be finished earlier than expected (modelled). However, whenever a clearance is given earlier (or later), which triggers the next operational step, a re-calculation of the ETOT is induced. Finally, so called sequence constraints, stipulating that a certain departure must be number one in the sequence, another one has to be number two etc., are considered as hard constraints, independent of whether these constraints were generated manually by a controller input or automatically.

The planning algorithm handles CFMU slots as soft constraints, although slot compliance is obligatory for ATC (see previous section). This must be done as under certain conditions there may exist no feasible solution without a slot violation. Whenever DMAN plans a takeoff time that violates a CFMU slot, the operational treatment shall not be to clear the flight for takeoff at the planned time, but to trigger some actions on ATC or airline side in advance, which may overcome the conflicting situation, e.g. slot re-negotiation or cancellation etc.

3.2.2.4 Planning Strategies

The option of having different planning strategies results directly from the chosen approach how to deal with the vector optimisation task (equation 1). The use of a scalar substitution function, which is a weighted sum of the single objective functions for different aspects of a proper departure management, offers the possibility to change the balance point of optimisation just by changing the weight vector **a**. In fact, the system allows the user to pre-define an arbitrary number of strategies, each of them characterized by a different meaningful abbreviation and weight vector **a**. For instance, the strategy "CAP+" with a weight vector $\mathbf{a}=[1\ 0\ 0\ 0]^T$ leads to an optimum solution that takes only throughput (capacity) into account, whereas another strategy "CAP" with $\mathbf{a}=[0.4\ 0.2\ 0.2\ 0.2]^T$ prefers capacity but

[1] The solution space *T* is subjected to the set of constraints *C* explained in section 3.2.1.2.

considers also the other optimisation aspects. The runway controller can change the strategy at any time to meet the particular needs of the actual (traffic) situation.

3.2.3 Timing

The term timing addresses the calculation of times which influence the planned schedule and/or the recommended times for the next clearances in the context of DMAN. Without going into details it can be stated that there are three subtasks of calculations for

- the Calculated Takeoff Time (CTOT)
- the Earliest Takeoff Time (ETOT)
- and the Managed Time for Next Operation (MNXT[1]).

For slotted flights the CTOT is five minutes later than the beginning of the CFMU slot by definition. For non-slotted flights the calculation is based on the Estimated Off Block Time (EOBT[2]) and the minimal required time for the operations in total to reach the state "ready for takeoff" $\Delta_{M(0)}$, which is derived from the operational model by a shortest path analysis.

$$t_{CTOT} = t_{ETOT} + \Delta_{M(0)} \qquad (2)$$

The planning algorithm forms a natural departure sequence on basis of the sorted set of CTOTs, which in turn is the initial sequence of the sliding window technique, described in section 3.2.2.1). The position in the natural departure sequence may constrain the position of this flight in the calculated takeoff schedule depending also on the parameter of the take-select strategy. If for example, for a certain flight the position is 9 in the natural departure sequence, the take-parameter is 7 and the select parameter is 1 then the minimum position in the takeoff schedule is 3 as there are two iterations of optimum planning for departure subsets which do not contain this flight.

The calculation of the ETOT is identically with the CTOT calculation as long as there was no clearance given (except en-route clearance) and the actual time does not exceed the EOBT. However, the timing algorithm updates the ETOT whenever a clearance has been given or whenever a clearance is missing. In the first case the ETOT calculation is

$$t_{ETOT} = t_{LAST(k)} + \Delta_{M(k)} \qquad (3)$$

where

$t_{LAST(k)}$

is the time of controller input of clearance k, and

$\Delta_{M(k)}$

is minimum required time in total for the remaining operational steps. When a clearance is missing the ETOT is delayed according to the delay of the current operational step. As the ETOT is a hard constraint for the planning for every flight $t_{MTOT} \geq t_{ETOT}$ holds.

The MNXT, that recommends an appropriate time for the start of the next operational step, is derived from the planned (managed) takeoff time MNXT.

$$t_{MNXT} = t_{MTOT} - (1+\varepsilon)\Delta_{M(k+1)}, \quad \varepsilon > 0 \qquad (4)$$

The expansion of the modelled time $\Delta_{(k+1)}$ by a factor of $(1+\varepsilon)$ yields a time buffer to compensate for unexpected additional delays.

