

PROGRAMME FOR  
HARMONISED AIR TRAFFIC  
MANAGEMENT RESEARCH  
IN EUROCONTROL



EUROPEAN ORGANISATION FOR THE SAFETY OF AIR NAVIGATION, EUROCONTROL



**DOC 97-70-13**  
Volume 1 of 2

## **PD/2 FINAL REPORT**

PHARE/DLR/PD/2-10.2/SSR;1.2



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Date: February 1998

Version: 1.2

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## Revision history

July 1997	Draft version 0
October 1997	Draft version 1, incorporating VAL and PCC review comments
January 1998	Version 1.1. Minor editorial changes prior to publication
February 1998	Final Version 1.2. Publication version

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## Executive Summary

This document is the final report for the PHARE Demonstration 2 (PD/2). It gives a comprehensive view on the pursuit of the experiment and the results achieved.

As part of the Programme for Harmonised Air Traffic Management Research in EUROCONTROL (PHARE), PD/2 formed the second major real time simulation exercise in a series of three PHARE Demonstrations to support investigations into aspects of the concept of the future European Air Traffic Management System (EATMS). The work programme of PD/2 to design, implement, and demonstrate the PHARE prototype air and ground computer assistance tools for air traffic management in the extended terminal area (ETMA) was led by the Deutsches Zentrum für Luft- und Raumfahrt (DLR). The participating partners were CENA of France, NATS of UK, NLR of the Netherlands, and the EUROCONTROL Experimental Centre at Brétigny (EEC). The PHARE programme is managed by EUROCONTROL Headquarters in Brussels.

The main objectives of PHARE Demonstrations are to determine the effect on controller workload and traffic throughput by introduction of computer assistance tools from the PHARE Advanced Tools (PATs) programme, in an environment with an increasing proportion of 4D FMS equipped aircraft with full two-way datalink, whilst gaining a degree of controller approval for the advanced tools introduced. In this respect, PD/2 succeeded to produce substantial and meaningful results.

The PD/2 system was demonstrated on DLR's real-time simulator ATMOS (Air Traffic Management and Operations Simulator), using 32 controllers from 7 European countries. The system incorporated advanced controller assistance tools with an associated ground human-machine interface (GHMI) designed in the PHARE GHMI project, as well as, by integration of the DLR Advanced Technologies Testing Aircraft System (ATTAS) Experimental Cockpit, simulated air-ground datalink and 4D experimental flight management systems (EFMS). Six pilots participated in an evaluation of the PD/2 on-board components developed in the PHARE airborne human-machine interface (AHMI) project.

A PD/2 airborne demonstration programme using the DLR ATTAS, with the ATTAS Experimental Cockpit integrated, was successfully accomplished. The ability of an aircraft to fly negotiated trajectories in a routine manner while operating on its inbound route down to the Approach Gate within continuous 4D tolerances, was convincingly demonstrated.

All participating controllers undertook a controllers training programme of one-week duration.. The training enabled them to work according to their roles in PD/2, in a reference baseline mode with paper strips based on current practice as well as in the PHARE advanced tools mode.

During more than one hundred hours of simulation a variety of performance and workload measures were recorded. Audio and video documentation, observer logs, debriefing sessions, and questionnaires were used to accomplish the PD/2 data collection.

The controllers considered the training as adequate and sufficient and appreciated the simulation set-up as being realistic and valid. The PD/2 GHMI gained a high degree of controller approval, with significant acceptance of display principles such as colour coding of aircraft labels, and an equally high acceptance of the interaction principles, such as using the mouse for on-screen interaction with aircraft labels and pop-up menus.

The quantitative analysis of system performance data revealed various gains from the introduction of the PD/2 PATs and GHMI in terms of traffic throughput and quality of service. Overall, benefits were achieved for the number of landings per time unit, average flight time of aircraft, inbound delays, and time precision of delivery particularly under conditions of high traffic load. An analysis

of the wake vortex category separations measured at the Approach Gate showed that these benefits were not achieved at the expense of closer separation.

Another general point was that, in parallel to the improvements gained with the advanced system, the variability of the measurements was considerably reduced. The controller team performances and work styles became more homogeneous, and thus more predictable.

It is concluded that improvements in traffic throughput and quality of service were achievable with the advanced ground system alone. The introduction of 4D FMS/datalink aircraft which automatically followed their negotiated trajectories in two steps of 30 % and 70 % of aircraft in the traffic samples, resulted in considerably higher percentages of aircraft which were delivered at the Approach Gate exactly on their planned time.

Statistical analysis of controller workload revealed some re-distribution of workload between tactical controller positions as an effect of the introduction of PD/2 PATs and GHMI. It is important to note the observed decrease of workload at the Approach Pickup controller position that was the position with the relatively highest workload under reference baseline condition. Furthermore, the introduction of 30 % and 70 % 4D FMS/datalink aircraft in the traffic sample showed a stepwise reduction of workload for all tactical controller positions involved.

The effect of releasing the controllers from the duty of transferring ATC instructions gave significant reductions in all objective workload measures at all controller working positions irrespective of traffic volume. It can therefore be concluded that workload from merely guiding traffic strongly decreased as the proportion of 4D FMS/datalink equipped aircraft increased.

In summary, PD/2 was a major, successful demonstration of the integration of advanced tools, 4D FMS and datalink into an air-ground air traffic management system in an extended terminal area airspace. Experimental evidence suggests that the PHARE concept of trajectory-based traffic guidance provided by the advanced tools and human/machine interfaces was approved by the controllers and pilots, and that it has the potential for improving traffic throughput and quality of service, at acceptable or reduced levels of controller workload.

**DOC 97-70-13 has been produced in two volumes**

**Volume 1 - MAIN REPORT**

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<b>Annex G</b>	<b>PD/2 Ground Human-Machine Interface</b>

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# 1 INTRODUCTION

## 1.1 SCOPE

This document is the final report for the PHARE Demonstration 2 (PD/2). The report consists of two volumes. The main report Volume 1 gives those with little or no experience of the Programme for Harmonised Air Traffic Management Research in EUROCONTROL (PHARE) an overview over the achievements of PD/2. For those with closer involvement in the PHARE programme, it provides a synthesis of the results, presents recommendations, and references the detail available in the measurement data and in Volume 2. Volume 2 consists of Annexes that provide detailed descriptions of the PD/2 experiment and results, namely:

- Annex A Experimental Design and Methods
- Annex B Controller Subjects and Training
- Annex C Analysis of Traffic Throughput/Quality of Service
- Annex D Analysis of Workload
- Annex E Analysis of Acceptance
- Annex F Airborne Aspects of PD/2
- Annex G PD/2 Ground Human-Machine Interface

## 1.2 CONTEXT

Estimates of the growth rate of air traffic in Europe continue to predict that the 1993 demand level - when the PD/2 project started - will have doubled by 2010 [European Traffic Forecasts 1980-2010, Air Traffic Action Group, Geneva, 1996].

Considerable gains in ATS capacity have been achieved during the late 1980s and early 1990s as a result of co-ordinated improvements for example with improved inter-centre communications, and improved radar coverage. However, few changes have been made to the level of external assistance being provided to controllers. Thus, this growth has for the most part resulted in greater demands being placed upon controllers alleviated where necessary by modifications to the structure of the airspace. The potential for further significant gains by these means is becoming small and unlikely to be sufficient to meet the forecast demands.

A means has to be found by which controllers can be enabled to handle a larger number of aircraft in a given airspace without significant increase in workload. This will have to be achieved whilst maintaining or improving system safety. One proposed method is the provision of automated assistance to support the controller in the resolution of conflicts and in the planning of the efficient use of airspace using data links to communicate aircraft trajectory predictions.

In providing such support and removing the controller and pilot from certain tasks by means of direct computer to computer communication, it is necessary to ensure that the tasks removed from the pilot and controller are those which are best executed by computer assistance, and those tasks which remain their responsibility are best executed using the flexibility and adaptability of human skills.

The areas where computer support is expected to yield improvements are those that make use of their capacity to rapidly calculate accurate predictions of future aircraft profiles, analyse potential options for the resolution of conflicts and sequence aircraft for optimum use of airspace and runways. To achieve this, detailed aircraft performance data, meteo condition information and

criteria concerning aircraft operational requirements are needed to be provided using data link communications.

The PHARE programme founded in 1989 has the objective to organise, co-ordinate and conduct studies and experiments aimed at providing and demonstrating the feasibility and merits of a future air-ground integrated air traffic management system in all phases of flight. The results of the programme should help to refine the description of the future Air Traffic System concepts needed to satisfy demand and provide information on the best transition from the current to the new system.

In PHARE a number of European research establishments assisted by the authorities concerned combined their ATC and aeronautics experience and resources. The participants in PHARE are:

- CAA/NATS (with sub-contracts to DRA Bedford & DRA Malvern), United Kingdom
- STNA and CENA, France
- DFS and DLR, Germany
- RLD/LVB and NLR, Netherlands
- EUROCONTROL Agency Headquarters Brussels and EUROCONTROL Experimental Centre, France.

The Commission of the European Communities participates in and supports PHARE. The FAA and Transport Canada are co-operating within the frame of relevant agreements. Within PHARE, the necessary ground and airborne tools are being produced and evaluated initially as prototype components. The culmination of this work is the execution of a series of real time simulations entitled "PHARE Demonstrations". These will allow the developments to be evaluated not just based on their individual capabilities but rather to establish how the elements work when combined.

### 1.3 PHARE DEMONSTRATION 2

To achieve its objective of demonstrating a fully integrated ATC system, PHARE set up a series of projects each led by one of the participating research organisations. These projects each contribute to the development of the various elements of the PHARE Operational Concept, which is to be tested in three major trials - termed demonstrations - of the proposed ATC system. Following the en-route demonstration PD/1 hosted by NATS, the TMA demonstration PD/2 was hosted by DLR on its Air Traffic Management and Operations Simulator ATMOS. This real time simulator is operated by DLR's Institute of Flight Guidance at Braunschweig, Germany.

The subject of PD/2 was the initial demonstration of PHARE concepts in a TMA environment after their evaluation in an en-route environment in PD/1. The results from both demonstrations are being used to guide further development and adaptation of facilities which will be evaluated in subsequent PD/3 demonstrations covering the full flight regime.

PD/2 addressed the terminal approach issues by simulating several sectors of an extended TMA and emulating entry and exit conditions of en-route sectors. The PD/2 trials were performed at the end of 1996 and during January/February 1997. To address the airborne aspects in June 1997 demonstrations were performed with DLR's Advanced Technology Testing Aircraft System ATTAS as a live aircraft.

The DLR PD/2 team was responsible for the successful execution of PD/2 on DLR's simulation suite. Other PHARE projects contributed advanced tools, methods and expertise to the PD/2 demonstration. Table 1 shows how the work was shared among the various PHARE projects:

<b>PHARE projects</b>	<b>Contribution</b>
PHARE Advanced Tools (PATs):	Trajectory Predictor (Trajectory Predictor), Conflict Probe (CP), Flight Path Monitor (FPM), Negotiation Manager (NM) and Arrival Manager (AM)
Ground Human-Machine Interface (GHMI):	GHMI Specification, GHMI Training Tool
Airborne Human-Machine Interface (AHMI)	Navigation Display (ND)
Experimental Flight Management System (EFMS):	Experimental FMS (EFMS),
Common Modular Simulator (CMS):	Tool Integration Platform (PARADISE), Application Interfaces (API)
Validation Tools (VAL):	Experimental Design, Measurements, Analysis Tools
PHARE Demonstration 1 (PD/1):	Lessons learnt from En-route Experiments
PHARE Demonstration 2 (PD/2):	Integration of Air Traffic Management and Operations Simulator (ATMOS), PD/2 Ground Human Machine Interface (GHMI), Datalink, Weather Model, Integration of ATTAS test aircraft and Experimental Cockpit, Test and Supervision environment, PD/2 Training System

*Table 1 PHARE Projects contributing to PD/2*

## 1.4 REPORT STRUCTURE

The operational concept, the tools, and the GHMI are described in Section 3. A description of the research facility is presented in Section 4. An overview of the experimental design and the primary assumptions used in the analysis is given in Section 5. A description of the controller training and its conclusions follow in Section 6. The main results derived from the PD/2 trials are given in Section 7. The report's conclusions are presented in Section 8.

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## 2 AIM OF PHARE DEMONSTRATION 2

Within the general objectives of PHARE to develop the various elements of the PHARE Operational Concept, and to demonstrate a fully integrated future ATC system that enables the controller to handle a larger number of aircraft without significant increase in workload, the specific objectives of the PD/2 trials were:

1. To assess **controller workload** and **performance of arrival traffic handling** in an ETMA environment with
  - introduction of computer assistance,
  - computer generated 4D profile-planning and sequencing,
  - controller support to plan and establish a conflict free trajectory covering all flight phases from Entry Fix to the Approach Gate of an airport,
  - an increasing proportion of 4D FMS equipped aircraft with full two-way datalink.
2. To gain a degree of **controller acceptance** for the introduction of computer assistance.

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### 3 THE PD/2 SYSTEM

This section briefly describes the underlying operational concept of PD/2 and PHARE Advanced Tools together with the specifically designed GHMI used in PD/2.

#### 3.1 OPERATIONAL CONCEPT

PD/2 focused on the management of arrival traffic in an Extended TMA (a Terminal Manoeuvring Area with its adjacent en-route sectors) and envisaged a system to be used in a post 2000 timeframe. Therefore it was assumed that the controller working procedures, the working environment and the airspace structure would have no major differences to the current system. The planning and control procedures would still be based on current ATC practices and the human functions of 'planning' and 'tactical' control were assumed to remain sector-based in PD/2.

The real-time simulations of PD/2 aimed at the comparison of three different modes of operation characterised by three organisations, named ORG 0, ORG 1, and ORG 2:

##### **ORG 0:**

Org 0 was a reference mode, by which the controller had to handle traffic samples with current standard means (radar data, flight plan data, paper flight strips, weather information, radio communication, and assistance from an arrival planning system with basic sequencing and scheduling functionality). The reference system emulated a planning system functionality which was limited to the **calculation of arrival times** using flight plan data, radar data, and weather information. It generated and displayed an arrival time sequence, but did not provide any trajectory information to the controller.

The following organisations made use of a new information element: The Trajectory.

A trajectory is defined as a series of profile and route points defining a 4D-path for an aircraft joined by straight or curved segments ( 4D or 4 Dimensional is used to denote positions in space defined relative to earth and time. These points can be considered as being latitude, longitude, altitude and time).

##### **ORG 1:**

Org 1 was an advanced mode with 4D profile planning, detection and resolution of planning conflicts. An arrival planning system (Arrival Manager) resolved most planning conflicts by separating all arriving aircraft in space and time. The following PATs assisted the Arrival Manager: Trajectory Predictor (Trajectory Predictor), Conflict Probe (CP) and Flight Path Monitor (FPM).

The implementation of **4D trajectories calculated by the ground system** was performed by using conventional radio communication to the aircraft. Advisories<sup>1</sup> displayed to the controller were generated by the ground system in order to support the controllers in meeting constraints of the Arrival Manager.

Deviations of aircraft from the planned trajectory as well as unsolved conflicts between planned trajectories (detected by the Conflict Probe) had to be resolved manually by the controller. The system supported the controller in this process by measuring deviations (done by the Flight Path Monitor) and displaying the deviations in time and space against the planned trajectory (calculated by the Trajectory Predictor).

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<sup>1</sup> Advisories are control instructions such as "Descend to flight level 100 at 1700 feet per minute"

Flight strips were not used and thus the controller worked within a stripless environment (neither paper nor electronic strips). The interaction between controller and ground system and also between the controllers was supported by direct label interaction mechanisms within the displays.

## ORG 2:

In addition to ORG 1, Org 2 introduced an **air-ground integrated** system. This allowed 4D FMS equipped aircraft to use datalink to negotiate and implement airborne calculated trajectories that fulfilled the constraints developed by the Arrival Manager in order to implement an arrival sequence and schedule. For unequipped aircraft, the trajectory support was provided by the ground system as in ORG 1.

Thus, the definition of the ORGs led to an operational concept that allowed three guidance modes to be applied:

- An aircraft in **class A guidance** mode was 4D FMS and datalink equipped and had the clearance to implement its own trajectory automatically.
- A **class B guidance** mode was available for all aircraft that were guided via R/T, and for which the ground system had support in form of a conflict-free trajectory and the associated advisories.
- An aircraft in **Class M or manual guidance** mode was guided via R/T without using trajectory information, as applied in the current systems.

That meant that in ORG 0 only Class M, in ORG 1 Class B and Class M and in ORG 2 Class A, B, and M guidance modes were possible. It should be noted that all guidance modes of the lower ORGs were further supported in the higher ORGs. It is an important result of PD/2 that definitions of operational scenarios for the higher ORGs could be found without the requirement of a revolutionary change when moving toward more advanced organisations. The compatibility with lower guidance levels down to Class M solves the problem of connections to or transitions between areas with different levels of capability. Another advantage is that lower guidance modes can be used as safety net in case of failure of the higher guidance modes.

Figure 1 shows the transitions between guidance modes that were modelled in the PD/2 trials. Controllers monitored the flight progress of a Class A aircraft. If no problem was detected these aircraft flew without R/T communications other than 'initial call' when entering and 'frequency change' when leaving the sector. However, every time controllers saw the necessity to intervene, e.g. due to safety reasons, they could guide the aircraft via R/T. The first heading, speed or level change command given via R/T to Class A aircraft implied that this aircraft was guided further via R/T. A negotiated contract between air and ground via datalink was no longer valid after the implementation of the R/T command and the status of aircraft automatically changed from Class A to Manual mode as the system was updated about the tactical intervention by GHMI input. As a rule R/T communication always had priority over datalink communication.

