REAL-TIME SIMULATION STUDIES CONCERNING THE OPERATIONAL ASPECTS OF TWO LANDING THRESHOLDS ON ONE RUNWAY AT FRANKFURT/M

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1 Introduction

All forecasts concerning the future growth of civil aviation predict an increasing traffic demand, especially at the major hub airports. The capacity of the runway system is essential in the discussion concerning capacity-enhancement. One of the most important bottle-necks is the achievable landing rate, especially if the closely-spaced parallel configuration of Frankfurt's runway system is taken into consideration. This configuration does not allow independent operation due to radar separation and wake vortex requirements even for staggered approaches

One possibility to overcome the hazard for medium jets imposed by the wake vortices of preceding heavy jets is the installation of an additional second threshold displaced by 1500 m on one of the existing runways. By this displaced threshold the glide path of the smaller aircraft is located approx. 90 m above the glide path of the heavy aircraft approaching the adjacent parallel runway. This system was trialed in a version, where only one threshold is active on each of the parallel runways in Frankfurt within the project HALS (High Approach Landing System). To achieve the maximal flexibility, it has turned out during the HALS trials, that the use of two active thresholds on one runway is highly desirable from the operational point of view.

Before the use of two simultaneously lit and operated thresholds on one runway (Dual Threshold Operations (DTOP) concept) can be operated on trial, further in-depth studies about the pilot's and the air traffic controller's situation in this new mode of runway operation were necessary. Two major simulator based studies will be described in this paper. Both studies are conducted within the scope of the governmental-funded LuFo III programme. The project is led by Fraport AG, and the Technische Universität Berlin (TU Berlin) is the associated project partner.

2 Apprehensions and their mitigation

The development of the new lighting and marking system was based on the postulate to use the two runway threshold on one runway simultaneously. The new threshold on the southern runway was named 26L in accordance with ICAO regulations for more than 3 runways in one direction, while the existing threshold maintained the name 25L. After the development phase, the involved pilots were reluctant to immediately use two active thresholds (25L and 26L) on one runway, a

compromise could be reached by using the newly developed system for threshold 26L only on its own on Frankfurt's southern runway. This mode of operation called HALS underwent a two-staged trial phase from 1999 to 2004.
Within the field trials of HALS it became evident, that by using only the extremely displaced threshold on Frankfurt's southern runway, an optimal operational utilization of the system was hard to achieve. Whenever the aircraft sequence did not consist of heavy and medium aircraft following each other, a lot of runway capacity was wasted. This problem becomes very obvious by consideration of an aircraft sequence of e.g. five heavies in a row - in this case, the southern runway could not be used for landings for almost 15 min.
Another aspect to be considered is the fact, that due to safety requirements during the switching from 25L to 26L and vice versa, no aircraft was allowed on the glide path closer than 8NM to the thresholds.
In expert discussions about the simultaneous use of the two thresholds and the associated lighting systems on the southern runway of the Frankfurt Airport (DTOP), the wish for an in-depth study of the human factors effects of the two operative thresholds on one runway was expressed by the involved pilots. Within the flying community, there were different assumptions about the potential disorientation and lack of situational awareness induced by the new system. Also the resulting workload was an issue to be considered.

On the other hand, the need for further research concerning operational (workability, safety and capacity) and human factors of the new approach procedure DTOP within the Air Traffic Control was recognised.

For the both topics Fraport AG initiated two large scale real time simulation studies:

- pilots human factors study "Real-time simulation of the cockpit situation", and
- ATC workability, operational efficiency, safety and air traffic controllers human factors study "Real-time Simulation of ATC environment"

These research efforts became financial support in frame of the governmental-funded LuFo III programme.

3. Real-Time Simulation of Cockpit Situation

The A330/340 Full Flight Simulator (FFS), installed at the TU Berlin in 1992 and operated by the Zentrum für Flugsimulation Berlin GmbH (ZFB), was used for this first human-factors study with professional airline pilots.
The simulator is certified for training of pilots but also for research operation with multiple data, video and audio recording.

Figure 1: Simulator trials [1]

The Human Factors Consult GmbH (HFC), as subcontractor in this project, was involved in this study and has fitted a complex system of measurement methods into the simulator recorded together with the so called "hard data" from the simulator on a common time basis:

- ECG (heart rate)
- EOG (eye movement)
- Eye Gaze video recording

Subjective data like the NASA Task Load Index (TLX), Interviews with the pilots were conducted separately and compared with the recorded physiological data. To evaluate the influence of the new lighting configuration on the pilot's behaviour, an eye-tracking method coupled with video recordings was used.