3.3 Architecture and Modules

3.3.1 Architecture

The DMAN consists of a set of modules, which can be distributed arbitrarily over a network of computers (fig. 1).

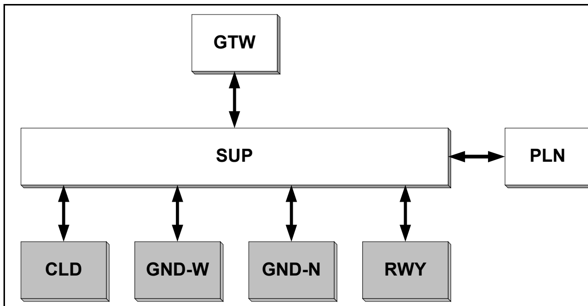


Figure 1: DMAN Architecture

This allows configuring the system according to the specific needs and constraints of a particular application (stand-alone demonstration, simulation, etc.), the number of controller working positions to be supported, the layout of the control room, or the required computer power. Two modules, namely the Supervisor (SUP, section 3.3.2.1) and the Planner (PLN, section 3.3.2.2), can be regarded as core system modules, as they must be part of any DMAN configuration. The HMIs for the CWPs "Clearance Delivery" (CLD), "Apron/Ground" (GND) and "Runway Control" (RWY) form a group of modules with similar properties and functions (section 3.3.2.3). Finally a Gateway (GTW) is needed when the DMAN is used in a simulated or real environment and not as stand-alone system (section 3.3.2.4).

[1] The abbreviations CTOT, ETOT, MNXT are used as indices within equations.
[2] This time is also termed Estimated Ready Time (ERT) by Eurocontrol

3.3.2 Modules

3.3.2.1 Supervisor (SUP)

The supervisor (SUP) is the central module of DMAN providing the data management as well as event and message handling. The centralised data management ensures that all modules have the same and consistent information about flight plans, aircraft data, system parameters and stored “knowledge” (e.g. a data base containing aircraft data, parking positions, SIDs, etc.). The supervisor also controls the distribution of dynamic information resulting from a controller input of a certain CWP. For example, when CLD enters an en-route clearance for a certain flight, which will be controlled next by GND-W (“For start-up and push-back contact tower on frequency ...(GND-W)”), this will immediately be displayed on GND-W and RWY, but not on GND-N.

Using the operational models, the supervisor controls not only the movement of electronic flight strips among the different CWPs according to the actual and future responsibility of control, but calculates also the ETOT as one important hard constraint of takeoff-time planning. In return, on basis of the planned takeoff times the supervisor uses the operational models to calculate for all departures the appropriate points of time for issuing the next clearance. These points of time, rounded to the next full minute, are converted into time flags indicating the remaining time for issuing the clearance and counting down to zero.

When DMAN runs as stand-alone demonstrator the supervisor allows an operator to start, to stop or to re-start a simulation run, to switch between real-time and fast-time simulation, to define break points and many other useful things concerning simulation control. It should be highlighted, that in case of a stand-alone demonstration, the supervisor deals not only with traffic scenario files defining the frame of a simulation run, but also with data-based simulation models. These models are used to simulate randomly the duration of operational steps corresponding to approximated (on the basis of measurements) or assumed (on the basis of knowledge) distributions of disturbances. For that reason, DMAN as a stand-alone system is not only a demonstrator but also a development and evaluation tool which enables parameter tuning and/or assessment of benefits.

After starting DMAN, the supervisor runs through an initialisation phase, which allows the operator to configure DMAN for a certain airport, runway configuration and system behaviour by selecting corresponding data files for the different models, data bases and system parameters.

3.3.2.2 Planner (PLN)

The planner (PLN) is the most demanding module with regard to CPU power, as it is continuously optimising the departure takeoff schedule (section 3.2.2.1) according to the actual situation. In addition to the planning task itself, the planner manages a large set of complex data, like aircraft separation tables, and search tree information, which is exclusively used for planning purposes.