An aircraft once degraded to Class B or Class M mode could not get back to Class A because a re-negotiation procedure was not implemented in PD/2. Whereas a transition between Class M and Class B guidance was always possible depending on the deviation of an aircraft from its 4D position on the planned trajectory as detected by the FPM.

With Class B guidance the 4D guidance of the aircraft along its trajectory was achieved by the Tactical Controller passing the advisories generated by the ground system to the aircraft by R/T.

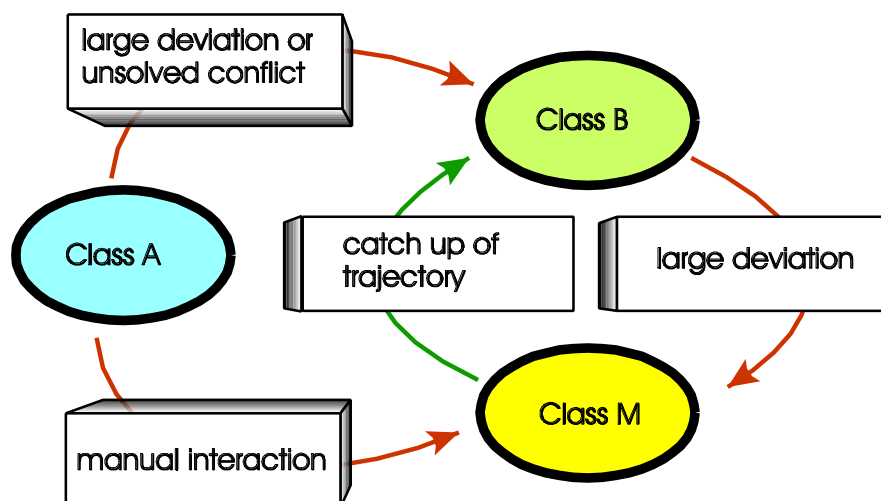


Figure 1 Transition of Guidance modes in PD/2

Transitions from Class M or Class B guidance modes back to a Class A guidance mode for 4D FMS by air-ground re-negotiation via datalink or voice as well as a Class B guidance via datalink messages from the ground were not exercised in PD/2 measured trials. However, these are options compatible with the operational concept that was developed for PD/2.

## 3.2 PHARE ADVANCED TOOLS

The PHARE Advanced Tools (PATs) provided the ground based support tools and functions to assist controller productivity. The following sections describe the subset of PATs that were integrated in PD/2.

### 3.2.1 Trajectory Predictor (TP)

For the ground system the Trajectory Predictor provided the trajectory as the new basic information entity extending the flight plan information in use today (for the airborne part an 4D FMS and datalink equipped aircraft can provide this information).

The Trajectory Predictor generated the trajectory information for each aircraft. In PD/2 only the arrival part of the trajectory was used, equivalent to about 30 minutes flying time including the top of descent from cruise level until the Approach Gate (10 NM from runway threshold). All trajectories were generated using standard arrival routes (STARs).

### 3.2.2 Conflict Probe (CP)

The Conflict Probe compared the new trajectory of an aircraft entering the simulation with all trajectories already stored within the flight database of the ground system. Any violation of separation criteria like radar separation or wake vortex separation was identified and displayed in space and time.

### 3.2.3 Flight Path Monitor (FPM)

The Flight Path Monitor compared each radar position of an aircraft against the 4D position taken from the active trajectory stored in the ground system. Deviations in terms of distance in space and time were produced with the surveillance update rate, for further processing by the supporting tools like the Arrival Manager, and for being displayed to the controllers.

### 3.2.4 Negotiation Manager (NM)

In PD/2 the Negotiation Manager took care of the air-ground exchange of information with respect to trajectories. The Negotiation Manager controlled the interface between the ground-based tool set and the 4D FMS equipped aircraft which were connected via the air-ground datalink system.

### 3.2.5 Arrival Manager (AM)

The Arrival Manager formed the central tool in the PD/2 environment. The tool worked over multiple sectors of an extended TMA in order to provide optimised scheduling and sequencing advisories for all arriving aircraft. Basic Arrival Manager functionality is in use in current day systems already; it is based on arrival time prediction which is typically integrated in those tools using flight plan information, for instance COMPAS. In the advanced concept of PD/2 this basic functionality of arrival management was extended and based on trajectory information, either generated by airborne systems within 4D FMS, or by a ground based trajectory predictor.

In addition for PD/2 the Arrival Manager generated the route, profile, speed and arrival time advisories based on the information from the trajectory, and these were then transferred to the GHMI. The AM also provided the functionality to update constraints either by deviation events given by the FPM or by controller inputs that affected the contracted trajectory status.

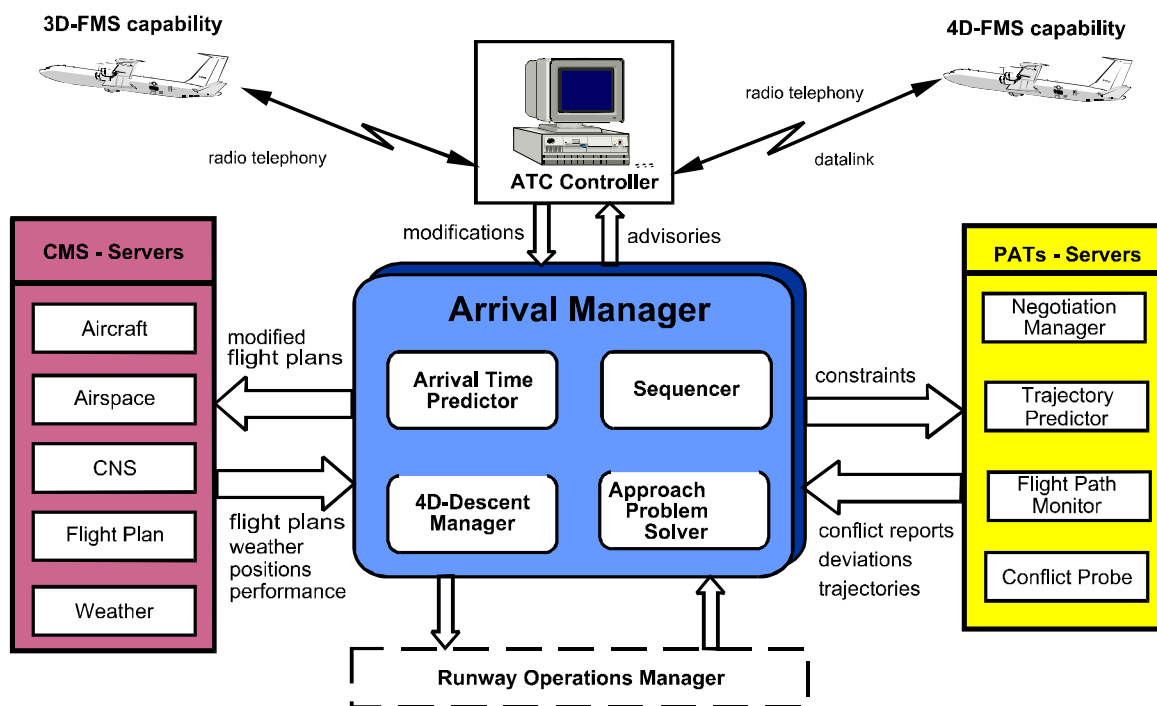


Figure 2 Arrival Manager in the PD/2 context

Figure 2 shows how the Arrival Manager was embedded in the tool set of the PD/2 system. On the left the tools available in current day ATC systems are represented by the CMS platform. On the right the advanced tools used for processing the trajectory information on the ground are listed. The information was exchanged with the airborne systems via the controllers R/T or via datalink. A connection to a Runway Operations Manager shown at the bottom was not implemented in PD/2, but was included in the AM concept.

The Arrival manager of PD/2 was composed of four main components: Arrival Time Predictor, Sequencer, 4D Descent Manager and Approach Problem Solver.

### 3.2.5.1 Arrival Time Predictor

The arrival time predictor gathered all necessary information, which was mainly airspace data and flight plan data, to prepare a constraint list. This constraint list was sent to the Trajectory Predictor tool for ground-based calculation of a preferred trajectory together with the earliest and latest possible arrival time at the Approach Gate. If alternative routes were possible a trajectory is stored in a separate context with the set of estimated arrival times together with those for the alternative routes. Each entry of a new inbound flight indicated by the ground system - at the boundary of the Extended TMA - activated the Arrival Time Predictor Module.

### 3.2.5.2 Sequencer

The sequencer tool provided the sequencing and scheduling functionality of the Arrival Manager based on the trajectory information of all known aircraft. In the first step the preferred times at the Approach Gate were checked against separation violations in time. If no violation was found the CP tool was triggered to check whether a separation violation existed between the trajectory under test and all other trajectories already planned by the system. If the CP reported no conflict, the aircraft was scheduled for the preferred time it is showed that a conflict free solution existed for the aircraft. If the aircraft was 4D FMS equipped then the NM tool was activated to initiate a negotiation via datalink. The ground constraint list was uplinked and the aircraft sent down an airborne trajectory. This trajectory was checked again by the CP against all other trajectories already planned and agreed. If no problems were detected the airborne trajectory replaced the one calculated by the Trajectory Predictor.

If aircraft were in conflict with their arrival times a branch and bound algorithm was activated to sequence according to predetermined rules such as first come first serve, close gaps in the sequence, optimise wake vortex categories. The arrival times were varied within the earliest and latest time limits in order to optimise the sequence. If alternative routes were allowed, which could even belong to different runways, those routes would also be checked for a better solution. The set of new constraints for these routes would be edited into the flight constraint list and a new trajectory would then be generated by the Trajectory Predictor to fulfil the new constraint for arrival times and possibly for a new runway allocation. If the Conflict Probe tool found no conflicts, the aircraft were scheduled for that target time. In that case 4D FMS equipped aircraft were uplinked a constraint list that already contained the optimised ground based arrival time and route. If the downlinked airborne trajectory fulfilled the constraints and was conflict free it replaced the ground-calculated one and the Negotiation Manager tool initiated an acceptance uplink to the aircraft. For aircraft not equipped to negotiate and implement airborne trajectories the Negotiation Manager tool immediately activated the corresponding trajectory, calculated by the ground system. The GHMI also received and displayed the information on the trajectory of new scheduled and sequenced aircraft

At the border of the Extended TMA, an equipped aircraft went through the following sequence of air-ground negotiation steps in order to agree or 'contract' its trajectory that it would then implement automatically:

1. Uplink of Constraints

A message was uplinked to the aircraft containing at least the route identifier and time constraints at the gate. This required that the Arrival Manager had completed the 4D planning of the aircraft, on the basis of information available on the ground. This can be a ground-based trajectory calculated by the Trajectory Predictor, or a trajectory already downlinked by the aircraft in a previous sector.

2. Downlink of Trajectory

If the aircraft accepted the uplinked constraints it downlinked a trajectory which fulfilled the constraints based on the current weather information obtained. If the aircraft could not fulfil the constraints it downlinked a message indicating that it was unable to fulfil the constraints. The aircraft was then guided via Radio-Telephony (R/T), as for an unequipped aircraft. Each downlink of a trajectory caused a new check of the trajectory against all other active system plans on the ground in terms of conflicts and constraints.

### 3. Uplink Clearance

If, as normally expected, there was no conflict with a downlinked trajectory that met the constraints, a "contract given" message is exchanged.

#### 3.2.5.3 Approach Problem Solver

In case of problems such as conflicts found by the Conflict Probe the Arrival Manager varied altitude and time constraints on other route points before the Approach Gate in order to obtain a conflict free trajectory. This capability included in the PD/2 Arrival Manager was limited because it took into account only the trajectories of the arrivals, but no departures and overflights.

If no conflict free trajectory solution could be found the scheduled time in the arrival sequence was maintained but the trajectory was marked as 'in conflict' on the controllers display. The Arrival Manager would still provide an arrival slot for those aircraft but could not provide a conflict-free solution. It was then the controllers' task to find a solution. This was normally easy to achieve simply by vectoring the aircraft off from its route to avoid the predicted conflict.

#### 3.2.5.4 4D Descent Manager

The task of the 4D Descent Manager module was to support the implementation of each scheduled trajectory. This was done by translating the trajectory representation into advisories applicable as control commands via R/T. Those advisories were generated for turns, descents, descent rates, and speeds. In addition, the position and time that the specific advisory should be applied was produced. This information was transferred to the GHMI before expected execution time to allow an advanced indication to the controllers of the application of advisories. Deviation messages were given regularly by the Flight Path Monitor were used by the 4D Descent Manager to decide whether the guidance mode of an aircraft had to be changed.

## 3.3 SIMULATED AIRSPACE

PD/2 addressed the terminal approach issues by simulating several sectors of an extended TMA and by emulating entry and exit conditions at en-route sectors. Figure 3 shows schematically the airspace used to model an extended TMA for arrival traffic. The organisation of the airspace was still assumed to be as it is today. The basic layout was taken from the Frankfurt TMA. Adjacent to the TMA were three en-route sectors, each controlled by an area control centre (ACC).

At the centre of figure 3 the parallel runway system (25L and 25R) is located. In contrast to Frankfurt, these were wake vortex independent. The dotted lines pointing to each of the parallel runways indicate the extended centrelines of an ILS. The arrival route structure is shown as solid lines. Inbound traffic entered the TMA via the metering fixes Rudesheim RUD, Gedern GED, and Spessart PSA. Traffic from north was planned to land on the northern runway (25R), traffic from south on the southern (25L). However, arrivals from the West could be routed either on a southbound or northbound STAR to the allocated runways. The arrival traffic was handed over to the tower controller (this position is not simulated in PD/2) about 10 NM from threshold at the so-called Approach Gate (shortened to 'Gate' in the following text). The Gate position corresponds to an altitude of 3000 ft. On Figure 3 the Gate is marked as blue line perpendicular to the extended centreline marks.

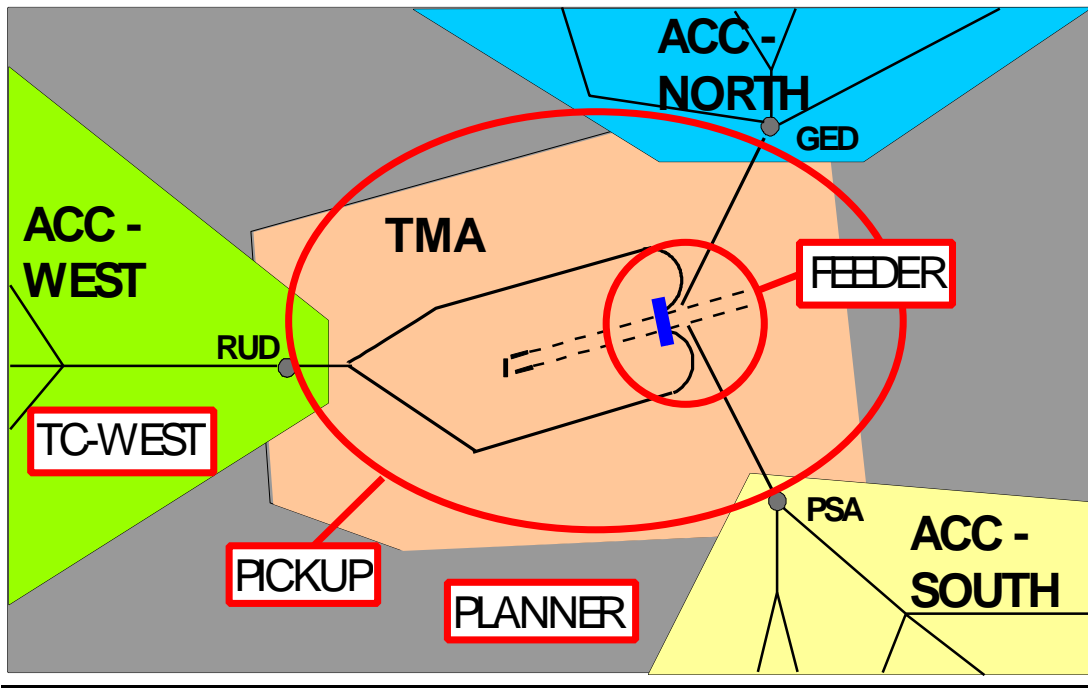


Figure 3 Extended TMA

### 3.4 Controller Roles

In the PD/2 simulation four different controller working positions were responsible to guide the arrival traffic (see figure 4).

#### **En-route controllers**

In PD/2 only the Area Control Sector West (ACC-W) was staffed with one Tactical Controller (TC-W). The other ACC sectors North and South were simulated automatically as if an ideal controller team was working there. The Tactical Controller ACC Arrival West (TC-W) controlled the arrival traffic and overflights (traffic from and to other airports) within the West Sector.

In PD/2 the TC-W also performed the task of the Planning Controller West (PC-W) because only the co-ordination with the adjacent TMA sector was modelled.

#### **Approach controllers**

Approach (APP) controllers controlled the TMA sector.

Two working positions for tactical controllers, a TC-P (for Tactical Controller APP Pickup) and a TC-F (for Tactical Controller APP Feeder) were needed working within the same airspace but on different R/T frequencies.

The team of the two tactical controllers was completed by a Planning Controller Approach (PC-A).

The three APP controllers sat alongside each other and shared their displays, supporting the necessary close teamwork and co-ordination between them in a very flexible and natural way.

#### **Planning Controller Approach (PC-A)**

The Planning Controller Approach had the following tasks:

- Identification and assessment of potential conflicts between aircraft offered into the sector by use of flight-plan/trajectory information, AM data, FPM and CP messages and Radar data, too.