Figure 2: Experimental design, HFC

Forty pilots participated in a two-week simulation effort, and each crewmember had to fly nine approaches to different runway and weather configurations. A normal approach under CAVOK-conditions to Frankfurt's runway 25L was used as a reference case for the lower limit of the pilot workload. On the other hand, the published NDB-DME approach to runway 25L was used as a high-workload reference scenario.

The study shows that the approach to the new system creates a workload in the same order of magnitude as approaching to a conventional system under ILS guidance. The high-load reference case, NDB-DME, leads to a significantly higher workload on the objective as well as on the subjective scale. The evaluation of the eye tracking shows no evidences for confusion and thereby decreased situational awareness by the new system. However, a few differences are visible and can be explained by the fact that elements of the first threshold are taken into account also for approaches to the second threshold. As a result, from the cockpit human factors point of view, no hazardous or overloading effects can be expected by the application of the DTOP-system.

4. Real-Time Simulation of ATC Environment

4.1. Simulation Airspace

The airspace of the DTOP simulation consisted of three parts:

- TMA Frankfurt (see below for details, measured airspace, light grey area shown in Figure 3)
- The so called Extended TMA (E-TMA) which was automatically controlled by the simulator. This area was not measured during the simulation (outer dark grey area shown in Figure 3).
- Area of responsibility Tower Frankfurt (not measured, inner dark grey area shown in Figure 3)

The area of responsibility of Frankfurt Approach includes the complete airspace C up to FL115 within the lateral boundary of the Frankfurt TMA. The maximum usable flight level is FL110.

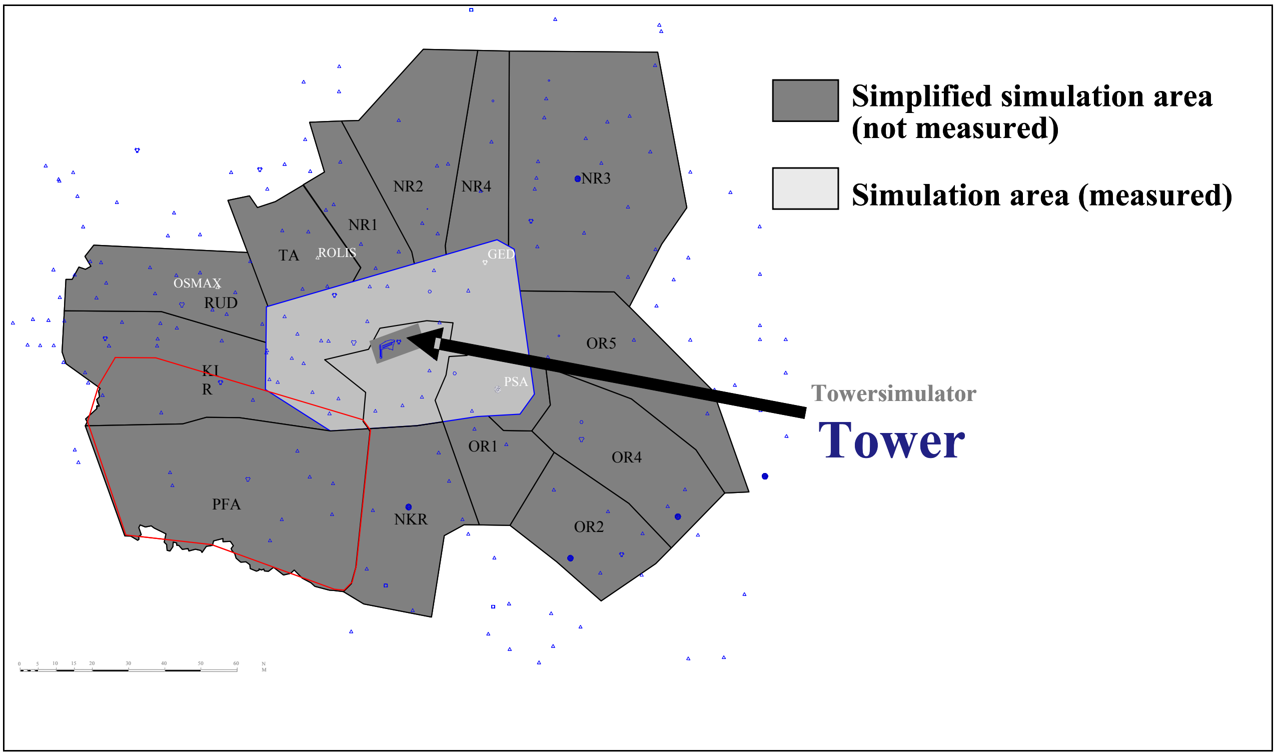

Figure 3: Simulation airspace

There are two types of arrival procedures defined towards Frankfurt airport: STARs and RNAV procedures. These procedures begin all at one of four transition points between area and approach control, so called "clearance limits":