3.3.2.3 HMIs for Controller Working Positions (CLD, GND, RWY)

The DMAN is able to support the following CWPs:

- one Clearance Delivery position issuing en-route clearances (ENR)
- one or more positions for Apron / Ground issuing (engine) start-up (SU) , push-back (PB) and taxi clearances (TX)
- one Runway Control position for Line-Up and Take-off clearances[1].

In order to input a given (and confirmed) clearance the controller has to click on a certain field of the electronic flight strip (fig. 2). The colour of strips indicates whether

- the flight is controlled by this CWP or is controlled by another one, but announced to be handed over in future for control (completely or partly coloured)
- the flight is selected for user interactions (clearances or manual change of flight plan or aircraft type data)

Figure 2: A departure flight strip on a ground CWP.

The strip carries the following information: departure sequence number (2); call-sign (SKX6011); aircraft type (E145), stand (59C, highlighted in white colour because it has been changed by this CWP); runway (01L);

The flight strips are arranged in tables which allow ascending and descending sorting of all columns.

The HMIs provide additional information for each flight with respect to detailed flight plan data, the history of given clearances, and controller messages or notes attached to a particular flight.

[1] Clearances might also be given as combined clearances, e.g. a combined start-up and push-back or a combined line-up and take-off clearance. However it should be emphasised again, that no module has knowledge about the meaning of the clearances, so that depending on the content of the operational models, other or additional clearances (e.g. for de-icing) could be given.

Describing the entire HMI functionality, would exceed the frame of this paper.

3.3.2.4 Gateway (GTW)

The gateway (GTW) serves as a translator between the external and the internal communication mechanisms, like TCP-IP, CORBA event channel, etc. Internally, DMAN uses a string based communication between the modules based on PVM. As there are almost uncountable variations of external communication principles, the gateway needs to be adapted to a particular environment by software re-coding.

3.3.3 Configurations

As mentioned before, the DMAN can be used as a stand-alone demonstrator system or can be embedded in a simulated or real tower ATC environment. In respect of configuration of the modules this means, that only for the latter case a gateway is needed. It has also already been explained, that both the number and the type of HMI modules may vary depending on which CWP should be supported. For example, in the real time simulation trials (RTS1) of the Gate-to-Gate (G2G)-Project, no CLD position was involved (section 4).

Another beneficial side effect of the modularisation is that DMAN core can be operated by external HMIs too. This is important when controllers already use traffic situation displays (TSD) for guidance and control. Then it must be aimed that every CWP has only one, but integrated traffic situation display, by which the user can interact with DMAN. The external HMIs may communicate with the supervisor through the gateway or, provided that they have an appropriate communication interface, directly with the supervisor.

4 First Results from Real-Time Simulation Trials

The DMAN was operationally tested in the course of the Gate to Gate (G2G) Project at LFV's Air Traffic Control Academy at Malmo (SATSA) from 15th to 18th of December 2004. This test phase, also called RTS1[1], was mainly dedicated to the test and assessment of an operational concept of tool supported departure management. Besides LFV, which was the leading and responsible organisation for the whole RTS1 and which was also providing the simulation facility SMART, the other technically involved parties were Eurocontrol/DLR providing the DMAN core (section 3.3.1) and Aerotech Telub (ATT) providing the traffic situation displays named i-acs [12]. Controllers came from Stockholm Arlanda Airport and pseudo-pilots from SATSA (both LFV).

4.1 Simulated Scenario

The simulated Airport, Stockholm Arlanda (ESSA), was considered using only two runways: 19R, exclusively for departures and runway 26, exclusively for arrivals (fig. 3).

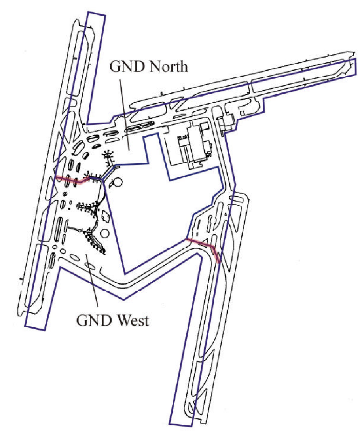


Figure 3: Arlanda airport layout and areas of responsibility of GND-W and GND-N.