- Notification to the TC-P and TC-F on any special conditions about the traffic before entering the sector.
- Co-ordination with TC-P and TC-F when a Class A to Class B aircraft planned change was to be applied.
- Co-ordination with PC/TC of adjacent sectors when entry and exit conditions had to be changed.

### ***Tactical Controller Pickup (TC-P)***

The main tasks of TC-P were to establish the AM landing sequence and to prepare a safe and efficient runway allocation for the TC-F.

In close co-operation with TC-F the TC-P was responsible for ensuring conflict-free passage of aircraft (minimum separation: vertical 1000 ft; lateral 3 NM, for Wake Vortex relevant combinations of aircraft up to 6 NM) through the TMA airspace. The TC-P had the following tasks:

- performing R/T Communication with aircraft (At least initial contact confirmation and frequency change command to initiate handover to TC-F for arrivals and to other ACC TCs for overflights),
- checking if aircraft have got the latest weather information,
- surveillance of aircraft using the radar information
- application of guidance and control commands in order to avoid separation conflicts,
- application of guidance commands until the transfer region (vicinity of extended centre-line for arrivals where the transfer to TC-F took place, Exit Fix for Overflights) in order to fulfil AM schedule and sequence using the AM display and 4D advisories for Class B arrival aircraft,
- updating the ground system with the guidance commands given,
- negotiation with TC-F and TCs (*and/or* PCs) of adjacent sectors when standing agreements had to be changed,
- holding aircraft within the sector if necessary, either on request of TC-F or in case of any doubt on the status of standing agreements.

### ***Tactical Controller Feeder (TC-F)***

The main task of TC-F was to guide the aircraft without conflicts (minimum separation: vertical 1000 ft; lateral 3 NM, for wake vortex relevant combinations of aircraft up to 6 NM) to the extended centreline. TC-F gave ILS clearances and to established separation over the threshold by speed commands up to the Outer Marker (4 NM from threshold).

The transfer of communication to the Tower Controller normally took place near the approach gate..

The TC-F had the following tasks:

- performing R/T Communication with aircraft (At least initial contact confirmation, ILS clearance and a frequency change command to initiate handover to tower controller for arrivals),
- surveillance of aircraft using the radar display and weather display,
- application of guidance and control commands for deconfliction,
- guidance of the aircraft to the approach gate to meet the Arrival Manager schedule and sequence using the Arrival Manager display and the 4D advisories for Class B arrival aircraft,

- updating the ground system if an aircraft had to be guided manually, if the AM guidance support can not be applied,
- giving clearance for allocated ILS,
- establishing separation on ILS,
- informing PC-A and TC-P when a sequence cannot be met,
- negotiating with TC-P and Tower Controller when standing agreements had to be changed,
- updating the electronic system when changes in aircraft status and applied commands were not in agreement with the recommended advisories from the 4D Guidance support system.

### 3.5 Limitations of the PD/2 System

Every real-time simulation has to make simplifications and idealisations as compared to a real system. In the interpretation of the results the following limitations of the system under investigation have to be taken into account:

For the periods of data collection stable operational conditions applied:

- No weather changes, no runway direction changes, no missed approaches, and no holdings were modelled.

The plans developed by the system were not changed within the TMA:

- No trajectory updates, therefore no re-negotiation and no recovery of Class A status was possible,
- no controller induced plan updates were allowed.

Co-ordination between sectors was simplified:

- Only the West sector was staffed. Traffic from the ACC South and ACC North sectors were simulated automatically, as if the traffic would be delivered by ideal controller teams in accordance with the computer generated plan (especially for ORG 0 this was a very optimistic assumption).
- The co-ordination tasks between ACC sectors were neglected, no further feeding ACC sectors were modelled.
- The airport to TMA interaction was excluded, therefore no Tower position was simulated.

The system worked under the assumption of de-coupled traffic streams:

- Departure traffic was assumed to be independent from arrivals. No departure traffic was simulated.
- Some overflight traffic was simulated as background traffic, but the PD/2 tools were primarily designed for inbound traffic for their calculations (no en-route – arrival interaction modelled).
- The staffed ACC sector had no trajectory-based tools specifically for handling of en-route traffic (as e.g. the HIPS<sup>2</sup> in PD/1)

PD/2 did not model short-term collision warning systems either on ground or in the air:

- No effect of airborne TCAS systems was modelled.

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<sup>2</sup> HIPS - Highly Interactive Problem Solver.

- No short-term conflict alert system was available for the controllers.

PD/2 was designed for a specific TMA with:

- only one airport within the TMA,
- a Parallel runway system that was assumed to be independent, and
- no obstacles or restricted areas were modelled

PD/2 worked on IFR procedures only:

- No VFR procedures were included
- ILS approaches only

### **3.6 Ground Human-Machine Interface (GHMI)**

The GHMI used in PD/2 was designed within the PHARE GHMI project and provided a prototype of a paperless system for approach controlling the advanced Organisations (ORG 1 and ORG 2). This section focuses on a short illustration of the principal elements of the GHMI. A detailed description is given in Annex G. The GHMI consisted of a multi-window environment that could be configured with the help of a GHMI administration tool to allocate the different tools (windows) to the different screens at the controller working position. For ORG 0 a reduced mode of this system was used, together with paper strips for flight plan information which served as controllers' scratchpad. The sequence of arrivals was indicated on a time ladder of the Arrival Management Display (AMD). The Plan View Display (PVD) simulated a conventional radar system with a two-line label at each target that showed callsign, altitude/flight level, and ground speed.

The main elements available on each working position were the Plan View Display for the Radar information together with a Conflict Risk Display (CRD) in case of conflicts between trajectories on the large screen and an Arrival Management Display for the planning controllers on the smaller screen. For the ACC controllers additional Sector Inbound List windows were shown on the PVD in order to provide the flight plan information in advance for selectable entry and exit fixes. Also in the ACC-position an additional Vertical View Display (VVD) window provided a vertical view of the traffic over fixes where holding patterns were normally located. However, note that holding patterns were not used in the PD/2 simulations.

#### **3.6.1 Plan View Display (PVD)**

The PVD showed the plan view of the airspace together with the labelled radar targets (Figure 4). A radar tool box window allowed the controller to select the centre, the scale, the number of history dots displayed together with the radar targets as well as the airspace elements to be shown and the label deconfliction method. In case of a planning conflict, the Conflict Risk Display (CRD) popped up on the PVD. In this window the callsigns of the conflicting aircraft were listed together with an indication of the time ahead of a conflict (minutes) and the minimum distance at conflict time (nautical miles). Optionally the labels of the associated aircraft were highlighted on both the PVD and AMD. Please note that no short-term conflict alert was included in the PD/2 system.

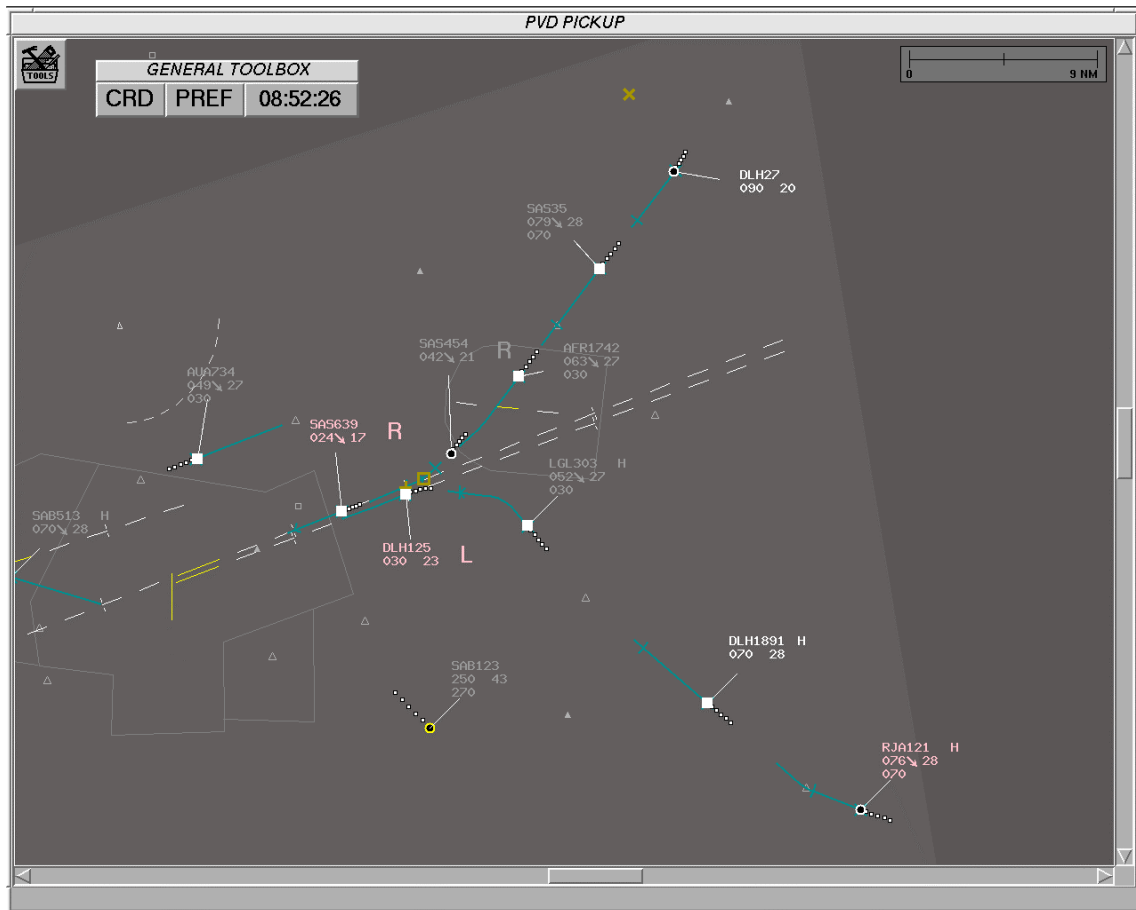


Figure 4 Plan View Display (PVD)

### 3.6.1.1 Aircraft Label

The aircraft labels provided the main interaction mechanism for the advanced Organisations. A controller selected a label simply by moving the mouse cursor over the label. Selection was indicated automatically by a background field containing the label lines in reverse colour. The label colours grey, pink and white indicated whether the aircraft was under the control of another controller, was in a transfer status, or was under the sector's control. Transfer could be initiated by clicking a transfer field in the upper left corner of each label. Pop-up menus from the labels were also available to input flight level, airspeed, and rate of descent/climb values. A heading change could be input by clicking on the 'heading' field to pop-up an arrow that could be dragged around the radar target by the mouse, helping to select a heading value which was also indicated numerically. Inputs were always carried out with the left mouse button whereas outputs extending the label data, such as destination airport or weight class, were obtained with the right mouse button. The same label interaction was also available on AMD and VVD by moving the mouse pointer over the callsign indicator of an aircraft.

The aircraft symbol showed the equipment level of an aircraft. A square indicated 4D equipment (datalink and 4D FMS), a circle indicated non-4D equipped aircraft. Class A aircraft with a cleared contract were shown as a filled square and Class B aircraft, with ground trajectory support only were indicated as outlined circle or square. If an aircraft was guided manually by the controller the target became yellow.

### 3.6.1.2 Trajectory representation

Figure 5 shows the PVD representation with selected label and complete trajectory on the example of SAS171 arriving on a northern route via metering fix Gedern to RWY 25R on the left bottom of the figure.

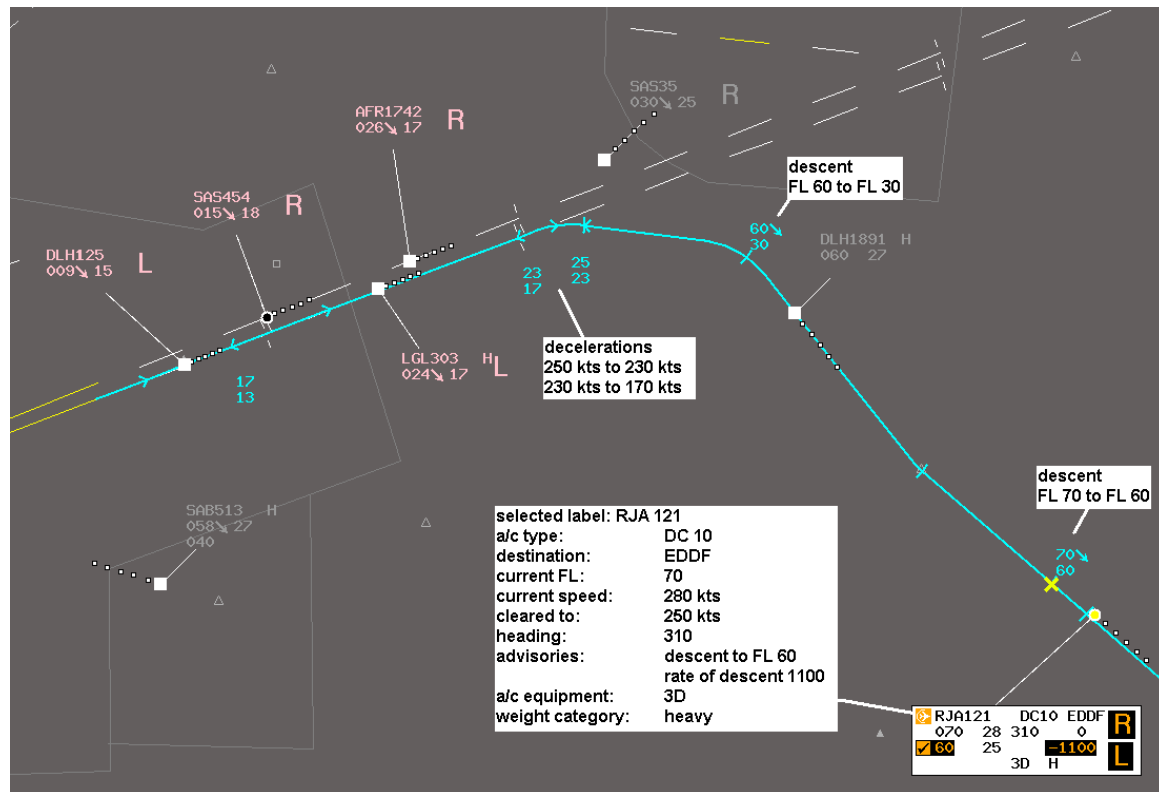


Figure 5 Trajectory Presentation at PVD

The trajectory information is visible on the PVD graphically as a blue line along the whole route for each aircraft individually. The planned position of an aircraft is marked as a blue cross at the trajectory line. Another option was available to make only the future planned path for all aircraft visible as blue lines starting with a cross at the planned present position. The length of this 'future-line' was selectable (in steps of 1 minute).

### 3.6.2 Arrival Management Display (AMD)

Sequence and scheduled time calculated by the AM was represented on a time scale (time ladder), with progression from top to bottom. Figure 6 shows the AM display layout for the Approach Controllers. Here the time for the Approach Gate is the reference time. For ACC West the time over metering fix RUD is the reference time.

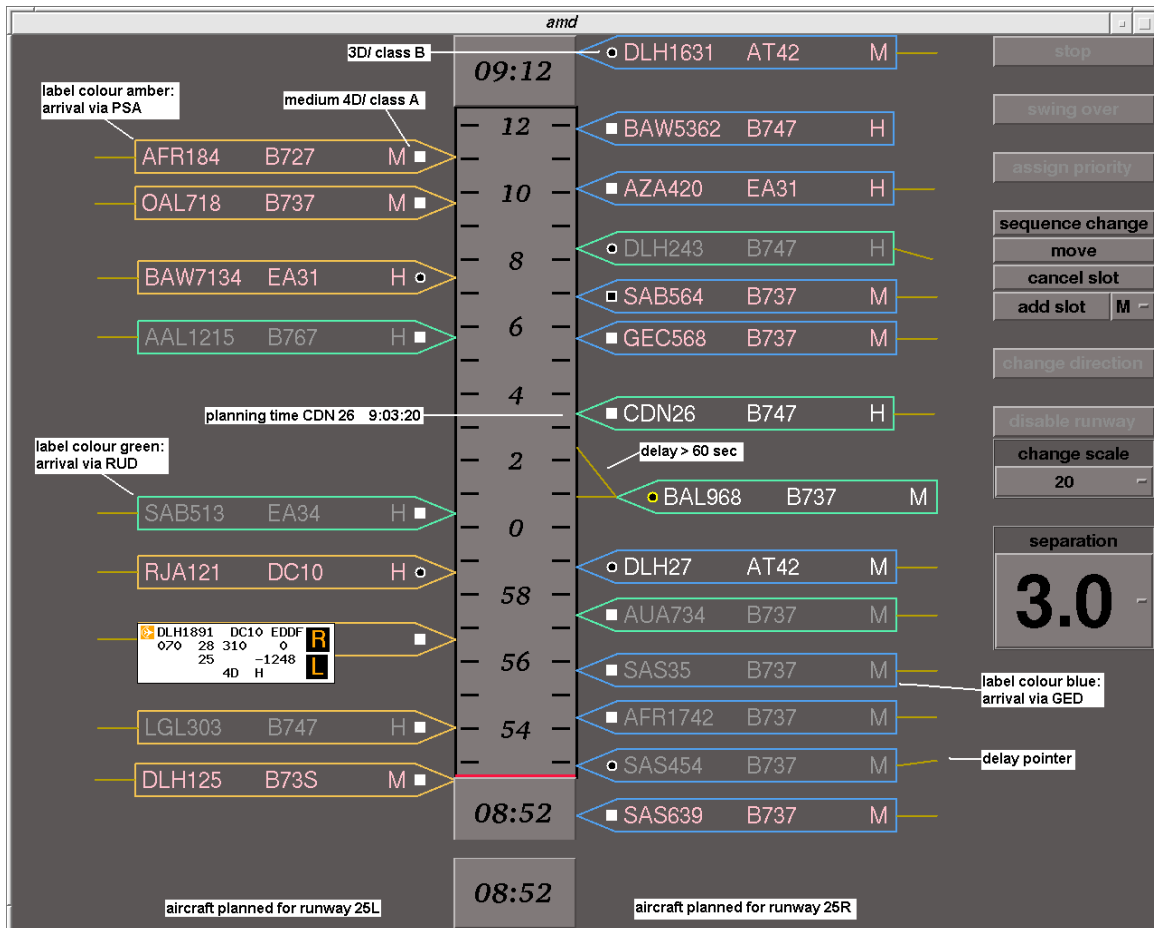


Figure 6 Arrival Management Display Approach

The input buttons shown at the right inform the Arrival Manager about significant changes of certain constraints such as RWY direction change, necessity to insert a slot, or change of the minimum separation in use. In order to keep the traffic demand during the experiments unchanged this functionality was not used in PD/2.