- PSA (Spessart)
- GED (Gedern)
- ROLIS
- OSMAX

Normally the RNAV procedures or radar vectoring are preferred by the approach controller. The RNAV procedures (so called "Transitions to Final") are defined from a clearance limit to the beginning of an ILS final approach fix and look like trombones (see Figure 4 for details). They are composed of a downwind leg, a base leg and a beginning of the final. The downwind leg and the beginning of the final includes several waypoints (named DFxxx), which can be used to shorten the route trough "direct" clearances to these waypoints (grey dotted lines in Figure 4).

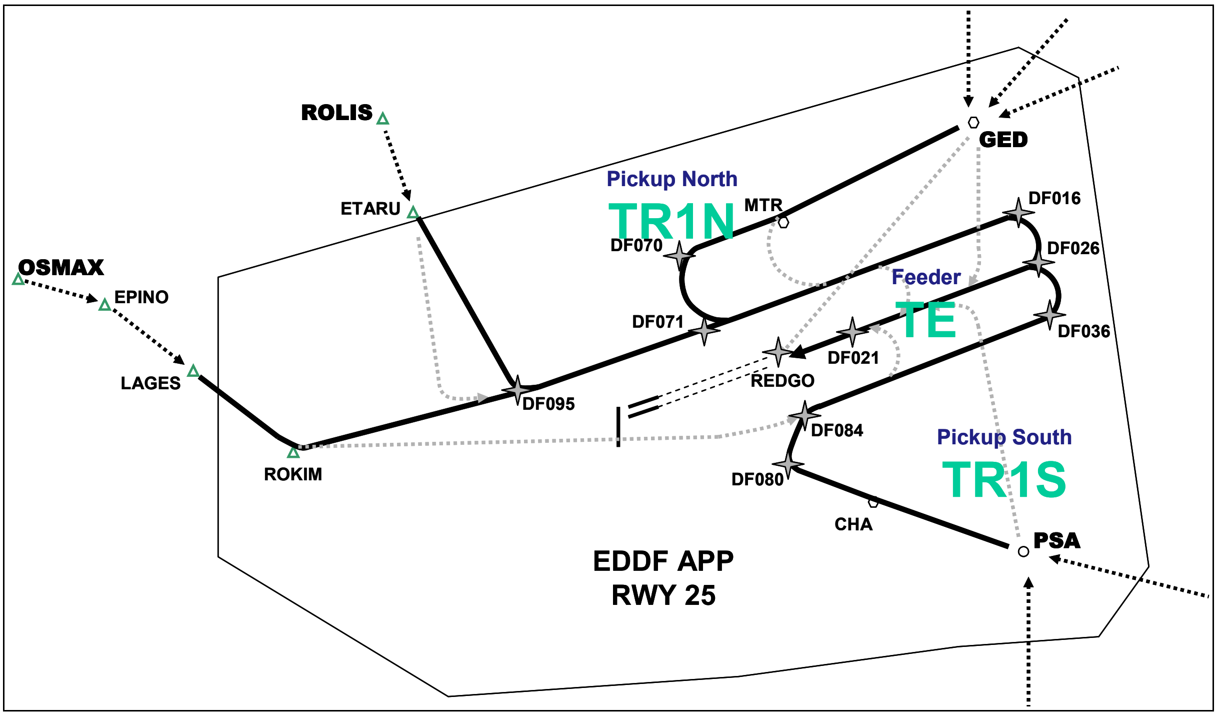

Figure 4: Procedures and working positions inside Frankfurt TMA (simplified)

The controller team of Frankfurt approach consists of three radar controllers for arrival traffic (see Figure 4 for details):

- Radar controller *Pickup North* (TR1N) is responsible for IFR approaches coming from GED, ROLIS and OSMAX.
- Radar controller *Pickup South* (TR1S) is responsible for IFR approaches coming from PSA.
- Radar controller *Feeder* (TE1) is responsible for the turn onto the final and for the final.

The departure controller (TR3) is responsible for IFR departures going to north. A second departure controller (TR2) is responsible for IFR departures going to south, south-east and west. During the simulation TR2 and TR3 were worked as one combined departure controller TR2/3 as in normal operations.
There are no fixed sectors inside the approach area. The work-sharing between the two Pickups and Feeder is flexible and depends on the load of traffic and on the controller team.