This configuration was controlled by three CWPs, two ground positions controlling the western or northern part (GND-W, GND-N) of the airport and one runway position (RWY) responsible for both: departing traffic from 19R and arriving traffic from runway 26. A clearance delivery position was not involved for purpose of simplification.

The traffic scenario[2], created by LFV, was composed of 50 departures and 40 arrivals in a realistic traffic mix in terms of weight classes and used departure routes (SIDs). It has not been proven, but it can roughly be assessed to be close to or even slightly higher than the practical capacity limit.

The tests were performed under the assumption that there exists some CDM functionality, broadcasting the time schedule, so that pilots were requesting (engine) start-up according to managed[3] off-block times.

The tests were organised as a comparison of two runs with the same scenario. One baseline run without DMAN, followed by a run with DMAN. A

[1] Real Time Simulation Trials 1

[2] There was also an other scenario with the same set of departures, but less arrivals (a subset), which is not considered in this paper.

[3] The terms "managed" and "target" are used as synonyms for "planned".

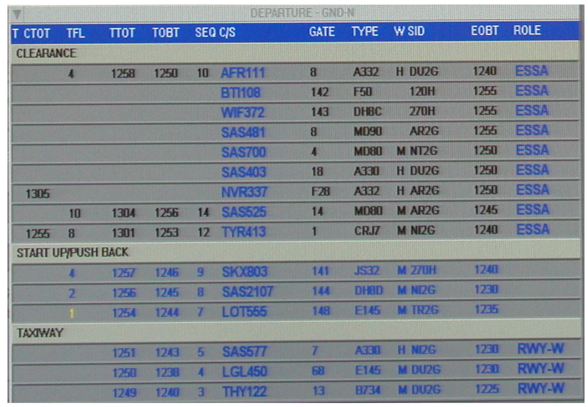
simulation run lasted about one hour, and was usually aborted when all departures had lined-up in a queue waiting for the takeoff, as the resulting takeoff times could be easily estimated without major error.

As SMART is a tower simulator without a simulated out of the window sight, guidance and control was solely based on the displayed traffic situation. The traffic situation display was also used to display planning information of DMAN and to enter given clearances, which were sent back to DMAN. It should be emphasised that DMAN did not use any surveillance information, so that it can be assumed, that similar results would have been achieved even without a surveillance system.

4.2 Operational Concept

For the explanation of the operational concept, it is fundamental to understand the particular characteristics of the considered runway configuration (runway 19R for departures, runway 26 for arrivals). For that configuration GND-N is the central CWP, as it has to send out all departures from its area in due time[1], and it has to merge this traffic with the departures coming from GND-W area. Once the traffic is merged, the resulting sequence of taxiing outbound traffic is identical with the takeoff sequence, as neither overtaking manoeuvres nor intersection takeoffs can be performed[2]. All three controllers involved, have to consider the incoming arrivals for conflict-free operations on ground.

With DMAN, the planned times for takeoff (TTOT) and off-block (TOBT[3]) and a so called time flag (TFL), were displayed in lists (fig. 4). By sorting the TTOT in ascending order a corresponding departure sequence number (SEQ) is derived and displayed both in the list and attached to the aircraft label. All SEQs are automatically counted down by one when a departure has taken off and the actual takeoff time (ATOT) of this flight is entered by the runway controller. In order to put in a clearance the controller has several easily-manageable options, e.g. by dragging-and-dropping a certain flight strip from one list section to the next one. However, many of the available DMAN features, especially the possibility to change the planning strategy, to set sequence constraints, and to change aircraft priorities were not accessible by the i-acs displays (section 3.2.2).