The aircraft labels in the AM Display of the Approach indicate the runway allocation, 25Left or 25Right. They are framed in different colours showing the different arrival routes (blue = north, yellow = south, green = west).

Aside of each label frame the angle of the 'delay pointer' shows the deviation in time as measured by the FPM. A pointer deflected downwards indicates an aircraft that is early, a pointer deflected upwards indicates a delay, whereas a horizontal tail line indicates no delay.

### 3.6.3 Advisories

In the complex approach environment control of aircraft by R/T can never follow a trajectory as accurately as a 4D – FMS. There will also be differences between the ground meteorological model and the actual weather. For these reasons, the end of the trajectory was marked with an X to indicate the desired position of the aircraft. Controllers were then at liberty to modify the R/T advisories as required to maintain the aircraft on its trajectory.

Special markers on the displayed trajectories indicated significant positions when the aircraft state would undergo changes such as start/end of descent or speed changes. Written at those markers in two lines were the previous and new target values. In addition for class B aircraft, yellow

markers showed where to apply the next advisories. An outlined square was used for a heading, a tilted cross for altitude and an upright cross for speed advisory positions. These markers disappeared when the controller confirmed the advisory.

The advisories of the Arrival Manager were displayed in orange colour in a third label line for advised altitude/flight level, airspeed, heading, rate of descent, and were preceded by a tick marker field that could be clicked on by the controller when the R/T command was activated. In that case the third line showed the last cleared FL if the aircraft had not reached it. The orange advisories disappeared automatically when the time of application was passed.

## 4 TRIALS FACILITY

The PD/2 trials were conducted on the Air Traffic Management and Operations Simulator ATMOS of DLR. The airborne demonstrations included the experimental cockpit and DLR's ATTAS. This section provides a brief overview of the facilities and their configurations for the trials.

The picture below gives an impression of the ATMOS environment and the controller working positions.



*Figure 7 Working positions of ATMOS during the PD/2 Experiment.*

### 4.1 ATMOS HARDWARE

The ATMOS hardware for PD/2 consisted of the following elements:

- a network of Pentium PCs serving the Sony PVD and 19" AM Displays, providing the controllers with an interface to the system
- a DEC 3200 workstation supporting the basic ATC simulation
- 6 pseudo pilot terminals connected to the DEC 3200 workstation by serial lines
- an DLR developed R/T system providing simulated R/T channels between controllers and pseudo-pilot as well as live R/T channels for use with the ATTAS aircraft
- a cluster of three Sun workstations supporting the PATs set in a CMS environment
- 4 Silicon Graphics Workstations supporting a datalink simulation, the interface between basic ATC simulation and CMS/PATs system, a data server for the GHMI data, and the trials data storage and pre-analysis

- An additional Pentium PC was used for the GHMI supervision and configuration control
- a connection to the ATTAS simulation environment, providing access to the EFMS either by a ground link based on Ethernet, or to the ATTAS aircraft by using a telemetry datalink
- Input devices for subjective workload assessments (SWAT)
- 6 video cameras with three video recorders for storing the trials on video together with the audio signals

For the training system some parts of the ATMOS hardware was duplicated:

- a network of PCs serving BARCO 2500 and 19" Displays, providing controllers with an interface to the ATMOS training system and the PC-based GHMI training tools
- a DEC 3200 Workstation supporting the basic ATC simulation without pseudo-pilot terminals
- a Sun workstation, supporting the PATs/CMS tools
- 2 Silicon Graphics Workstation supporting the interface between basic ATC simulation and CMS/PATs system and holding a data server for the GHMI data

## 4.2 SOFTWARE

The major software components of ATMOS were:

- PATS tool set embedded in the CMS platform PARADISE
- a ground human-machine interface (GHMI)
- a multi-aircraft simulator model
- a surveillance and tracking system
- a datalink simulation with an interface to a telemetry datalink
- a flight plan and traffic generator
- a traffic simulation for unstaffed sectors
- a weather model
- supporting databases
- analysis tools for stored experimental data

## 4.3 ATTAS EXPERIMENTAL COCKPIT

For one run in each week of the PD/2 trials the ATTAS Experimental Cockpit, operating as a fixed-base cockpit simulator of DLR's ATTAS aircraft, was introduced into the simulated traffic scenario (Figure 8). The controllers handled the simulated ATTAS aircraft in the same way as the other simulated aircraft. The pilot was enabled to communicate with ATC by connection to the simulated R/T communication network. Also, due to the equipment of the Experimental Cockpit which allowed direct control of the ATTAS when fitted to the aircraft, the pilot was able to operate the Experimental Cockpit as Class A or B aircraft. Data link communication between the PD/2 ground system and the Experimental Cockpit, i.e. the EFMS as part of the cockpit environment, was realised by TCP/IP and Ethernet.

AHMI evaluation trials were performed with the Experimental Cockpit in the laboratory utilising the equipment described above. Six pilots participated in the experimental evaluation which focused on the Navigation Display layout as well as the interaction with EFMS by means of touch pad input as cursor control device for the Navigation Display. For purpose of these AHMI evaluation trials a

Data Link Dialogue Test Facility replaced the ATMOS connection to the EFMS and simulation, to ensure pre- and in-flight modification and re-negotiation of constraint list and trajectory. However, the connection was realised also via TCP/IP and Ethernet.



Figure 8 ATTAS Experimental Cockpit

#### 4.4 LIVE AIRCRAFT

For demonstration and evaluation runs during the PD/2 demonstration week in June 1997, DLR's ATTAS aircraft was introduced into the simulated traffic scenario as live 4D FMS aircraft (Figure 9). Aircraft control responsibility was allocated to the pilot seated in the Experimental Cockpit that in this case was fitted to the aircraft. For data link I/O, the pilot utilised the Control Display Unit of the EFMS or the AHMI, i.e. the interactive Navigation Display for planning the flight.

The aircraft was handled by the controllers in the same way as the other simulated aircraft, but with the trajectory negotiation process being conducted directly between the planning controller working position of the PD/2 ground system and the EFMS installed in the aircraft. The data link communication between the PD/2 ground system and the EFMS was conducted over DLR's telemetry data link system. A voice communication system enabled the pilot to follow ATC advisories in case of a downgrade of the ATTAS aircraft class from Class A.

The demonstration runs were performed in the local Braunschweig/Hannover area, a requirement that resulted from utilisation of the DLR telemetry data link system. However, for the experimental pilot the Frankfurt approach situation was simulated by means of an area offset calculation performed on-board the aircraft.

Whilst, in the majority of demonstration runs, the ATTAS was operated as a full 4D FMS aircraft (class A aircraft), two demonstration runs were performed with the ATTAS representing a Non 4D FMS aircraft, i.e. an aircraft without 4D FMS and data link. The controllers handled the live aircraft using R/T advisories in the same way as the other simulated Non-4D FMS aircraft.

The configuration details of the simulation facility during the trials are shown Figure 10.



Figure 9 DLR's Experimental Aircraft (ATTAS)

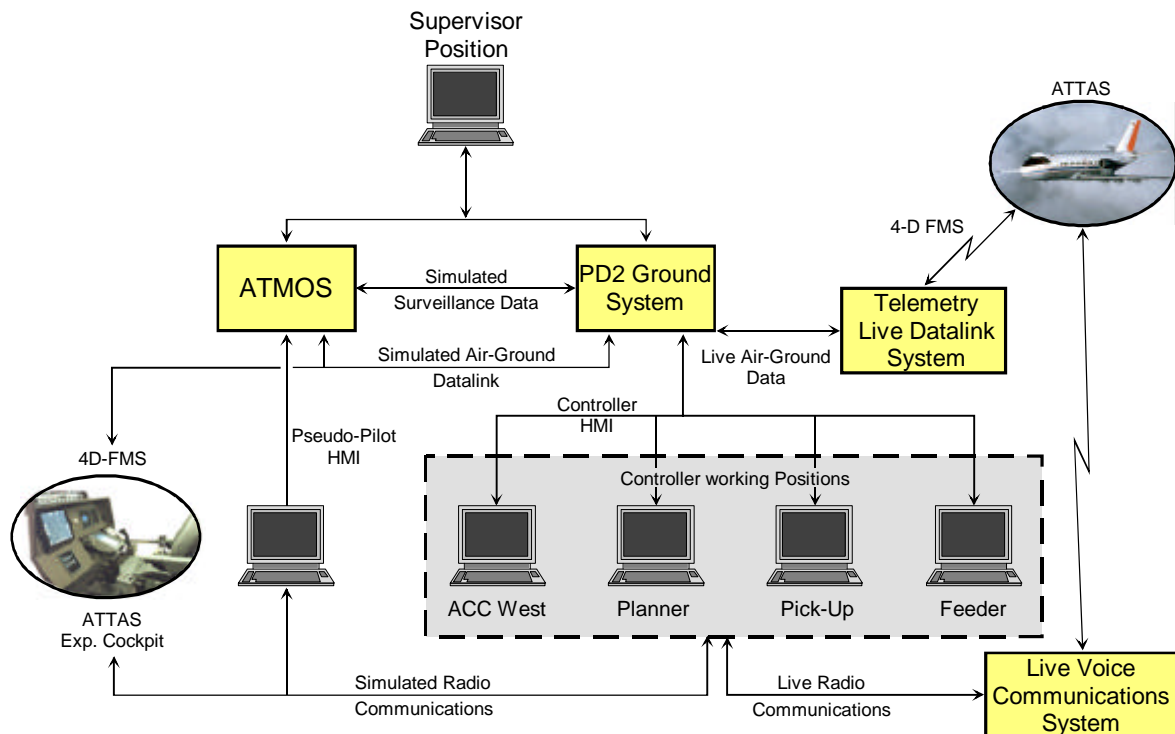


Figure 10 PD/2 Trials Configuration

## 5 METHODS

This chapter describes the experimental design, the methods used for collecting data, and the participating controller teams in the PD/2 trials. A more detailed description is given in Annex A.

### 5.1 EXPERIMENTAL DESIGN

Two independent variables were defined in PD/2: system organisation and traffic volume. Three different organisations (ORGs) were used:

- a baseline system (ORG 0), which corresponded to a typical strip-oriented ATC system with limited planning aids like those actively used today (e.g. COMPAS),
- an advanced system (ORG 1), in which the PHARE Advanced Tools and a new GHMI were implemented to assist controllers,
- ORG 2/ 30% and ORG 2/ 70% that had the same functionality as ORG 1, but additionally 30%, or 70% of 4D FMS and datalink equipped aircraft were introduced.

Table 2 below summarises the differences and conformities of the different ORGs, respectively and shows how they related to the objectives of PD/2. Analysis of ORG 0 against ORG 1 data focused differences due to effects of introducing computer assisted tools (PATs) and GHMI. Whereas the effects of increasing proportions of 4D FMS/datalink aircraft were shown by a comparison of ORG 1 data against ORG 2/ 30%, and a further comparison against ORG 2/ 70% data.

	<b>ORG 0</b>	<b>ORG 1</b>	<b>ORG 2/ 30%</b>	<b>ORG 2/ 70%</b>
PATS	Conventional planning	PATS trajectory based planning	PATS trajectory based planning	PATS trajectory based planning
GHMI	Reference system with paper strips	Advanced, no paper strips	Advanced, no paper strips	Advanced, no paper strips
4D FMS datalink	None	None	30 % of a/c in traffic sample	70 % of a/c in traffic sample

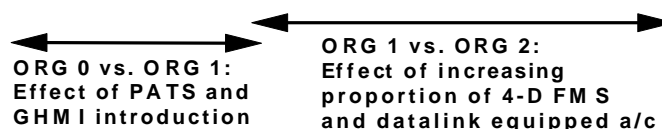


Table 2 Summary of Organisations

Two traffic samples were developed:

a 'medium traffic' sample in which traffic volume, mix of aircraft weight categories, and distribution over the arrival routes were tuned to represent a typical today's situation of Approach controller workload in peak traffic periods, and,

a 'high traffic' sample with an increase of more than one third of the 'medium' traffic. Actually, the sample had 37% more aircraft, with linear increases of both the number of aircraft per weight category and the number of aircraft on different arrival routes.

By using the two traffic samples in each ORG two different volumes of inbound traffic were employed:

- 'medium', corresponding to a traffic demand of 48 inbound aircraft per hour, and
- 'high', corresponding to an increased demand of 66 inbound aircraft per hour.

These figures were not further varied because the aim of PD/2 was not to increase runway capacity but to determine the effect of introducing computer assistance tools and 4D FMS/datalink. The experiment was based on repeated measurements of eight teams with four controllers in each team. All teams performed the same experimental programme. Four different ORGs, each performed under high and medium traffic load, resulted in eight measured runs per team.

The sequences of runs were balanced between teams, which meant that the order of the tasks was systematically varied to avoid any bias by learning, fatigue, or other order effects. Within a team's trials the Approach Pickup and Feeder controller rotated their positions, in conjunction with alternating between high and medium traffic volume in consecutive runs. This kind of repeated measurement design allowed a quantitative analysis of data that was supported by statistical significance tests of non-parametric statistics using matched pairs of observations. The chosen significance criterion for the statistical tests was  $p \leq 0.05$ . Full details of the experimental design and the data analysis are given in Annex A.

## 5.2 MEASUREMENTS

Early in the PHARE programme, a guideline entitled "Template of Measurements to be used in PHARE Demonstrations" identified the overall objectives of PHARE Demonstrations as being related to the criteria of system performance, controller workload, and acceptance. It defines a set of agreed, mandatory measurements and recordings that were to be applied throughout all PHARE Demonstrations. The table below gives an overview.

Criteria	Measurements and Recording
System Performance	<ul style="list-style-type: none"> <li>• Planned Traffic Data</li> <li>• Actual Traffic Data</li> </ul>
Controller Workload	<ul style="list-style-type: none"> <li>• ATC instructions issued</li> <li>• Subjective Workload Measures</li> </ul>
Controller Acceptance	<ul style="list-style-type: none"> <li>• Questionnaires</li> <li>• Debriefings</li> </ul>

Table 3 *PD/2 Evaluation Criteria, Measurements and Recording*

The data listed in the table were recorded directly from the simulation system and from controller responses. They were complemented by video-/audio-recordings of controller activities taken simultaneously from the four working positions during all the simulation runs, and by observer's notes logged by two PD/2 staff observers on each run. In this way, objective and subjective data were collected.

### 5.2.1 System Performance

The key measurements of system performance which were produced from the recorded data are the following:

- Number of Landings
- Flight Time

- Inbound Delays
- Precision of Delivery
- Separation

The performance domain refers to measurements of traffic throughput as well as quality of service because of the close relationship between the quantity of traffic throughput and the quality of service provided to airspace users. For instance, for a constant traffic sample as was applied in all ORGs of PD/2, the number of aircraft served per time unit (in PD/2 the **number of landings** per hour) which is often used as the most straightforward indicator of throughput. This value correlates with the average flight time in the TMA and average flight time is immediately relevant for an airline's perception of quality of service, since it affects delays, fuel consumption, etc.

**Inbound delay** was calculated in PD/2 as the difference between the *actual* time of Gate overflight and the *estimated* time of an aircraft's Gate overflight. The estimated, or preferred, time is computed at the early stage of an aircraft's entry into simulation and refers to its time over the Approach Gate if there were no other inbound aircraft and it could therefore follow its preferred trajectory. This preferred trajectory corresponded to the initial trajectory an aircraft sent down to the ATC and took into consideration not only an environmental flight-path but also the airlines operational procedures.

**Precision of delivery** was calculated from the difference between actual time over Gate and planned time over Gate. Note that the planned time over gate may already include an inbound delay because the planning algorithm has to account for the overall traffic situation either by using merely arrival time estimates in ORG 0, or by using conflict-free trajectories in ORG 1 and ORG 2. Precision of delivery was considered to be a useful indicator of how precisely the tools-generated plans were actually implemented.

Finally, **separation** over gate was chosen as an indicator to check whether potential benefits (in terms of flight time, delays, etc.) were achieved at the expense of reduced minimum separations.

### 5.2.2 Controller Workload

Workload was stated as one of the crucial elements of the PHARE demonstrations. To measure the effect of the PHARE operational concept on controller workload objective and subjective sources of data were analysed in PD/2:

#### Objective Workload Indicators

- Number of ATC instructions issued
- Frequency of R/T calls
- Percentage of simulation time spent for R/T communication

Three different parameters of workload indicating the activity of the tactical controllers while giving ATC instructions, respectively how much radio/telephony (R/T) communication is necessary for this, were calculated. These operational measures are often referred to as objective workload indicators.