4.2. Simulation system

The real-time simulation infrastructure operated at the DFS R&D division is the Advanced Function Simulator (AFS). The AFS core simulation engine is a commercial product (ATCoach), supplemented by DFS-owned software in the areas of e.g. HMI, FDPS emulation or data analysis. The system allows for up to 12 controller working positions and 9 simulation pilot/adjacent controller positions. Voice communication is provided by the EUROCONTROL AudioLAN product. As performance model, Game/BADA is used, which is supplemented by DFS-developed enhancements especially for the TMA area.
Special system features are the extensive scalability (from single position to large scale systems) and the capability of driving complete ATM systems (like a complete ACC) in simulation mode for technical or operational purposes.
It was necessary to couple the AFS with a tower simulator (TOSIM) in order to provide the

measured controllers with a realistic environment. Therefore the system used for the DTOP simulation consisted of two parts, a measured en route/approach simulator (AFS) and a simplified tower simulator (TOSIM).

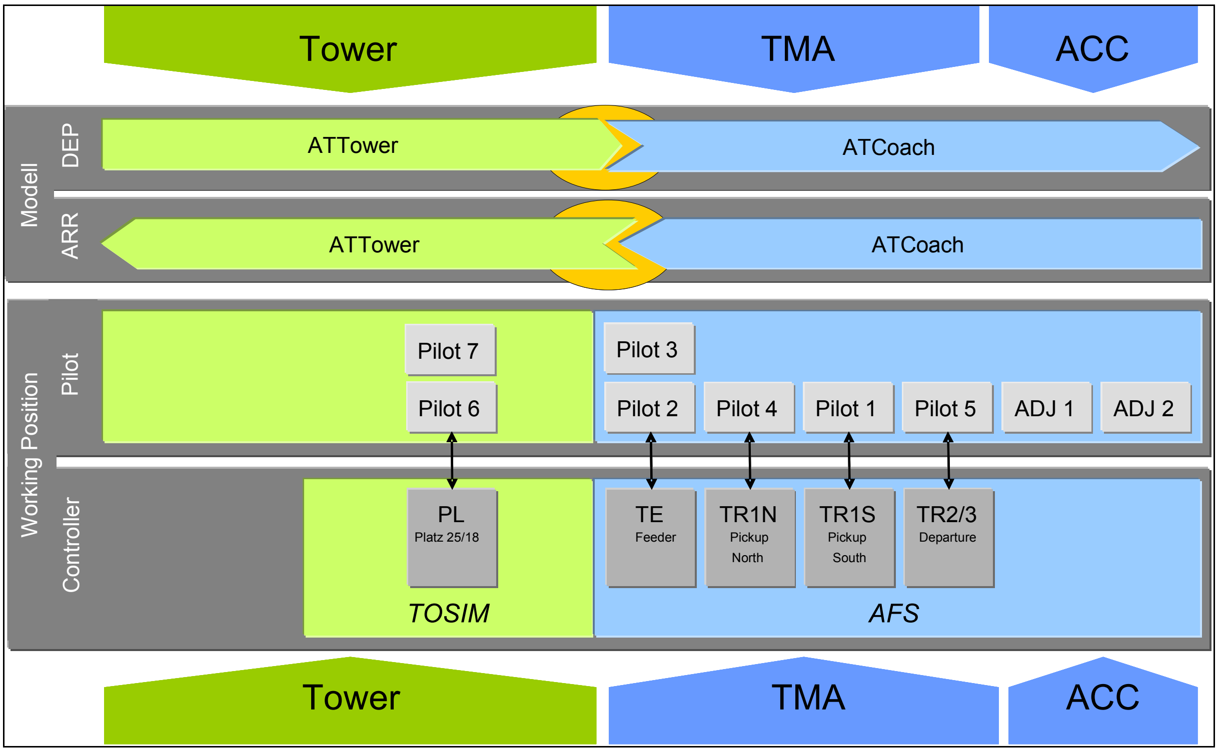

Figure 5: Setup of the simulation system

Figure 5 shows the setup of the simulation system used. The part of the AFS consisted of:

- 4 Controller working positions
    - TR2/3
    - TR1N
    - TE
    - TR1S
- 5 Simulation pilot positions
- 2 Adjacent controller positions
- 1 Supervisor position (not shown in figure 3)

As Figure 5 shows three working position were used in the TOSIM part:

- 1 Controller working position
- 2 Simulation pilot positions

4.3. Experimental setup

In the present simulation two main objectives were investigated. The first objective was to probe if the DTOP procedure is workable. The second objective was to examine possible effects of the DTOP procedure on airport airside capacity in case the procedure is found to be workable.