DEPARTURE - GND-N

T CTOT	TFL	TTOT	TOBT	SEQ	C/S	GATE	TYPE	W	SID	EOBT	ROLE
CLEARANCE											
	4	1258	1250	10	AFR111	8	A332	H	DU2G	1240	ESSA
					BTI108	142	F50		120H	1255	ESSA
					WIF372	143	DH8C		270H	1255	ESSA
					SAS481	8	MD90		AR2G	1255	ESSA
					SAS700	4	MD80	M	NT2G	1250	ESSA
					SAS403	18	A330	H	DU2G	1250	ESSA
1305					NVR337	F28	A332	H	AR2G	1250	ESSA
	10	1304	1256	14	SAS525	14	MD80	M	AR2G	1245	ESSA
1255	8	1301	1253	12	TYR413	1	CRJ7	M	NI2G	1240	ESSA
START UP/PUSH BACK											
	4	1257	1246	9	SKX803	141	JS32	M	270H	1240	
	2	1256	1245	8	SAS2107	144	DH8D	M	NI2G	1230	
	1	1254	1244	7	LOT555	148	E145	M	TR2G	1235	
TAXIWAY											
		1251	1243	5	SAS577	7	A330	H	NI2G	1230	RWY-W
		1250	1238	4	LGL450	68	E145	M	DU2G	1230	RWY-W
		1249	1240	3	THY122	13	B734	M	DU2G	1225	RWY-W

Figure 4: List of flight strips with planning information (TFL, TTOT, TOBT, SEQ)

A very important question, which was discussed intensively and partly controversial among all participants was, how the controller should use the DMAN planning information, especially the time schedule which is reflected in the TFL values. This "philosophy of use" spans a range roughly speaking from "use the DMAN strictly" to "use the DMAN as an advisory tool". Of course, this question can hardly be answered by definition, but better by experience. DLR gave the following recommendations:

General recommendation: As long as a controller has no good reason for deviating from the plan he/she should follow the DMAN timing and sequencing.

Particular recommendations for the different CWPs:

GND-W: Should follow the time schedule very strictly (whenever possible) as otherwise he/she may complicate the traffic merging task which is to be solved by GND-N.

GND-N: Should rather centre on establishing the planned sequence of aircraft taxiing to runway 19R, than focus on timing. TFL information will probably help to solve the merging task smoothly without the need of issuing "hold short" commands frequently. He/she may deviate from the planned departure sequence, if the control effort for merging according to the plan is regarded too high.

RWY: As the runway is exclusively used for departures, i.e. there are neither landings nor crossing operations, there is no particular need to stick to the takeoff schedule. He/she should give takeoff clearances so, that departures are minimal but safely separated.

[1] or according to the planned schedule, when using DMAN

[2] On Arlanda Airport there are in exceptional cases some possibilities for overtaking or intersection takeoff. However, for reasons of simplifications such manoeuvres were not considered in the simulations.

[3] TOBT is regarded as due time for issuing the combined start-up and push-back clearance.

4.3 First Results

Looking back to the early beginning of the whole DMAN development period, one can recognise, that it was commonly expected by experts that a DMAN will help to rise airport capacity whilst there were major concerns as regards controller's workload with a tool supported departure management. Having this in mind, but being aware of the lack of a sufficient number of experiments, the RTS1 trials show surprising results, at least at first glance.

When considering capacity in terms of throughput, i.e. takeoff operations per hour, there was no difference between a supported and a conventional departure management. The steady state[1] value of throughput can roughly be estimated as 39 movements per hour for runway 19R in both cases. A similar statement can be made with respect to slot compliance as there were no CFMU slot violations in both cases. Obviously the controllers were able to feed the runway sufficiently with traffic. The controllers could achieve an optimum separation by skilfully merging and grouping of traffic, so that for instance several times favourable sequences (e.g. medium-heavy-heavy, instead of heavy-medium-heavy) could be achieved which left no space for a further optimisation by DMAN. However, in order to avoid a premature generalisation of this fact, one should keep in mind, that particular circumstances of this configuration may promote this result. At first, there is no complicated SID structure so that wake vortex separation constraints dominate the whole departure process. Secondly, but may be more important is the fact, that there was no interference with other traffic on the runway, neither arrivals nor ground traffic that had to cross. In more complicated cases, in those the "fitness" of a sub-sequence depends on the actual takeoff and landing times, since for example a medium-heavy staggering is unfavourable when both takeoff operations will take place in the same arrival gap but may be good, if there is a landing in between, it can still be assumed that DAMN will have positive capacity effects.

However, the situation changes completely when other evaluation aspects for departure management are assessed. In respect to efficiency of operations the taxi-out times decrease considerably when using DMAN (fig. 5). The reduction of taxi-out time with DMAN was directly observable as the queue length of departures waiting on the taxiway to get a line-up and take-off clearance.

[1] The scenario starts with a period of empty runways, comparable to the first morning hour.