#### Subjective Workload Estimates

- SWAT (Subjective Workload Assessment Technique)
- NASA-TLX (Task Load Index)

Subjective workload estimates were collected during the course of simulation runs using SWAT, and by using the NASA-TLX method after completion of each run.

SWAT is a three-dimensional approach to workload measurement. The dimensions or factors of workload in SWAT are Time load, Mental effort load, and Psychological Stress load.

Every two minutes during the simulations controllers were requested to give their estimates of workload by entering a number (1,2 or 3) for each factor. SWAT combines the entries into an overall workload score on a scale ranging from 0 to 100, thereby accounting for individually different importance weightings of the factors. The weightings have to be assessed once beforehand from an introductory session to SWAT. So SWAT provides a quasi-continuous record of workload during an exercise or simulation run.

NASA-TLX provided an off-line summary workload estimate immediately after the simulation runs from each controller. TLX identifies six factors contributing to workload: Mental demand, Physical demand, Time pressure, Effort expended, Own performance and Frustration experienced.

At the end of a run, the TLX input dialogue popped up on each of the controller screens. It asked him/her first to determine the relative importance of the six factors for this run by 'pairwise' comparison of the factors, and then to rate his/her workload for each factor on a 20-point scale from "low" to "high". From combination of weights and ratings, an overall score is calculated to estimate the controller's workload.

All tactical controllers rated their perceived workload themselves, whereas a different method was foreseen for the planning controller. As became apparent during the pilot phases of PD/2, the introduction of the PATS and furthermore the increasing proportions 4D FMS/datalink equipped aircraft had a tremendous impact on the role of the planning controller. The effect was that his tasks were re-distributed to the pickup and feeder controllers and it was little left for him to do. Therefore, in all trials of all ORGs the planner controllers were asked not to assess their own workload but that of the pickup and feeder controllers who constituted the approach team.

### **5.2.3 Controller Acceptance**

Acceptance, naturally a highly subjective matter, is nevertheless of great importance. It is based on subjective responses from controllers, but can be assessed objectively using questionnaires and a consensus of opinion of observers and from debriefing sessions. Therefore, controllers participating in PD/2 were intensively asked for their opinions, comments, and criticisms they had regarding the experiment, i.e. the simulation environment and training, as well as regarding the PD/2 concept in terms of the human/machine interface, operational procedures, and individual tools and functions.

This was done in two different ways. First, a debriefing session was held after each run. This was a tape recorded group interview. The PD/2 staff made use of a structured interview guide, observer logs, and simulation output data immediately available after each run (e.g. radar plots of horizontal flight paths).

Additionally, several questionnaires were applied: three questionnaires to collect the controller judgements for the three ORGs individually, and additionally a final questionnaire to collect the overall, non ORGs-specific issues. (A timetable is given in Annex A.)

## **5.3 RUNNING THE EXPERIMENT**

After two pilot phase weeks in October and November 1996 the PD/2 main experiment took place from Dec. 2, 1996 to Feb. 21, 1997. All controller teams were available for a two-week period, one week of training and familiarisation with the PD/2 concept and the environment, the following week for measured trials. The training of one team and the experimental trials of another team were

mostly conducted in parallel. Having a stand-alone training system enabled this approach and therefore there was no interference between trials and training sessions.

During each week of trials, eight measured runs of 90 minutes duration had to be performed. The measured runs were performed in blocks of two runs of ORG 0 and ORG 1, and four runs of ORG 2. The order of the blocks was varied systematically across teams. Each block was preceded by a warm-up run. After completion of the measured runs of ORG 2 a demonstration run was performed in which a live aircraft (ATTAS) was included in an additional ORG 2 traffic scenario. This produced a programme with 12 runs per week.

The demonstrations of the AHMI in the ATTAS Experimental Cockpit were carried out in a period between May 2 and June 15, 1997. Six pilots (one per day), with backgrounds as airline or test pilots, participated in the demonstration programme which consisted of a series of simulated flight tasks including FMS and datalink simulation. They evaluated the AHMI during five different flight tasks including on-board generation, negotiation, and implementation of 4D trajectories. The method of evaluation was to use structured interviews in which the following areas were addressed: the operational philosophy, display modes and functions, the interaction device and edit functions.

## 5.4 CONTROLLERS

The PD/2 trials were generously supported by many national organisations that supplied their controllers. 32 controllers participated in the trials, from 7 European countries. They represented all kinds of backgrounds in military and civil ATC, and a wide range of computer experience. There were teams that used to work together in their home unit over years as well as teams whose members had never met before PD/2. A mixed military/civil controller team was also involved. The table below gives an overview of the participants.

<b>PD/2 Pilot Phase</b>	
one team of 4 military controllers from UK	
<b>PD/2 Main Phase</b>	
32 controllers (eight teams) from	
• France (ADP)	• Romania (ROMATSA)
• Germany (DFS)	• Sweden (LFV)
• Italy (SICTA)	• United Kingdom (NATS)
• Netherlands (MilATCC)	

Table 4 Supporting organisations for controllers in PD/2

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## 6 TRAINING

Before the trials each controller team participated in a one-week training phase.

The objectives of the training were:

- introduction of the PD/2 concept
- GHMI familiarisation
- getting hands on experience in learning to use the PD/2 system in a profitable manner

The controllers had to be enabled to take part in the PD/2 trials with full understanding of the system handling and philosophy. All details of the conducted training and of lessons learned can be reviewed in Annex B.

### 6.1 THE COURSE

From December 1996 until February 1997 eight controller teams from seven European countries took part in the PD/2 training. The training course was conducted as a five-day training course, one week in advance of the measured trials.

To be able to conduct the training in parallel with the measured runs, a specially built stand-alone training system was used. The PD/2 training course was conducted in one large training room that provided a sufficient training environment for three tactical and one planning controller. The equipment included one workstation, three PC's, an overhead projector and screen, a conference table and chairs. All PD/2 related training was conducted in this facility.

Specific training material, covering the overall concept, the simulated airspace, and the handling of the GHMI was provided.

To satisfy the controllers' technical and operational questions and concerns, the instructor team consisted of an experienced Frankfurt controller and a technical trainer with system knowledge. The trainers mainly provided assistance in system handling and airspace management while the controllers were free to use their own choice of control practices.

See Annex B for a detailed description of the training course.

### 6.2 CONCLUSIONS FROM THE TRAINING

The PD/2 training programme succeeded in meeting the training objectives. The experience of the controller teams in the handling of today's PC systems differed a lot. However, due to their flexible approach to the training, all participating controller teams reported they were well prepared for the measured runs. Although the training programme was standardised, the PD/2 trainers succeeded in adjusting the programme in accordance with the individual crews' performances by varying the way the training was conducted. The results of the questionnaires (Annex B) reflect the good quality of the training programme and show that all participants fulfilled the above stated objectives.

During the training, some controllers did not use the stand-alone part of the system to their full benefit. Reading text written in a foreign language (English) and explaining a new and complex concept was tiring some of the teams and they initially failed in assimilating all lessons of the stand-alone training. These 'gaps' had to be filled during the training runs afterwards. Instructors should closely monitor how stand-alone training is being conducted by their trainees. It is important to ensure that there is always an instructor available, even if only needed for some simple translation assistance.

Aiming for a mixture of operational and technical knowledge in choosing the appropriate instructors seems to be the right way to ensure that all operational and technical questions and concerns of the controllers are being answered in a competent manner.

The training system should be a one-to-one copy of the main system. Due to the missing pseudo pilot interface at the PD/2 training system, the R/T communication could only be 'simulated' during training. Nevertheless, the 'warm-up' runs conducted before each measured run, proved to be sufficient enough to get familiar with the pseudo-pilot communication while handling the system.

The PD/2 team makes the following recommendations for future system trials:

- Some teams needed more training to get used to the specific TMA airspace and air traffic load, others needed additional lessons in PC handling (usage of mouse, menus, clicking, etc.). Therefore, the training course should be conducted in the most flexible way to accommodate for differences in knowledge and experience of controllers
- The course should provide a combination of operational and technical expertise
- A computer based training (CBT) course in advance of the main training activity would be of benefit, e.g. to provide controllers with CBT to use at their home base
- If possible, controllers with basic computer experience should be chosen for trials of advanced systems.

## 7 RESULTS

### 7.1 INTRODUCTION

The objectives of the PD/2 trial were to determine the effect on traffic throughput and controller workload by introducing PATs and 4D FMS equipped aircraft, as well as gaining a degree of controller approval for the concept and tools. The results are presented in detail in Annex C: Analysis of traffic throughput/quality of service-, in Annex D: Analysis of workload -, and in Annex E: Analysis of acceptance. This section summarises the major results presented therein.

PD/2 was a demonstration of the PHARE operational concept (section 3.1). It was not designed as a pre-operational system, going into service soon, but instead was meant for experimental and evaluative purposes. Therefore it is emphasised that the results presented in this section and in the annexes cannot be transferred directly to a situation or system used in reality. However, significant positive effects of introducing the PD/2 system identify a benefit that might occur in a real system. The absolute magnitude of effects that can be expected in real systems will certainly depend further on the actual characteristics of ETMA regions, route structures, and local operational constraints.

Finally, it has to be pointed out that a considerable number of class A aircraft were downgraded from class A during the simulations as a consequence of controller intervention, or because the PATs were unable to compute conflict-free trajectories in time for some aircraft supposed to be class A. In the PD/2 trials, there was no functionality to re-negotiate a trajectory and recover class A status (see section 2.1 of the Main Report for the mechanisms of transition between a/c classes). Therefore, the *actual* proportions of class A aircraft, i. e. those aircraft who kept their class A status throughout the ORG 2 simulation runs, were smaller than the defined ratios of 30% and 70%. In fact, the results reported for ORG 2 refer to the following overall ratios actually achieved at the Gate:

High traffic scenarios

ORG 2 (30%): 19% class A; 81% non-class A,

ORG 2 (70%): 39% class A; 61% non-class A.

Medium traffic scenarios

ORG 2 (30%): 21% class A; 79% non- class A,

ORG 2 (70%): 52% class A; 48% non-class A.

### 7.2 TRAFFIC THROUGHPUT/QUALITY OF SERVICE

This section summarises the results of the statistical analysis of the traffic-related data recorded during PD/2. Aspects of traffic throughput and aspects of quality of service are treated together here, because in the TMA a close relation between the quantity of traffic throughput and the quality of service provided to airspace users can be assumed to exist. For instance, the number of aircraft passing through an airspace per time unit which is often seen as the most straightforward indicator of throughput, can be expected to correlate highly with the average flight time of aircraft. Flight time is immediately relevant for an airline's perception of quality of service, since it affects delays, fuel consumption, etc.

PD/2 analysis extracted the following parameters from the simulation traffic data: number of landings, flight time, inbound delays, precision of delivery, and separation.

Generally, under medium traffic-load, none of these measures were significantly influenced by the difference in the organisations. There was a generally relaxed atmosphere prevailing in the medium traffic-load simulation runs, as indicated by the notes of the observers and comments of the controllers. The controllers succeeded in deploying their basic skills in ORG 0 in such a way that an equivalent or sometimes even slightly more efficient guidance of inbound aircraft resulted than in the advanced ORGs with strict observance of the system-generated advisories and consequent strict adherence to the system trajectories.

In distinct contrast to that, under the high traffic load conventional sequence planning reached its limits under ORG 0, and higher traffic demand was handled more smoothly with the PD/2 advanced ORGs. As a consequence this chapter will concentrate on the results obtained under high traffic load. Annex C of the report provides full details of the results.

### 7.2.1 Number of Landings

In the figures which follow in this section the dots represent arithmetical means (M) of the eight scores obtained from the eight teams, vertical bars indicate the standard deviations (SD) of the eight scores, and thus the variability between teams.

The number of inbound aircraft that completed their flights through the simulated airspace of PD/2 and were brought in to land on either of the two parallel runways was analysed as a first overall indicator of traffic throughput.

In the ORG 0 reference mode an average number of 62.2 landings per hour was measured under high traffic load. As can be seen from Figure 11 that shows the total means and standard deviations per ORG over all eight teams, the average number of landings was noticeably higher in the advanced ORGs. 64.6 landings per hour in ORG 1 showed a significant ( $p \leq 0.05$ ) increase over ORG 0. Under the same traffic demand more than two aircraft more per hour were achieved to land.

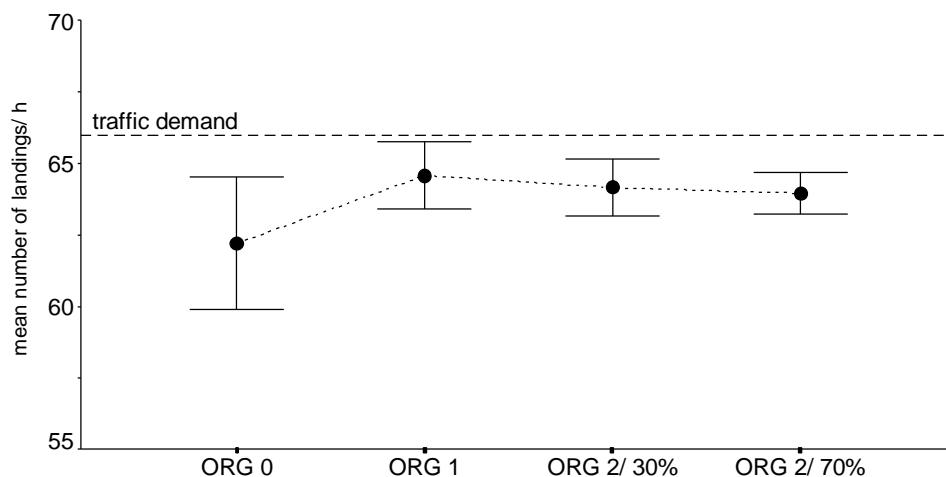


Figure 11 Mean number of landings in high traffic scenarios

Two more things can be seen from Figure 11. First, mean landing rates of ORG 1, ORG 2/ 30 %, and ORG 2/ 70 % were nearly equal with no significant difference between them. In all advanced ORGs conditions the average landing rate was higher than in the ORG 0 reference mode, no matter if any, or how many class A aircraft were involved. Second, the standard deviations of the eight teams' landing rates, as they are indicated by the deviation bars, were highest in ORG 0. The standard deviations that characterise the variability between the teams were smaller in all advanced ORGs.

### 7.2.2 Flight Time

The time that inbound aircraft took for their way through the simulation illustrated the close relationship with the data for landing rates: shorter flight times coincided with higher landing rates. Figure 12 shows for the pooled data over all arrival routes that the average flight time observed under reference conditions (25.2 minutes in ORG 0) decreased to 24.4 minutes in ORG 1 where the PD/2 PATs and GHMI support was introduced. The difference, which is equivalent to about three per cent of flight time, was statistically significant ( $p < .05$ ), whereas no such significant difference of overall flight time was found when ORG 1 and ORG 2 were compared. Again, the variability between teams was considerably smaller with the PD/2 advanced system.

Under the same traffic demand, the flight time in the approach sector could be reduced significantly when the PD/2 advanced tools and GHMI support was used. Even more important is the reduction in the variability, which means that arrival times became more predictable (as shown further in sections 7.2.3 and 7.2.4)

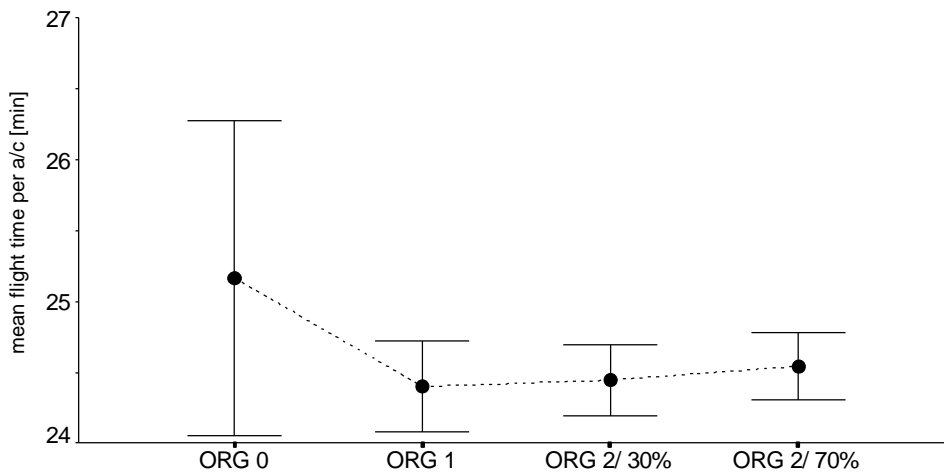


Figure 12 Mean Flight Time per aircraft in high traffic scenarios, all arrival routes combined

### 7.2.3 Inbound Delays

Inbound delays, as measured by differences of preferred against actually observed time over the Approach Gate, are depicted in Figure 13. The pattern of results looks very much like that of flight time (Figure 13), thus indicating a benefit at first glance, i.e. a reduction of delays from reference (ORG 0) down to a lower level under the advanced ORGs, and again showing no further benefit from introducing class A aircraft. But, other than for flight time, in the pooled data over all arrival routes no significance was found for the ORG 0/ORG 1 difference of about 35 seconds, presumably due to the high variability among the eight teams which could be observed again particularly under ORG 0. An important observation is that again variability was considerably smaller in the advanced ORGs.