The scenarios for the present simulation were composed using recordings of real traffic. Each run had a duration of 90 minutes. The first 15 minutes at the beginning of the scenario served to feed traffic into the TMA, the following 60 minutes made up the actual evaluation period. The last 15 minutes of the scenario served as buffer time.
In the simulation four different conditions were measured. There were scenarios with a lower percentage of aircraft corresponding to the wake vortex category “Heavy” and scenarios with a higher percentage of heavy aircraft. These

scenarios are referred to as “10 Heavies” and “20 Heavies”, respectively. However, the amount of traffic did not differ and represents a high load scenario. Each of the scenarios was run with and without use of the DTOP procedure. Altogether 4 training runs and 24 measured runs were carried out.

During the simulation objective and subjective data was collected. The recordings of the simulator (e.g. radar data, r/t communication, pilot commands) served as objective data. Subjective data was collected using different questionnaires (demographic and training questionnaire, post-run questionnaire, and final questionnaire). Furthermore the NASA-TLX was presented on the Touch Input Device and filled in by the controllers every 10 minutes. After each measured run a structured interview was conducted.

The participants of the simulation were 11 controllers of the DFS. Out of these, 10 controllers had experience with HALS already. On average the controllers were 35.5 years old and had 10.6 years of experience as controllers at Frankfurt Approach.

Figure 6 shows the experimental setup. At the controller working positions the departure controller, pickup north, feeder, and pickup south can be seen. The employees of TU Berlin doing a task analysis and a supervisor are seated behind the controllers.

Figure 6: Experimental setup

4.4. Results of the Real-Time Simulation of ATC Environment

The number of arrivals and departures was analysed according to the four measured conditions. Figure 7 shows the mean number of arrivals and departures for the different conditions. Thereby the column for arrivals summarises the arrivals on runways 25L and 25R as well as 26L in runs with DTOP. The column for departures summarises departures from runways 25R and 18.

Figure 7 shows that in runs with "10 Heavies" more aircraft could be landed when working with the DTOP procedure in comparison to runs without DTOP. In the runs with "20 Heavies" it was possible to land more aircraft in runs with DTOP procedure as well.
In the "10 Heavies" condition there were slightly less departures in runs with DTOP. In runs with "20 Heavies" without the use of the DTOP procedure there were also slightly less departures in comparison to runs with "10 Heavies" under non-DTOP conditions. Thus, the differences are marginal. Therefore it can be said that in conventional non-DTOP operations the Heavy proportion in the arriving traffic does barely affect the departure capacity. In contrast to this a clear negative impact on the departure capacity can be seen in runs with "20 Heavies" and DTOP procedure.
Overall it can be said that in runs with "10 Heavies" the number of movements (arrivals and departures) could be increased by the use of the DTOP procedure in the simulation. In runs with "20 Heavies" the number of movements decreased when using DTOP.