The dynamic of the queue length clearly shows that DMAN together with the controller team acts like an (automatic) control system in a closed loop control stabilising the departure traffic demand at the runway at a low level (fig. 6). The level itself, i.e. the average number of waiting aircraft, thereby depends on a DMAN parameter, the extension factor (section 3.2.3).

The airlines gain directly from the reduction of taxi out times as this decreases unnecessary engine running time and fuel burn. The airport gains indirectly, as any reduction of costs of their customer would make this airport more attractive in comparison to other competing airports. Another aspect, that becomes more and more important, is the environmental impact. Here the surrounding communities profit directly from the reduction of noise and emissions. However, as it may be expected, that upper limits for environmental impacts could be established in the future on the basis of laws and regulations, again an airport may indirectly gain economic benefits.

At first glance a little bit surprising, but in correlation with the taxi-out times clearly understandable, is the reduction of workload when using a DMAN. Whilst in the baseline run without DMAN there was a period of about 40 minutes, in which the GND-N needed to give clearances and commands almost continuously, with DMAN such a period could not be observed at any time. Both ground controllers stated that working with the tool was quite relaxing.

Further aspects, which also become more and more important, are the predictability and reliability of operations and schedules. The key to any operational improvements is the availability of updated planning information within the technical systems. Here the introduction of a tactical departure management tool offers the opportunity to involve stakeholders and decision makers of the air transport system as DMAN can periodically broadcast the planned schedule. Although these information change dynamically (fig. 7), they can be used as best estimates of the actual takeoff times. The forecast horizon can be increased if enough computer power is available to include a larger set of departures into the planning process and if the quality of EOBT estimates is sufficient.

The dynamics of planning information shows the correlation between improved forecast quality with waning forecast time (fig. 8).