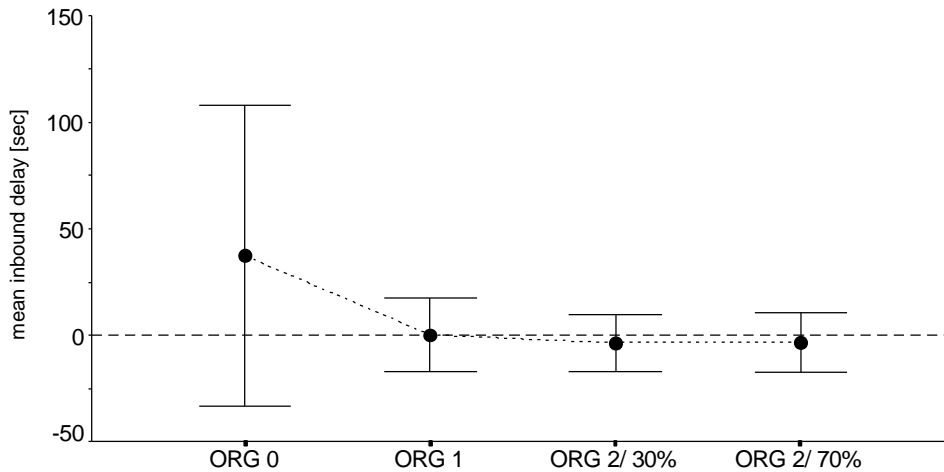


Figure 13 Mean Inbound Delay per aircraft in high traffic scenarios, all arrival routes combined

## 7.2.4 Precision of Delivery

Since flight time and inbound delays reported so far are, in principle, common products of both the planning tools' performance and the controllers' performance, precision of delivery is considered as a useful indicator of how precisely the tools-generated plans were actually implemented.

Precision of delivery is calculated from the observed differences between actual time over Gate and planned time over Gate. Note that the planned time over Gate may already include a delay because the planning algorithm accounts for the overall traffic situation either by using merely arrival time estimates in ORG 0, or by using conflict-free trajectories in ORG 1 and ORG 2.

As aircraft can be delivered earlier or later than exactly at planned time, positive and negative deviations might cancel each other when averaged. To avoid this, precision of delivery was measured by the absolute magnitude of the time difference between planned and actual Gate overflight of an aircraft (Equation 1).

$$(1) \quad \text{absolute mean} = \frac{\sum |t_a - t_p|}{n}$$

where  $t_a$  = an aircraft's actual time over Gate,

$t_p$  = an aircraft's planned time over Gate,

$n$  = number of aircraft.

Precision of delivery is shown in Figure 14. Again, the introduction of PD/2 PATs and GHMI had a significant effect. The average precision of 91 seconds measured in ORG 0 improved to 21 seconds in ORG 1. This was significant beyond  $p \leq .05$ . The enormously high deviations from the planned times as they were registered in ORG 0 resulted from frequent changes of arrival sequences. As there were no control advisories available in the reference system (ORG 0) the entirely manual guidance with its inherent larger variability often resulted in ad-hoc decisions to rearrange initially planned sequences later on.

For the effect of having class A aircraft in the sample, Figure 14 shows the improvement in precision of delivery with increasing proportions of class A aircraft. The ORG 1 mean of 21 seconds decreased to 15 seconds in ORG 2/ 30 % and to 11 seconds in ORG 2/ 70 %. This effect was also statistically significant at the required level of  $p \leq .05$ .

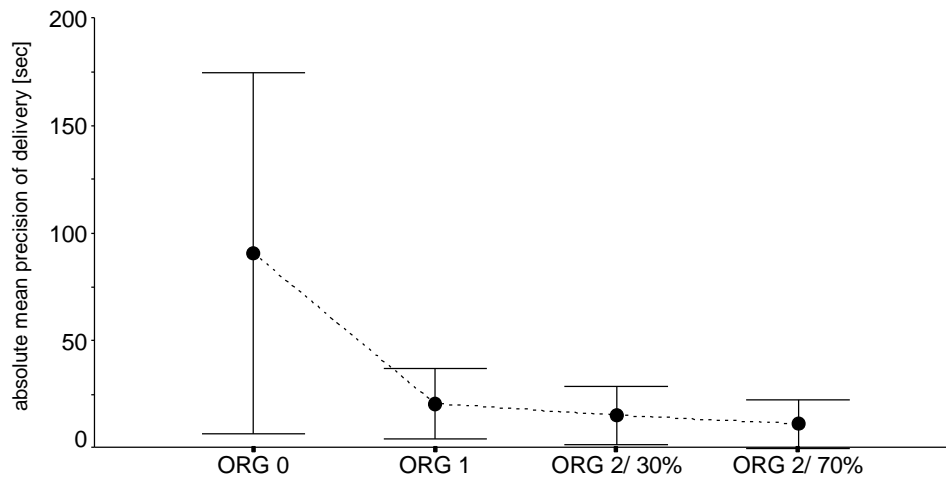


Figure 14 Mean precision of delivery in high traffic scenarios, all arrival routes combined

Figure 15 provides more detailed information. For the interval of  $\pm 60$  seconds deviation from planned time the distributions of precision of delivery are shown for the different ORGs. Each bar represents the interval between the tick marks (e.g. the bar above 0 corresponds to the interval from  $-5$  to  $+5$  sec).

Note that, by definition of class A and class B, all aircraft exceeding a  $\pm 15$  seconds precision of delivery interval must have been guided manually.

The two graphs on top of Figure 15 illustrate the transition from ORG 0 to ORG 1. With the reference (ORG 0) type of arrival sequence planning which provided no further information to the controller about which control strategy to select for implementing the plan, a flat distribution over a wide range of plan deviations emerged. With support of trajectory-based PATs planning and the PD/2 GHMI in ORG 1 more than 10 % of the aircraft were delivered exactly on time.

The two bottom graphs display what happened when 4D FMS/datalink aircraft entered the game. Larger portions of aircraft were delivered perfectly on time. In ORG 2/ 30 % more than 35 per cent of all aircraft in the traffic sample were delivered on time. In ORG 2/ 70 % about 62 per cent of all aircraft were delivered on time.

Broadening the view onto an interval of no more than ten seconds early or late delivery at the Gate (which of course includes delivery exactly on time) shows that

- 16% of all aircraft were delivered within  $\pm 10$  seconds in ORG 0,
- 60% of all aircraft were delivered within  $\pm 10$  seconds in ORG 1,
- 71% of all aircraft were delivered within  $\pm 10$  seconds in ORG 2/30%,
- 79% of all aircraft were delivered within  $\pm 10$  seconds in ORG 2/70%.

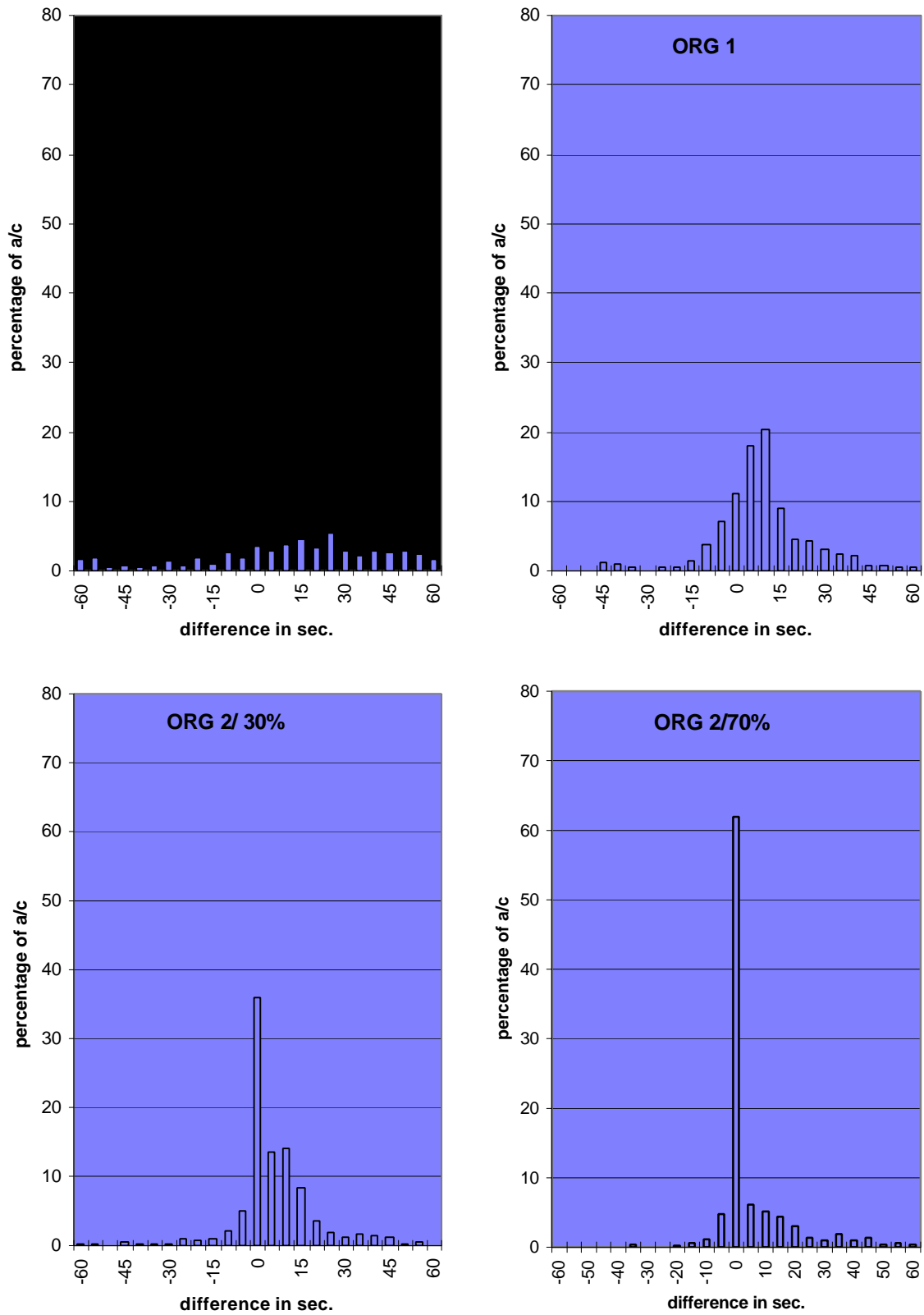


Figure 15 Distributions of precision of delivery in high traffic scenarios

### 7.2.5 Separation

Separation over the Approach Gate was taken as an indicator of whether potential benefits in terms of reduced flight time or reduced delays were possibly achieved at the expense of separations less than published wake vortex separation standards. The average numbers of separations less than standard are displayed in Figure 16.

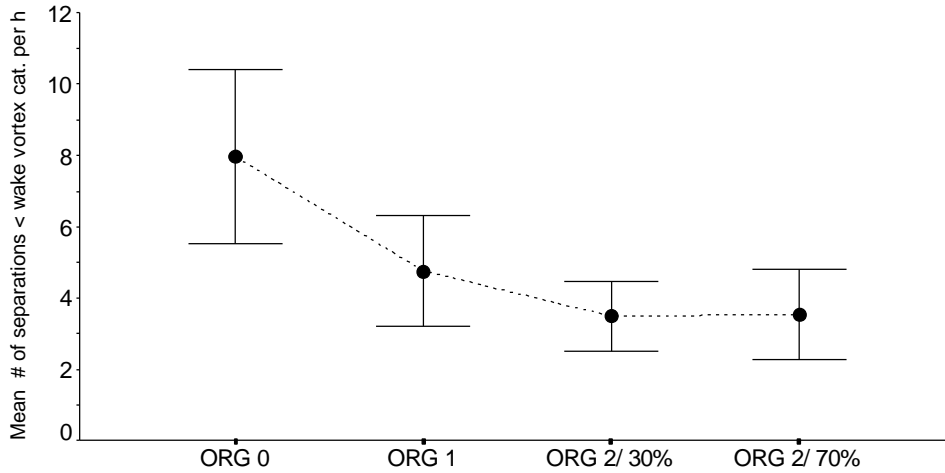


Figure 16 Mean number of separations smaller than wake vortex categories in high traffic scenarios

A significant ( $p < .05$ ) decrease of the number of separations less than standard was found for ORG 1, as compared to ORG 0. There was a trend of further decrease in ORG 2 but this was not statistically significant.

However, it can be excluded that positive effects of the PD/2 concept on traffic throughput were achieved at the expense of separation. Quite the reverse appears to be true. With the advanced system there was even less need to separate aircraft closer than the published standards.

### 7.2.6 Summary Discussion of Traffic Throughput/Quality of Service Results

Table 5 compiles the results of the statistical tests of the parameters analysed under both, high and medium traffic load. The '=' indicates that there was no statistically significant difference of an analysed parameter between compared ORGs, whereas the '+' indicates a significant positive effect.

	medium traffic		high traffic	
	From ORG 0 to ORG 1	From ORG 1 to ORG 2	From ORG 0 to ORG 1	From ORG 1 to ORG 2
Number of landings	=	=	+	=
flight time	=	=	+	=
Inbound delays	=	=	=	=
Precision of delivery	+	+	+	+
Separation	=	=	+	=
Variability between teams	=	=	+	=

Table 5 Summary of results: effects on traffic throughput/quality of service

This table summarises the data in total whereas Figure 17 exemplifies typical patterns of traffic guidance that were observed in singular simulation runs. The radar plot examples given in Figure 17 illustrate horizontal flight paths of aircraft in all ORGs of PD/2. They were taken from one controller team's measured runs under high traffic load. They are displayed here to visualise directly some of the effects that are discussed below.

The reference, or baseline, ORG 0 system represented the functionality of today's ATC system with paper strips and conventional arrival sequence planning. Transition to ORG 1 introduced as a key element ground-based 4D trajectory planning of inbound traffic. The system supported the controller by generating 4D advisories and by providing a stripless GHMI for interacting with the system.

As a general observation found from nearly all measured parameters, the highest variance was in the data of ORG 0, indicating that work styles differed largely between controller teams. This was not a surprise when the type of ORG 0 planning support is considered. The proposed arrival sequences were displayed, but no information on particular tactical control measures how to implement the planned sequences was provided. In ORG 1, with control advisories generated that applied to individual trajectories, the variance between the teams' data was generally smaller. Work styles and performances of the different controller teams became more homogeneous, and thus more predictable.

Apart from this, various gains of the PD/2 concept were found when compared to the ORG 0 baseline. Significant benefits for the number of landing per hour, average flight time of aircraft, precision of delivery, and separation were reported. It should be noted that the positive effects were mainly present under high traffic load. Whereas the data obtained under medium traffic load suggested that the controllers could make use of their basic skills in such a way that an equivalent, or sometimes even slightly more efficient guidance of inbound traffic resulted than with observance of the system-generated advisories in ORG 1.

Under the higher traffic load which was in the PD/2 simulations equivalent to increasing the traffic volume by about one third, the ORG 0 type planning reached its limits, and advantage could be taken from introducing the PATs and GHMI in ORG 1. The radar plots Figure 17 include a typical example for the transition from ORG 0 to ORG 1 (It is worth mentioning that the ORG 1 simulation run in this particular week was made at the beginning, the ORG 0 run at the end of the week; therefore any learning or practising effects in favour of ORG 1 can be excluded). Nearly all traffic throughput and quality of service parameters were better than in ORG 0. The improvements were statistically significant, only the observed reduction of inbound delay failed to reach the five per cent significance level.

In summary, it can be concluded that a benefit of the introduction of PATs and GHMI in ORG 1 could be observed such that particularly higher traffic demand could be handled more smoothly and more efficiently. That efficiency gain was achieved without any detrimental effect on separation. There was even a significant positive effect on separation by the ORG 1 introduction of tools.





The transition from ORG 1 to ORG 2, with its increasing proportions of class A aircraft, did not change anything about the functionality of the PD/2 system. The basic principles of tools and GHMI support remained unchanged, the difference was in the use of mixed class A and non-class A traffic in ORG 2. While all traffic in ORG 1 was handled as non-class A, in ORG 2 some portions of aircraft in the traffic sample were supposed to make use of on-board 4D FMS/datalink equipment and thus to proceed automatically along their trajectories which had been established upon entry into simulation. The controllers' only interaction with that aircraft was to assume control, establish initial radio contact, and transfer them later to the next sector, or the tower. Without any control advisories the aircraft followed their plan and arrived at the Gate exactly at their scheduled time, by definition in the simulation. In case of a tactical intervention of a controller, such an aircraft lost its class A status.

The main question was, did throughput and quality of service in the ETMA, for the traffic sample as a whole, benefit from having class A aircraft in that traffic sample? The simulation results showed significant gains in precision of delivery of the aircraft at the Approach Gate. All other improvements over the baseline system were achieved by the controllers using the advanced tools in the PD/2 system, in both cases, regardless of how many 4D FMS/datalink aircraft were involved.

This needs some further explanation. By nature of the PD/2 trials the 'optimal' traffic guidance will theoretically be reached when all aircraft (class A and class B) follow their trajectories in a perfect manner. Then the actual mix of class A and class B aircraft would not matter at all; no further benefit could be expected since all aircraft adhere strictly to their 4D trajectories. The simulation data suggest that already under ORG 1, with trajectory-based guidance entirely implemented via controllers' R/T advisories a result close to that optimum could be achieved. Of course, this optimum is very specific for the trajectories actually used in PD/2, and it does not tell anything about how optimal those trajectories were. Without any doubt there is still room for further improvement of trajectories, for example by using parallel routes and shortcuts, by calculating generally for higher airspeeds, or by increasing the inbound traffic flow rate through reducing minimum separation. All these measures would lead towards a capacity gain. However, it must be emphasised that those capacity issues were not within the scope of PD/2.

Moreover, restricting the tools to work only for a fixed route structure as in PD/2 makes the problem-solving task more difficult and often leads to sub-optimal solutions. This is because tools working on the basis of fixed routes will follow the standing agreements used by the humans in the control-loop. On the other hand, although advanced tools will probably find easier and more optimal solutions in a free route environment, the solutions may be less easy to understand by the human controllers in the loop.