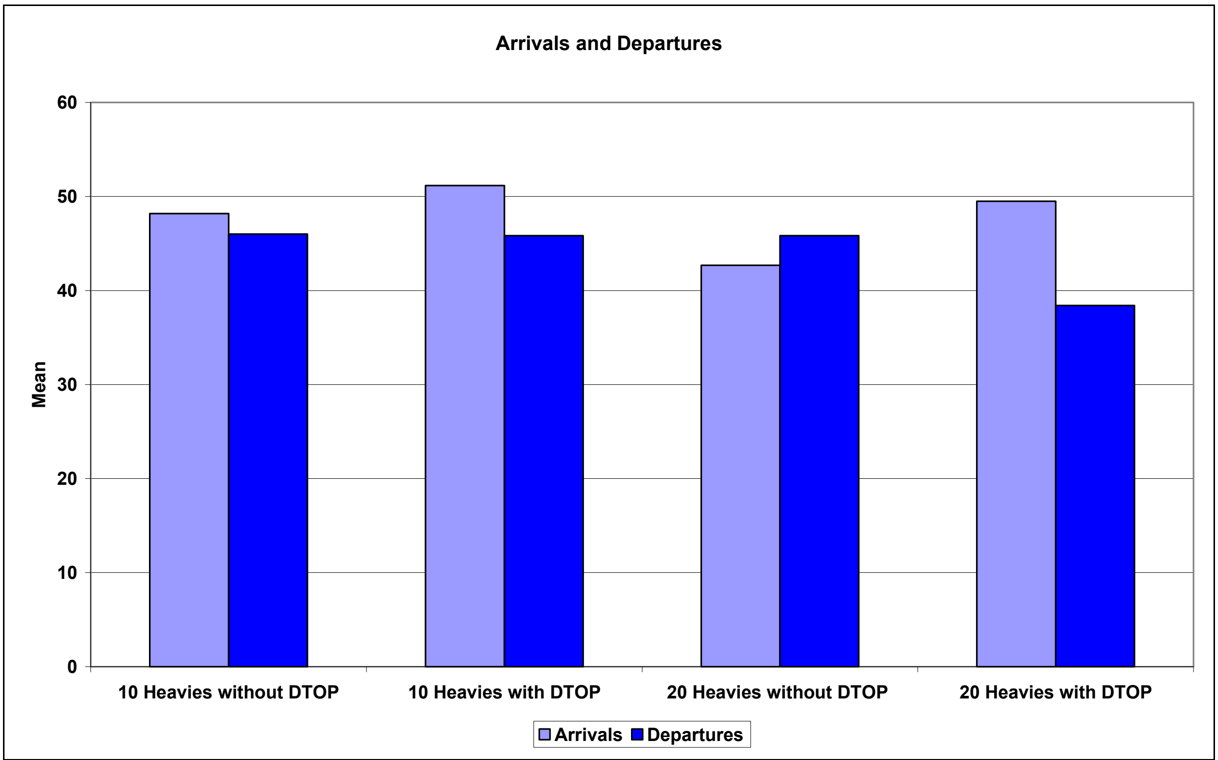

Figure 7: Arrivals and Departures

However, the overall numbers of arrivals and departures only account for the present simulation. In real operations this high throughput is not achieved. Nevertheless a tendency for more possible arrivals when working with the DTOP procedure can be expected. On the other side a capacity reduction for departures in situations with a higher percentage of heavy aircraft when working with the DTOP procedure can be expected.
In addition to the objective data the subjective opinion of the controllers was asked for. Figure 8 shows the evaluation of the DTOP procedure in the final questionnaire. The statements are rated for present procedures and the DTOP procedure, respectively.
The figure shows that according to the controllers it was possible to work efficiently with both present and DTOP procedures. Concerning flexibility the DTOP procedure is rated much lower than present procedures even though theoretically the DTOP procedure offers more options (25L, 26L, and 25R) to the controller. This rating is due to the fact that

once the exact sequence of aircraft for the DTOP procedure is established any change (e.g. by go-around, delayed pilot reactions) disrupts the sequence. The controller then has to rearrange the DTOP sequence for an optimal use of runway capacity which results in additional Taskload and Workload. Regarding safety the DTOP procedure was rated less safe than present procedures. Nevertheless the mean rating is still above the average of the scale. Regarding the results of the questionnaire it has to be mentioned that the ratings of the controllers did strongly differ for all statements except for the safety of present procedures.