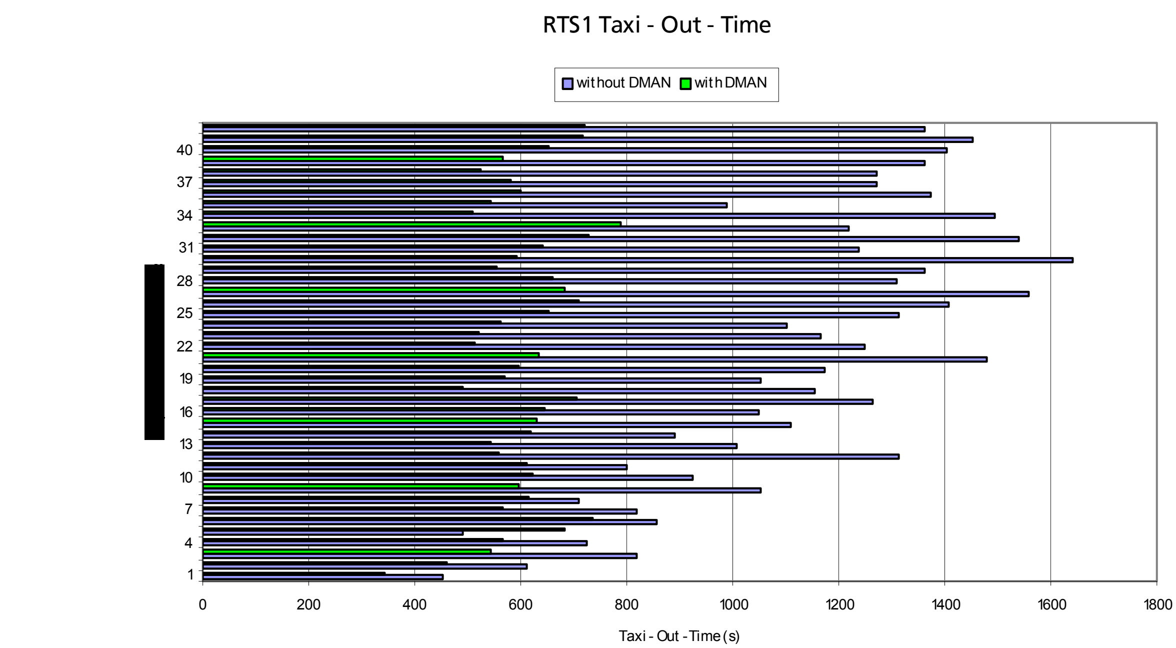


Figure 5: Comparison of taxi-out times with and without DMAN

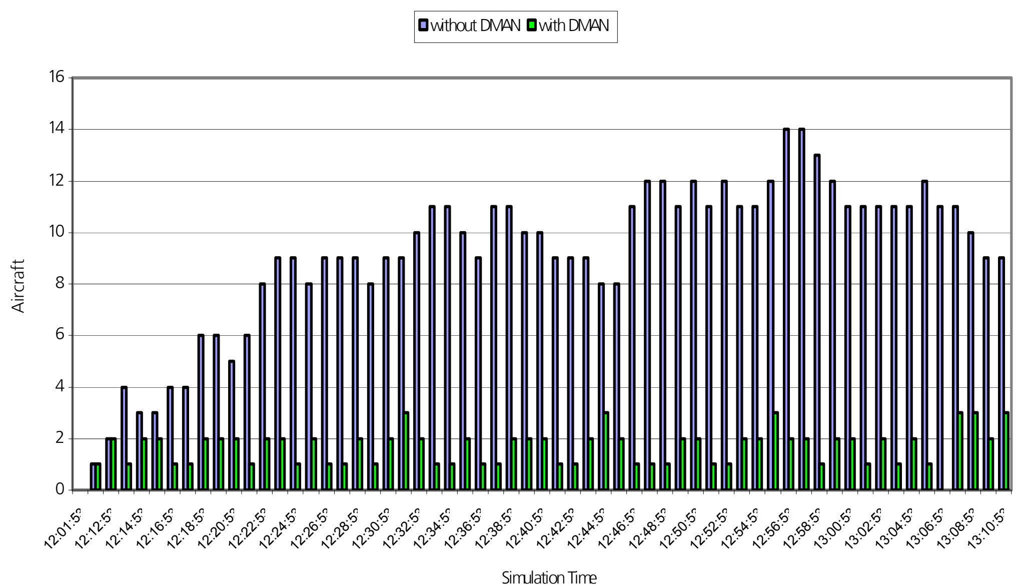


Figure 6: Dynamic of queue length of waiting aircraft

An improved forecast quality has a positive impact on punctuality, as it will contribute to the harmonisation of ATM operations even at other places. For instance, a better prediction of the takeoff time for a certain domestic or short range flight may help to improve the scheduling of the turn-around process at the destination airport. Also, especially the airlines and finally the passengers will profit from an improved awareness of possible delays as this enables earlier re-arrangements, like slot re-negotiations between airlines and CFMU.

Finally the RTS1 trials affirmed that the use of a DMAN is prerequisite or at least enables/promotes other advanced ATM procedures, especially new CFMU functions (e.g. automatic slot negotiation/update) [13], CDM in general, and

CPDLC on ground in particular. So, for specific tests of data link based ground movement control, which were performed at the last day of the test period, LFV set baseline trials aside, as they considered such procedures without DMAN as not practicable.

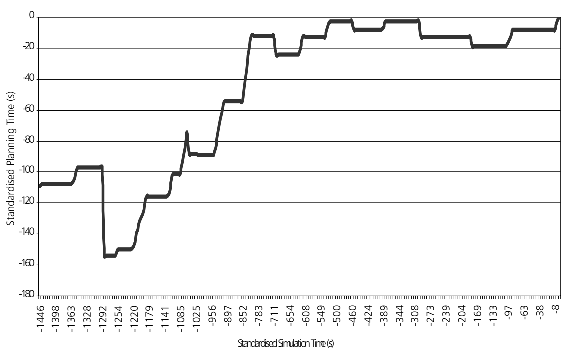


Figure 7: Variation of planned takeoff time for departure SAS525

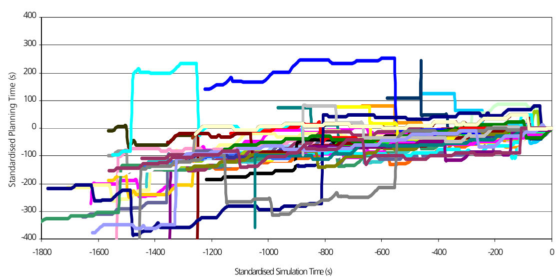


Figure 8: Variation of planned takeoff time for 40 departures

4.4 Lessons Learnt

The RTS1 trials showed that the introduction of DMAN does not require an extensive training period. Controllers were able to adapt to the new procedures very easily. Even for the difficult "philosophy-of-use" question, i.e. whether decisions should be strictly or loosely based on the planned schedule, controllers found good answers very quickly.