Another question of utmost relevance to aircraft operators is whether some specific benefit could be expected for class A aircraft from using their on-board 4D FMS/datalink capabilities. The answer from the PD/2 simulations to that question is clear but perhaps too simplistic. Of course there is a benefit, the precision of delivery in Figure 15 has illustrated this impressively. However, by nature of the simulations, for class A aircraft which frequently were downgraded from class A there was no re-negotiation. The lack of system functionality to allow recovery of the class A status certainly underestimates the potential benefit of 4D FMS/datalink equipment. Therefore, more research is necessary to fully address this question and to quantify that benefit exactly.

### 7.3 WORKLOAD

Several objective and subjective indicators for the workload of controllers were analysed. All these measures are closely related to each other, which is confirmed by considerable high positive and throughout significant correlation among them. The lower, still significant, correlation was found among the subjective and the objective workload indicators. This is an indication that certain elements immanent to the simulation additionally contributed to workload than the mere controlling air traffic by transferring of ATC commands. It is assumed that the impact of the introduction of a new ATC concept with new procedures and tools, with a certain degree of automation is twofold. Firstly, every new system has workload associated with it that was not present before due to different tasks to be performed and the lack of routine with using the new tools. Secondly, there is increased mental demand through monitoring what the system is doing. These effects are nearly always present as long as controllers are not totally familiar with a new system. Thus, any potential of a beneficial effect on workload when introducing a new system is counteracted by the costs of novelty. This has to be considered when interpreting the summary of results in Table 6.

All three objective workload indicators (number of ATC instructions issued per minute, frequency of radiotelephony (R/T) contacts per hour, and percentage of simulation time spent for R/T) correlated highly with each other and showed a very uniform pattern of results. Therefore, the summary of results presented in Table 6 applies to all three objective workload indicators, whereas subjective indicators are presented separately. For more details on each of these measures refer to Annex D. This table is a compilation of the statistical tests conducted on the various workload indicators analysed under high and medium traffic load. Again the '=' indicates that there was no statistically significant difference between compared ORGs, whereas the '↗' and '↘' symbols indicate significant increases and decreases of workload, respectively. The brackets indicate that the results missed the significance criterion ( $p \leq 0.05$ ), but a trend was apparent ( $p \leq 0.10$ ).

	medium traffic		high traffic	
	From ORG 0 to ORG 1	From ORG 1 to ORG 2	From ORG 0 to ORG 1	From ORG 1 to ORG 2
Objective indicators				
Pickup	↘	↘	↘	↘
Feeder	=	↘	=	↘
ACC	↗	↘	↗	↘
SWAT				
Pickup	=	=	(↘)	=
Feeder	=	↘	=	=
ACC	=	=	=	(↘)
TLX				
Pickup	=	=	=	(↘)
Feeder	↗	(↘)	=	↘
ACC	↗	=	=	=

Table 6 Summary of results: effects on tactical controller workload

### 7.3.1 Workload Comparison Between ORG 0 and ORG 1

ORG 0 corresponds to a typical strip-oriented ATC system with limited planning aids such as those which are actively used in arrival management today (e.g. COMPAS). Compared to this baseline, ORG 1 is a move towards a stripless system with more advanced computer assisted planning tools (PATs) and associated new ATC procedures. Furthermore, ORG1 includes the introduction of a novel computerised human-machine interface with the mouse now being the main interaction device.

In general, the introduction of the PATs alone had tremendous impact on the task allocation and responsibilities at the different working positions. This has to be considered when interpreting the findings of the various workload indicators. In the baseline system the planning controllers were actively supporting the pickup position next to them by pre-sorting the flight strips according to the displayed Arrival Manager sequence, and occasionally by helping with strategic advice. Under special consideration of the limitations in the simulations, the planning controllers literally lost their task when the PATs entered the field, especially in medium traffic scenarios. This became apparent in the pilot phases and was finally the reason to create a job-enrichment for the planner position by assigning to him additional responsibility for the workload estimates (SWAT, TLX) of the tactical approach team. Most importantly, the loss of the planners' tasks caused a shift in the tasks of the other TMA controllers, mainly that of the pickup controller and to a lesser extent of the feeder position. The pickup took on the planner's tasks and also became responsible for a more strategic control in planning and sequencing inbound traffic.

Therefore, the results of the workload measures were not uniform and were strongly dependent on the controller working positions. When comparing the different objective workload measures, the pickup controllers were the ones who could profit most from the introduction of the advanced tools. In general, it was at this working position that the highest objective workload of all controllers was found in the baseline condition. Under high traffic load all objective measures were considerably and significantly reduced when moving from ORG 0 to ORG 1. The conclusion is that the PATs did support the pickup controllers in several ways. The pickup controllers could accomplish their task of establishing the landing sequence much better, were able to cope with additional duties assumed from the planner and had much less work keeping separation and flow of inbound traffic.

Furthermore, the PATs caused a positive change in work-style or influence of skill at this controller position. In ORG 0 the pickup controllers' expertise had great impact on the quality of their work. This was supported by a large variability of number of ATC instructions and of R/T frequency between the eight different teams' scores. In fact the highest number of ATC instructions under ORG 1 was about the same as was the lowest number under ORG 0. It is evident that in the advanced ORGs this variability was greatly reduced through the support of the tools.

The positive effect of an advanced ORG 1 for the pickup controllers was partly supported by subjective workload measures. Only under high traffic the SWAT ratings tended to show a reduction from ORG 0 to ORG 1, whereas for TLX scores no effect was found (compare Figure 18 and Figure 19).

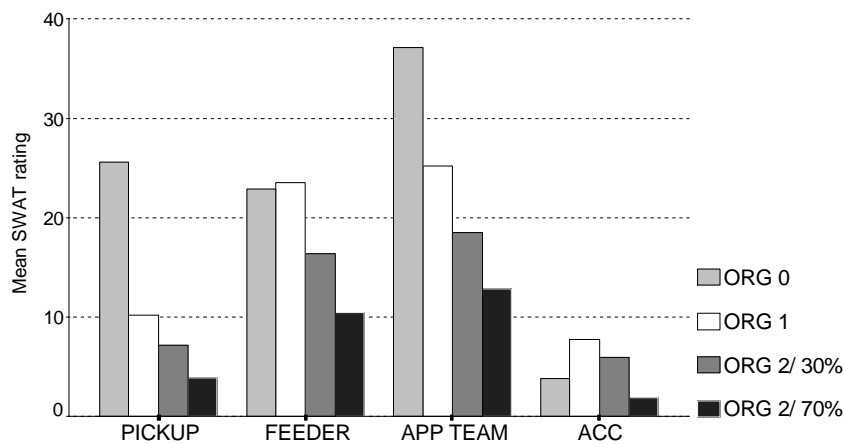


Figure 18 Mean SWAT workload ratings in high traffic scenarios.

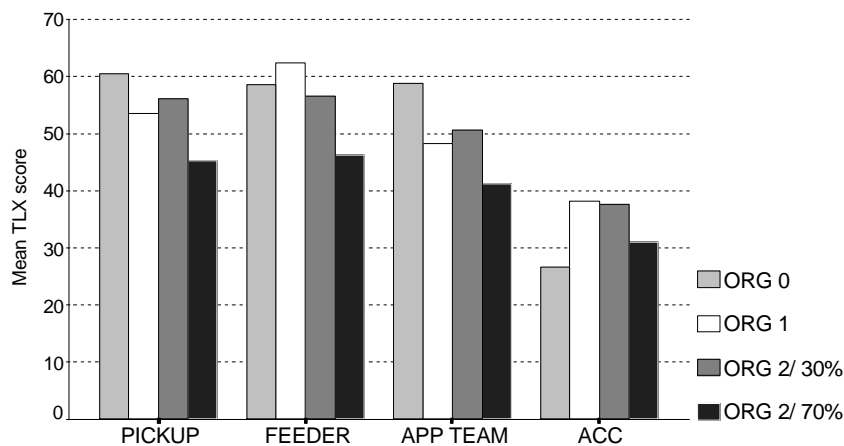


Figure 19 Mean TLX workload ratings in high traffic scenarios.  
The planner assessed the workload of the APP team.

At the feeder position neither subjective nor objective workload measures revealed a difference between ORG 0 and ORG 1. Observations suggest that the flight-time of inbound a/c was simply too short to benefit from the advanced tools. In the simulated airspace of PD/2, aircraft were handed over to him when they were on downwind or on base leg. He was then responsible for turning them onto finals, issuing an ILS clearance and reducing their speed for the final staggering between aircraft on right and left runways. This gave him about five minutes in control, compared to the approximately 10 minutes of controlling done before by pickup controllers. Hence, the performance of the pickup had a strong influence on the feeder's work. If inbound traffic was already pre-sequenced in accordance with the Arrival Manager, well staggered and at a convenient altitude when handed over to the feeder, there was a lower load put on him. Therefore, he had less need for additional computerised tool support.

On the other hand, in depth analysis on type of control commands revealed that the feeder controllers did indeed benefit through introduction of the PATs. Their main task was to guide aircraft to the extended centre-line and to give ILS clearance, and therefore the feeder controllers were using mostly heading commands. The PATs supported this task well as this type of command was significantly reduced but at the expense of (non significantly) increasing the number of altitude commands, and thus resulting in no overall effect.

The workload of the ACC controllers was overall the lowest of all controllers, irrespective whether objective or subjective measures were concerned. Furthermore there were no obvious differences in the pattern of results between medium and high traffic scenarios. The statistically significant increase of some objective workload indicators, i.e. number of ATC instructions and R/T frequency, is therefore considered not to be operationally of great consequence, but to remain within acceptable limits.

The increasing number of issued ATC instructions, and a rising R/T frequency at the ACC controller position when moving from ORG 0 to ORG 1 reflect the fact that the quality of the tools was in some respects sub-optimal. They were not specifically designed for the needs of en-route sector control as in PD/1. Thus, the provided tools did not fit with the usual work style of the ACC controllers or the requirements of airspace and route structure. From observations during the trials and a closer look at the raw data it became apparent that in ORG 0 sector controllers had a tendency to let aircraft fly without intervention, if possible, until close to metering fix RUD, i.e. just before entering the TMA. Only then did they issue descent and speed reduction commands. Contrary to that procedure, controllers reported in debriefings that when they were supported by the PATs in the advanced ORGs a number of advisories generated were unnecessary or even unrealistic, e.g. multiple descent and speed advisories instead of one continuous descent or a single speed reduction. Overall these advisories caused more commands to be issued and consequently increased R/T activity. This burden was confirmed in a tendency to higher subjective workload ratings in ORG 1; though only one of these results became statistically significant (TLX, medium traffic).

### **7.3.2 Workload Comparison Between ORG 1, ORG 2/ 30%, and ORG 2/ 70%**

The change from ORG 1 to ORG 2 corresponds to the introduction of different proportions of 4D FMS and datalink equipped aircraft. These aircraft offered full utilisation of the advanced tools and they were able to follow an optimal trajectory without controller intervention. The effect of releasing the controllers from the duty of transferring ATC instructions showed significant reductions in all objective workload measures at all controller working positions irrespective of traffic volume. The only exception was for the R/T frequency of the pickup controller in medium traffic, which was only close to significance. Therefore, it can be concluded that R/T workload associated with traffic guidance decreased strongly with increasing proportions of 4D FMS/datalink equipped aircraft.

For the subjective workload ratings this finding is less distinctive. Even though the SWAT ratings showed a clear tendency of reducing with increasing proportions of class A aircraft, not all of the statistics supported the significant results of the objective indicators. When comparing TLX scores a virtual reduction was found if 70% class A aircraft were involved but the overall effect failed to prove significant. Only if single comparisons were conducted between ORG 1 and ORG 2/ 70%, representing the minimum and maximum proportion of class A traffic in PD/2, significant differences were found at some controller positions.

What might be the reasons for such a distinction between the objective and subjective workload parameters? The lower correlation among objective and subjective workload estimates indicate that in addition to the mere traffic guidance via R/T, other factors contributed to perceived workload. Subjective workload estimates like SWAT and TLX are indicators for the overall load a controller experiences, whereas objective measures represent only partial aspects of workload. Apart from the amount of ATC instructions the R/T load, the associated cognitive load for continuously monitoring the traffic and for selecting appropriate instructions is hidden to objective recordings. If correlation among objective and subjective workload estimates are calculated an

implicit assumption is made that both are proportional to each other. This need not always be the case, hence the correlation among subjective and objective workload measures were lower than among equivalent workload estimates.

Further indications arose through comments during debriefings. Approach controllers reported about a higher need for co-ordination, especially in tight approach sequences, when mixtures of class A and class B aircraft were involved in the simulation. Controllers were instructed to refrain, if possible, from interacting with class A aircraft in order to avoid a downgrading of the aircraft' status, because only as class A would they fly absolutely precisely in space and time. When there were only 30% class A traffic simulated, these 'automatic' aircraft were the minority in the simulations, but nevertheless, they affected the manually guided aircraft majority. For instance, if the arrival manager tool scheduled a class B aircraft between two of class A, controllers were forced to guide this class B in an extremely precise manner in order to avoid separation infringements. This was an exacting task because, as in reality, controllers could not anticipate the precise timing of the class B 'pilot's responses to R/T commands. When 70% datalinked aircraft were involved the relationship between rule and exception was reversed, and it then seemed to be a less demanding task to guide the fewer class B aircraft between the class A majority. Still controllers preferred "...if class A aircraft are involved a 100% would be best..." to overcome these difficulties of traffic mixture. But this issue raised discussion about operational aspects more deeply addressed in section 7.4.3.

### **7.3.3 Planner Controllers' Assessment of Workload of Tactical Approach Controllers**

Every controller except the planner had to assess his/her own workload in every run using two subjective assessment methods (NASA-TLX and SWAT). For the planner a different method was foreseen. The reason was that during pilot phase of PD/2 it had become apparent that within the limitations of the simulation the introduction of the PD/2 advanced system caused a shift in task responsibilities of the approach controllers (planner, pickup, and feeder). This shift was such that the planner controllers literally lost their tasks. Therefore, no differentiating results could be expected for the planner controllers' workload ratings during the main phase (the statistical term is 'floor effect'). For this reason it was decided to let the planner assess not his own workload but the workload of the two tactical approach controllers as a joint team score.

The planners assessment of the APP team's workload yielded only two significant results. These were comparison of SWAT ratings between ORG 0 and ORG 1 in high traffic scenarios and comparison of SWAT ratings between ORG 1 and ORGs 2 in medium traffic scenarios. an information gain was only achieved with the first of these results. That means the significant result of the planners' APP team assessment has no equivalent result at pickup and feeder positions. This was mainly due to somewhat higher ratings of the planner under ORG 0 than those of pickup and feeder which resulted in a clearer decrease when moving to ORG 1. The generally higher SWAT ratings of the planner (compare Figure 18) mirrors what several observers noted during the trials. Some pickup and feeder controllers gave rather lower SWAT ratings than could be expected by the commensurate amount of traffic. This is of course a highly subjective impression of the observers but it shows a tendency that some approach controllers possibly rated their workload lower due to an effect of social desirability or to prove their capability. For these cases, to overcome the dangers of subjectively bias, it proved to be useful to have workload ratings from a less personally involved observer with the same experience as the tactical controllers.

To statistically check for concurrence of the planners' workload ratings of the APP team with those of the approach controllers themselves correlation (Spearman's  $\rho$ ) among the workload ratings of

the different controller positions were computed. Most correlation proved to be significant, though higher correlation were uncovered for the SWAT ratings both under high and medium traffic scenarios than within TLX scores. Especially low correlation was found for TLX scores under medium traffic volume ( $\rho \leq .21$ ), the only non-significant correlation. The reason for better correspondence in SWAT ratings between planner and tactical approach than in TLX scores was that the instantaneous assessments of workload were based on much more information directly available to the planner, like the radar, traffic flow, amount of radiotelephony, voice (pitch and speed). TLX on the other hand has sub-scales of factors for which the answers of the tactical controllers were not as reasonable and sensible as the planner's. These are the factors not related to the actual task but rather to the subject, like 'Own Performance', 'Effort', and 'Frustration'.

## **7.4 ACCEPTANCE**

After each completion of an ORG, controllers were presented questionnaires to collect their judgements on the three ORGs individually. At the end of trials weeks a final questionnaire was presented to collect the overall, non ORGs-specific issues. The questionnaires consisted of more than 70 individual questions. The results are summarised below, covering the different sections of the questionnaires individually. For further in depth analysis refer to Annex E.

### **7.4.1 Simulation Environment and Training**

In general the work environment (lighting, seating etc.) was not a matter of major complaints. Responding to the SWAT was accepted by most of the controllers.

All the training issues addressed in the final questionnaire achieved significant positive controller responses. The training which the participants received in the week before their trials was nearly unanimously accepted as being sufficient to get familiar with the PD/2 airspace and route structure, with the HMI tools and functions, as well as with the controller roles and tasks.

Traffic samples and the way in which feed sectors were simulated were significantly well accepted. When controllers judged their interaction with the pseudo pilots, they significantly agreed in saying the pseudo pilots were adequately trained. Nevertheless, adverse effects caused by the controllers themselves were not clearly excluded, particularly during traffic peaks when controllers put a high R/T load on the pilots.

Distractions/disturbances from other activities in the control room were not a matter of concern, the responses were significantly positive. Obviously, this includes the presence of observers, as controllers clearly negated that these had any influence on their work.

The results altogether, and the many positive responses, support the conclusion that the simulation environment and the training provided in PD/2 had been accepted sufficiently well by the participating controllers and were highly approved as being realistic and valid. This is also an important factor for credibility of the simulation results in general.