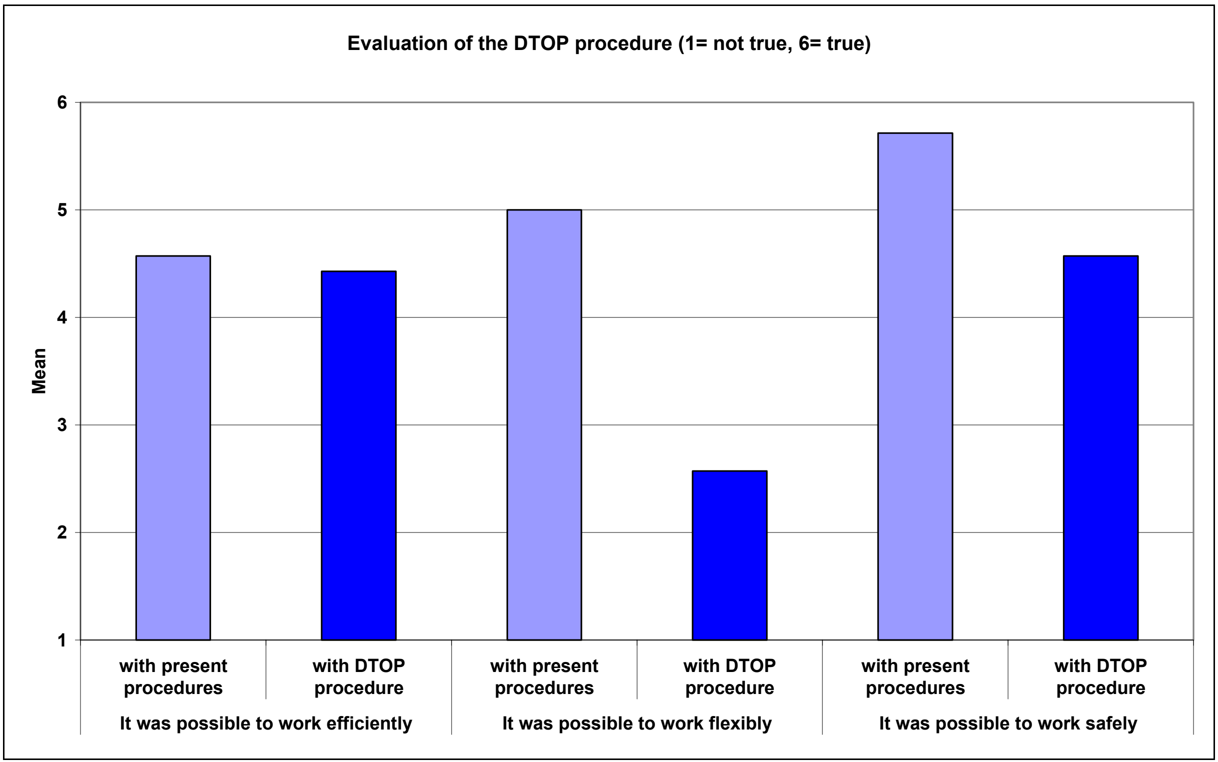

Figure 8: Evaluation of the DTOP procedure

Summing up the results with respect to the objectives of the simulation the DTOP procedure was found as workable under the given experimental conditions. Further a positive tendency for arrivals and a negative tendency for departure capacity when using the DTOP procedure could be observed. The air traffic controllers involved in the real-time simulation showed a good level of acceptance for DTOP. The ATCOs' feedback also identifies the need for tools supporting coordination among ATC positions.

4.5. Human factors of ATC-simulation – ATCOs' Activity Analysis

The analysis of the air traffic controllers' (ATCOs') activities was done in order to answer the following questions:

- Under the same traffic conditions, is the ATCOs taskload higher with DTOP than without DTOP?
- Under the same traffic conditions, does radiotelephony increase with DTOP?
- Under the same traffic conditions, do coordination effort between ATCOs increase with DTOP?

During the simulation, the following ATCOs activities were registered:

- r/t (communication with pilots)
- strip marking
- communication with pickups
- communication with tower ATCO
- communication with adjacent sectors
- radar

Activities were compared for the DTOP vs. no DTOP condition with 10 or 20 heavies.
Result show that with 20 heavies, the feeder was active (in terms of registered activities) longer in the DTOP condition (M=2514.8s, SD=123.0) than in the no DTOP condition (M=2207.5s, SD=161.4). With 10 heavies, there was no difference. When regarding the different activity categories separately, it shows that most of the active time (over 90%) was spent with communication with pilots. With 20 heavies, there was a tendency to spend more time with r/t with DTOP (M=2339.0s, SD=156.6) than without DTOP (M=2082.5s, SD=165.9). Feeders also tended to spend more time with communication with the pickups with DTOP (M=147.5s, SD=54.1) than without DTOP (M=64.5s, SD=17.9) in the 20 heavies - condition. Again, there were no differences with 10 heavies.
However, when times per aircraft instead of total times are regarded, the picture is different. With DTOP, ATCOs handle more aircrafts than without DTOP. Differences between DTOP and no DTOP found for communication with pilots disappear, in both conditions they communicate for about 41s per aircraft. Communication with pickups is still more with DTOP (M=2.6, SD=0.9) than without DTOP (M=1.3, SD=0.4) (see figure 9)
For about one quarter of the active time, feeders did multiple activities simultaneously, especially r/t and strip marking was done simultaneously. There were no differences between DTOP and no DTOP, neither with 10 nor with 20 heavies.