Having in mind the positive experience of a very productive cooperation with a small group of LFV staff first, it can be expressively recommended to work out the operational concept and the concept of use with only a few expert controllers first. This offers better chances for detailed discussions of the DMAN concept, its limitations and possible improvements. Once the expert controllers are more familiar with both the new operational concept and the tool they are in the best position to introduce these to their controller colleagues.

Although it is essential to involve the users very early in the development process, one should be aware of the fact that user feedback concerning usefulness and practicability of operations may vastly depend on the familiarity with the tool. So for example, there was some concern about workload in the beginning but finally assessed as being easy for a controller to follow the DMAN timing when controlling the traffic. As a conclusion, one may recognise that the development process of a new "intelligent" planning tool cannot be a linear (stringent) process from user (and system) requirements to the function and system design. It needs enough room for discussions, explanations of the things which are desirable and feasible, i.e. it is learning process for both, developers and users.

The quality of the DMAN planning information depends on a large set of parameters. This gives on the one hand the possibility to adapt the behaviour of the tool to particular needs and circumstances of a certain airport, but requires on the other hand both, a skilful parameter tuning and many trials under similar conditions to see the influences and interferences on results. So, it can be done best in simulation by performing many runs with the same scenario. For RTS1 there was not enough preparation time, so that further improvements can be expected with better parameters. As the users are not fully aware of these correlations they tended to pre-matures assessments especially in cases where the DMAN did not act properly.

When the DMAN development was started, it was intended by Eurocontrol to use DMAN in so called shadow-mode trials at several European airports. However, since the DMAN has to be operated in closed loop rather than open-loop probably no benefits will be observable if the loop is opened. Hence, if the DMAN should be tested in real tower environments, the author recommends using shadow-mode trials for technical tests only and to close the loop for first operational tests during times of low traffic load.

5 Further Development

The DLR DMAN will be further developed and tested in several European projects. It will be used in the European project EMMA at the airport of Prague. It will also be used in the German KATM-project for Frankfurt airport and it may be used again[1] for Gate-to-Gate RTS3, in which particular approaches for AMAN-DMAN coordination and cooperation will be

[1] There is no final decision at the time being.

explored. Focussing on these projects two key aspects of further development can be identified.

The first one is to improve the functionality by employing surveillance data. Making the DMAN seeing, will avoid situations where the controllers can clearly see that a planned sequence cannot be established anymore, because of the actual situation of taxiing aircraft. The challenge of this task will be to find appropriate solutions for different levels of modelling of the airport layout.

The second one is the AMAN-DMAN coordination. DLR focuses on an approach, which coordinates existing instances of both tools within a coordination layer based on the method of balanced optimisation, but without the need to make substantial changes to the AMAN and DMAN systems, and the operational procedures on arrival and departure side.

6 Summary

The Eurocontrol / DLR DMAN offers a wide range of application areas. It can be easily adapted to different airports and different purposes. So the DMAN can be used as a stand-alone demonstrator or as a development system, with witch a first parameter tuning and benefit evaluation can be done. The DMAN can be embedded in real or simulated tower ATC environments. The tool was operationally tested in the RTS1 trials of the Gate-to-Gate project. The results indicate, that for the controllers the operational concept of a tool supported closed-loop departure management is easy to understand and to perform. The main benefits result from the reduction of taxi-out delays in terms of enhanced overall efficiency, reduced environmental impacts and harmonised traffic flow. In addition, the DMAN not only improves predictability and reliability of schedules, but enables and/or promotes other future advanced ATM concepts, like CDM and CPDLC. The lessons learnt may be helpful to introduce such a tool at European airports.

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Key Words

ATM, Departure Management, Planning, Optimisation, Real Time Simulation Trials

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