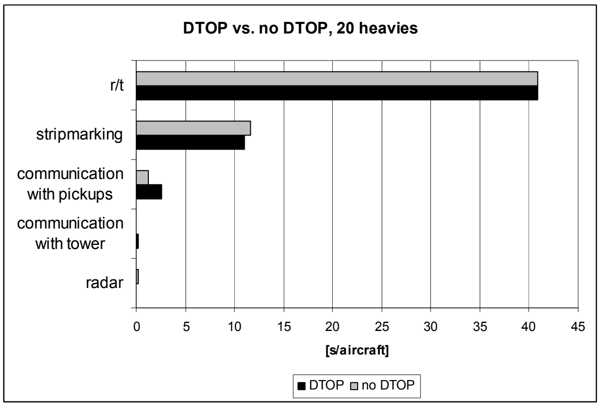

Figure 9: Comparison of feeder activities per aircraft for DTOP vs. no DTOP with 20 heavies

These data suggest that taskload and radiotelephony load do not increase with DTOP. However, there is an increase in coordination efforts between ATCOs.

4.6. Human factors of ATC-simulation – Physiological Measurements

To enhance the validity of the ATCOs' subjective assessments of the workload generated by the new procedures, measurements of ATCOs' physiological (cardiovascular) parameters were implemented. Physiological parameters are assumed as not suggesible consciously.

This part of the investigation was aimed at the working hypothesis to be examined:

- Under the same traffic conditions, is the ATCOs' mental workload higher with DTOP than without DTOP?

The following physiological parameters of the test persons were derived from the recorded cardiovascular parameters and analyzed:

- heart rate (HR)
- rMSSD
- low frequency (lf)
- high frequency (hf)
- low frequency/high frequency (lf/hf)

These parameters are indicators for mental workload [1], [2].

Cardiovascular parameters were recorded with the Polar S810i system. The Polar S810i was successfully validated in terms of precision in a comparative experimental study (S810i vs. ECG equipment) at the TU Berlin [3].

Artefacts in the raw data were corrected as recommended in [4]. The physiological derivatives were used for the comparison of the DTOP vs. no DTOP condition with 10 or 20 heavies.
For the feeder position, which is shown here exemplarily, no differences between DTOP vs. no DTOP in both conditions (10 or 20 heavies) were found (see Tab.1, Tab. 2).

	DTOP		no DTOP	
	M	SD	M	SD
HR	68.862	9.838	67.748	10.147
rMSSD	0.041	0.004	0.041	0.003
lf	2486.042	799.554	2198.779	731.497
hf	536.791	116.456	505.418	86.483
lf/hf	5.099	2.166	4.616	1.115

Tab. 1. DTOP vs. no DTOP, 10 heavies. N=4

	DTOP		no DTOP	
	M	SD	M	SD
HR	65.081	6.09	63.119	2.463
rMSSD	0.04	0.005	0.043	0.003
lf	2447.062	610.804	2270.686	708.080
hf	450.071	93.56	549.185	76.591
lf/hf	5.834	0.473	4.618	2.19

Tab 2. DTOP vs. no DTOP, 20 heavies. N=3

Based on the cardiovascular indicators it can be stated that there are no significant differences between DTOP and Non-DTOP szenarios in ATCOs' mental workload. This conclusion backs subjective assessments of the new procedure by means of the NASA-TLX-Test.

5. Conclusions

Faced with capacity bottlenecks, major airports worldwide are looking for solutions. The airport authority of the Frankfurt Airport Fraport AG initiated significant research efforts to back experts' decisions considering the trial operations of Dual Threshold Operation (DTOP). DTOP is a non-conventional approach concept to overcome the wake vortex separations restrictions for airports with closely spaced parallel runway like Frankfurt Airport. The potentials of DTOP are seen in ensuring high landing capacity even under poor visual conditions when no delegation of the separation responsibility to the pilots on the final approach is possible.
Before DTOP with its two simultaneously lit and operated thresholds on one runway can be used on trial, questions about the new procedure's effects considering

- the pilots' situation awareness and taskload, and
- the operational issues (workability, safety and capacity) of the new ATC procedures of DTOP) as well as air traffic controllers' work- and taskload

have to be investigated.

The two large scale real time simulation studies initiated by Fraport AG:

- pilots human factors study "Real-time simulation of the cockpit situation", and
- ATC workability, operational efficiency, safety and air traffic controllers human factors study "Real-time Simulation of ATC environment"

were conducted and results are presented here.
From the cockpit human factors point of view, no hazardous or overloading effects can be expected by the application of the DTOP-system. DTOP proved its applicability and operational efficiency on the ATC's arrival side. In the simulation environment negative impact on the departure capacity was experienced in runs with high heavy proportion. The feedback of the ATC test staff also identified the need for tools supporting coordination between ATC positions. The air traffic controllers involved into the real-time simulation showed a good level of acceptance for DTOP.
The results of DTOP research efforts provide the decision support for Fraport AG and its airport partners concerning further implementation of this innovative approach procedure.

6. References

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