### **7.4.2 HMI: Displays, Interaction**

This section deals with aspects of interacting with the PD/2 system, display characteristics and some general HMI aspects, which apply mainly for the PD/2 advanced ORGs.

The mouse was significantly accepted as a suitable device for interacting with radar labels and pop-up menus, but sometimes an overloaded simulation system caused problems and the subsequent slow response times sometimes made it difficult to select specific elements.

Controllers generally agreed with the screen layout and size, as well with the readability of text, and there were no problems with the abbreviations used. Also, the concept of colour coding of the labels, for indication of the control status, was regarded as being very easily understood and useful. Together with the indication of the actual mode of guidance (class A, class B, or manually guided) which was given by the aircraft symbol, these were significantly well accepted by the controllers.

The options of changing the displayed length of the trajectory prediction and changing the track history which enabled controllers to have a look on the past and the future of any aircraft's flight path, were highly appreciated.

### **7.4.3 Operational Aspects: Traffic Handling, Procedures**

Several items of the questionnaires addressed particular aspects of the controllers' practical work, and to get insight into their views of the operational concept as a whole.

The proportion of controllers saying that data link reduced their workload was highly significant. This is in parallel to the SWAT and NASA-TLX results where workload estimates were found to decrease - at least in tendency - at higher percentages of class A aircraft. Similarly, and thus appearing as a logical consequence of this, a significant proportion of controllers indicated they would prefer all aircraft to be 4D FMS equipped. However, in the debriefing sessions controllers frequently raised some important issues beyond mere workload. Assuming a hundred percent class A aircraft scenario, many controllers could see themselves acting in a monitoring role only, sometimes characterised as "underloaded" or even "boring", and with detrimental effects on their job satisfaction. Moreover, retention of basic control skills was addressed as a problem in this context that might even become a safety issue in case of a system breakdown or unforeseen emergency events.

In general, there was significant acceptance by controllers that 4D FMS equipped aircraft following their previously cleared trajectory, should do so without having further clearances transmitted to them. Controllers apparently agreed with this because it reduces much of the communication workload. Additional comments indicated that the controllers' readiness to accept this procedure is increased with the ease of access to trajectory information through the GHMI.

Differentiated per ORG, the controllers were asked about safe handling of traffic. In all three organisations the controllers agreed significantly in saying that the traffic could be handled safely, and they disagreed with suggestions that it was difficult to handle the traffic by using the tools provided. Closely related is the question about keeping aircraft well separated. Controller responses were significantly positive under ORG 0 and ORG 1, but only in tendency positive under ORG 2. Debriefing sessions and written comments revealed two reasons for some controllers' perception that it was more difficult to keep separation in a mixture of class A and class B aircraft as it was given in ORG 2 only. A reason quoted by some approach (Pickup and Feeder) controllers, was that in a tight approach sequence, a class B aircraft planned between two class A aircraft had to be guided in an extremely precise manner between the "automatic" class A aircraft to avoid separation infringements. The other reason was that particularly ACC tactical controllers sometimes observed in their view unrealistic speed behaviour of inbound class A aircraft, such that they felt "... some trajectories were dubious in the way that they kept aircraft apart ..." and reported that "... several times I had to intervene in order to keep separation ...". They claimed further that this kind of difficulties could be alleviated by having more flexibility in routing the trajectories, i.e. by using more than one track for all west inbound traffic up to the RUD fix.

Nevertheless, significant positive responses were given for all ORGs, regarding "maintaining the picture", and that the controllers always felt in control of the system. The system's support for conflict detection and conflict resolution was rated much less favourably, the least favourable for ORG 0, because "... there wasn't a tool ..." to provide conflict resolution. Acceptance of the advanced ORG's support was considerably better. Although the majority of controllers agreed with the support given to detect conflicts they disagreed with the support given to solve these conflicts. Obviously, a better acceptance was prevented by some shortcomings of the CRD that will be discussed in the tools and functions section below.

Did the system also allow the controllers to work according to their personal work styles? ORG 0 received significant approval, as it was closest to the today's operational procedures and conventional work style. ORG 1 was approved in tendency only. Some controller comments indicated that they missed the ability to choose between laterally separated trajectories. Overall, ORG 2 was rated as being relatively least in line with controllers' personal work styles. However, there was nearly a complete balance between positive and negative responses. Again presumably because of the mixture of class A and class B aircraft in ORG 2, where controllers were compelled to handle class B a/c to conform to the prerequisites of class A traffic. Another reason as mentioned above, was the controllers' concern about automation leaving them in a monitoring role and losing their skills.

However, despite their work-style preferences, in total controllers clearly and significantly estimated that they could have handled even more traffic under each ORG. The ACC controllers thought they could do this best under ORG 0, whereas approach (pickup/feeder) controllers estimated more clearly that they could do this under the advanced ORGs.

An item related to the support of controllers was the efficacy of the advisories. Controllers were asked whether the advisories (for class B aircraft) generated by the system were always appropriate. Although a small majority of approach controllers agreed that they were always appropriate, a similar small majority of ACC controllers disagreed. However, none of the responses was significant. There was a lot of discussion on this issue in the debriefings which can be summarised as follows: a major area of discussion was that controllers frequently encountered apparent shortcomings of trajectory generation, and thus of the advisories to implement the trajectories. Most of these problems could be overcome by introducing one or more additional trajectory updates (see Section 3.5 about the limitations of PD/2). More generally, this point was also about controllers' perception of what was appropriate. Many controllers felt, even when they admitted that all of the current system's trajectories and advisories were consistent, conflict-free, and always appropriate, that they would sometimes have done the job in a different way., For example not strictly following the Standard Arrival Routes. The feeling was summed up by the quote "...[it is] as if the system and the human are like two controllers working on the same area. You would never do this in reality ...". Despite this discussion, controllers reported significantly and clearly that there were no problems with the PD/2 concept of how and when to interact with the different classes of aircraft.

Many issues in this section were raised in discussions during debriefings because the controllers became aware of the limitations of the PD/2 system. They were regarded as major items of further investigation to improve future developments of ATC concepts and associated tool support.

#### 7.4.4 Individual Tools and Functions

In order to assess controller views on the tools and functions that were provided to them by the PD/2 system, a set of seven questionnaire items was used to evaluate the tools. The tools evaluated were: the Arrival Management Display (AMD) and the Conflict Risk Display (CRD), which were available to both ACC and Approach controllers, as well as the Vertical View Display (VVD) and the Sector Inbound List (SIL), which were specifically dedicated to the ACC position.

The controller responses that were obtained for the AMD reflected different views about the benefit of this tool, dependent on the controller working positions. Approach controllers appreciated the AMD far more than their ACC colleagues did. The majority of approach tactical and planning controllers reported that they used the AMD frequently, it was relevant for their work, they found it helpful for avoiding conflicts, it reduced their workload, and also that the kind of interaction with the AMD was suitable to their personal work styles. In particular, they appreciated the capability to have the same interaction with aircraft labels on the AMD as on the PVD. Opposite tendencies for all the above matters were found in the ACC controller judgements. This underlines the differing relevance of the AMD for different positions, once forcefully put by an ACC controller as "... it was good for APP controllers but not helpful for ACC ...".

Overall, there were no significant positive responses given at all on the Conflict Risk Display (CRD). As mentioned earlier, this indicated some shortcomings of the CRD, which were extensively commented by the controllers. In total, controller approval was significantly negative regarding frequent use of the CRD and its relevance for controller work. The automatic pop-up of the CRD on *all* PVDs at the same time was severely criticised, mainly because controllers often found the CRD displayed conflicts were not relevant in their sector. It was observed during the simulations that controllers frequently closed the CRD window immediately after it was displayed. Presumably, there would have been more acceptance of the CRD if, as controllers suggested, it had been modified so that it only appeared on the display of the sector concerned. The assessment of the CRD's helpfulness for avoiding conflicts showed no clear indication of approval or disapproval. The criticism here was that "... it is useful to detect the conflict but not to solve it..". Tactical controllers would have appreciated some advisories to solve conflicts. No clear indications were found in their judgements about the CRD's usefulness for reducing their workload.

Only ACC controllers were asked to assess the Vertical View Display (VVD) and the Sector Inbound List (SIL). They commented that in principle they appreciated the VVD as an excellent means to provide a side-view of vertical stacks as a useful supplement to the PVD. Whereas they regarded the VVD as very helpful in a holding situation, they did not feel that it was an important tool if there was a normal flow of traffic. Since in the PD/2 simulations there were no aircraft held in stacks, the VVD was not used for its designed purpose. Therefore, no indications could be obtained from the questionnaire of its frequent use, relevance for work, helpfulness for avoidance of conflicts or workload reduction.

In contrast to this, many more ACC controllers reported they used the SIL frequently. It was of essential relevance for their work because "... in a stripless environment it's the only way to have information about incoming a/c." Whilst this was an expected response, the other potential benefits of the SIL for avoiding conflicts, or reducing workload can not be deducted from the questionnaire responses.

In summary, the questionnaire results about tools and functions, as compared to the much more positive results of the sections before, indicated that the controllers differentiated well between good acceptance of the PD/2 concept and HMI. Although they saw some need for further development and improvement of the tools and functions to better support their work under this concept.

## 7.5 AIRBORNE DEMONSTRATIONS

As was described in section 4.4, DLR's ATTAS aircraft (see Figure 9) was employed as a live aircraft in demonstration runs of the PD/2 trials. The airborne demonstration element is fully described in Annex F. This section summarises the results.

The PD/2 airborne demonstration programme was very successful, confirming the ability of a 4D FMS equipped aircraft to agree conflict-free 4D trajectories with ATC and to fly them, while operating within continuous 4D tolerances. Specifically, the demonstration flights confirmed that:

- a digital data link enabled detailed information on flight status, proposed trajectories and imposed 4D constraints to be transmitted between the aircraft and an ATC arrival planning system
- the airborne system was sufficiently flexible to be able to implement revised trajectories to comply with altitude and time constraints imposed by the arrival planning system
- live aircraft were able to follow the trajectories very precisely within continuous 4D tolerances
- guidance accuracy was remarkably high. The cross track error was within 0.03 nautical miles. Altitude error was within 20 ft in level flight, within 300 ft in en-route descent and within 100 ft in TMA descent
- time control was also very accurate. The arrival time error at a Metering Fix and an approach gate was in the order of +/- 5 seconds
- accurate weather forecasting and engine performance models are essential if the aircraft is to fly close to its optimal thrust setting and calibrated airspeed (CAS) schedule

The results of the AHMI evaluation trials performed in the fixed-base Experimental Cockpit (see Figure 8) can be summarised as follows:

- Display Layout –

The basic display organisation incorporating a horizontal and vertical display for both Plan and Monitor mode was appreciated by all pilots (Figure 20 and Figure 21 show the Lateral and Vertical Display layout, both for PLAN mode). In addition, button realisation, menu and sub-menu organisation as well as constraint list, trajectory, and contract representation were appreciated, in general. However, the mechanisms for selection and display of different constraint lists were rejected.

- Input Characteristics –

Whereas touch-pad size and the corresponding cursor dynamics as well as cursor representation on the screen were appreciated, the location of the touch-pad stimulated several proposals for improvement. Additionally, two of the pilots requested 'hot-spot' activation for some of the functions.

### Input Philosophy –

The function-oriented display was well accepted. Pilot action requests initiated either by data-link or by system-generated messages were favoured.

- Operational Aspects –

Due to the missing control display unit (CDU) within the experimental set-up, a large amount of incompatibilities between conventional CDU input strategy and navigational display (ND) input sequences were revealed by the pilots.

- PHARE Trajectory Negotiation Concept –

The strategic trajectory negotiation procedures were accepted by all pilots. However, a large amount of pilot comments referred to the integration of tactical aircraft operation and strategic planning.

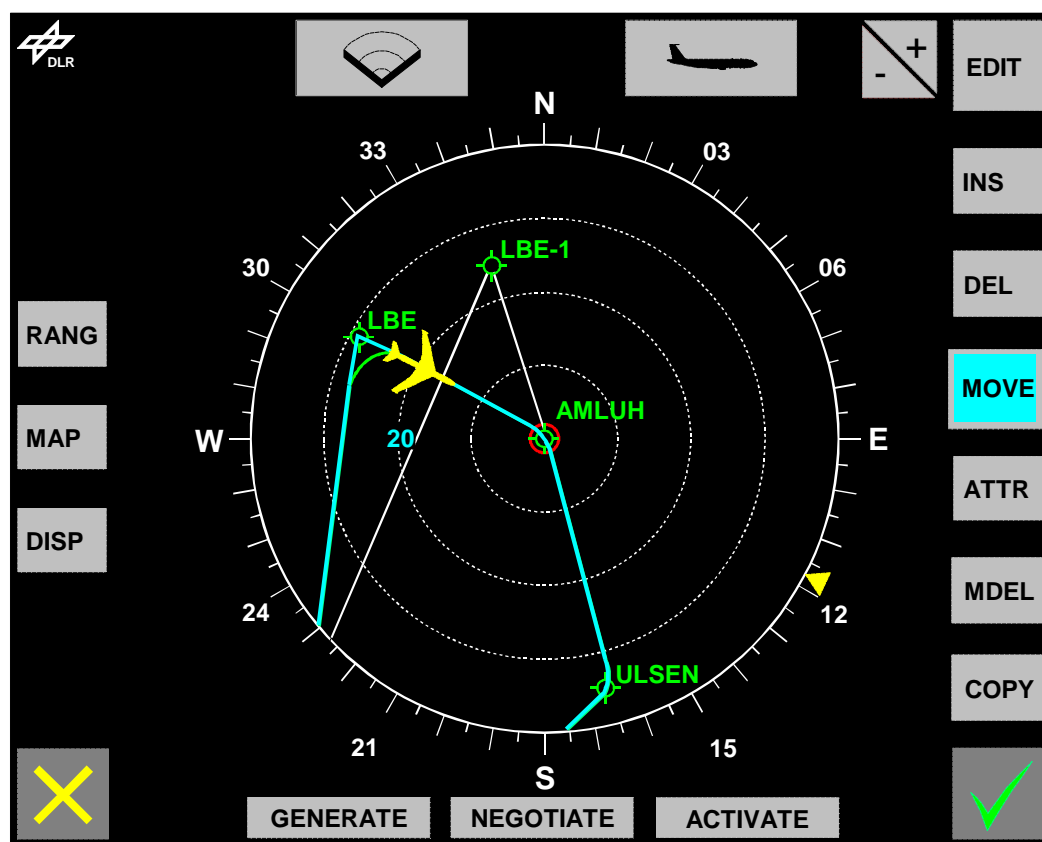


Figure 20 Navigation Display layout: Lateral Display, PLAN mode

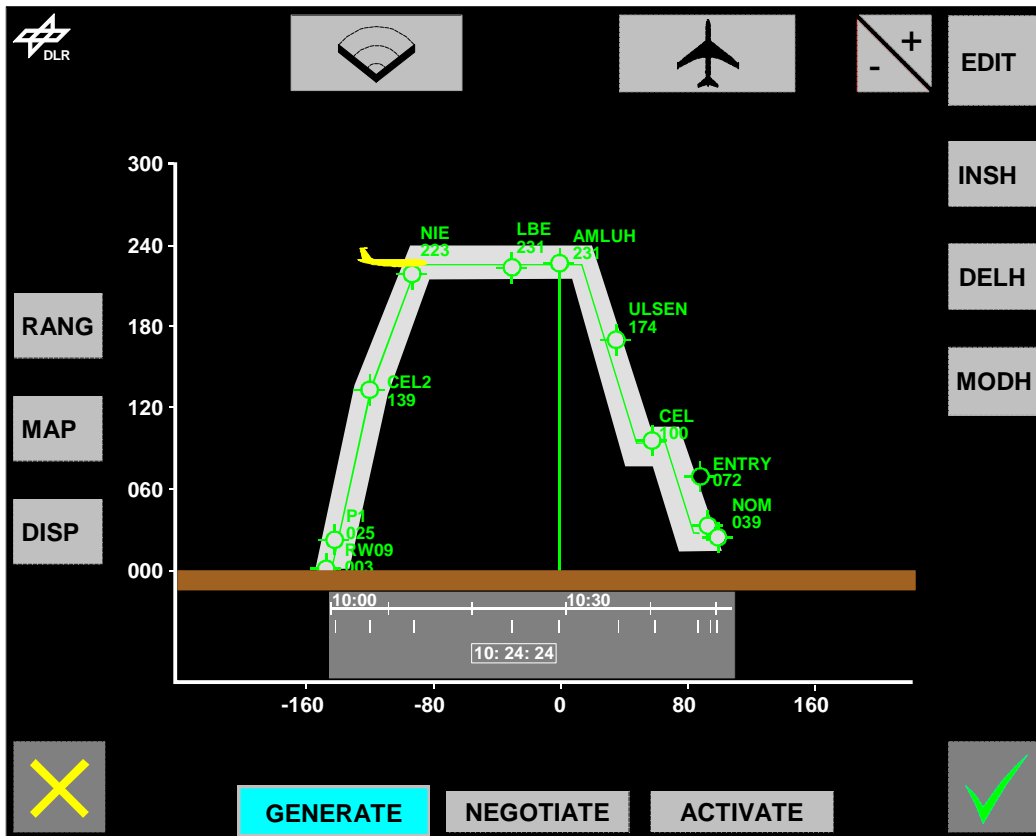


Figure 21 Navigation Display layout: Vertical Display, PLAN mode

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## 8 CONCLUSIONS

As part of the Programme for Harmonised Air Traffic Management Research in EUROCONTROL (PHARE), PD/2 formed the second major real time simulation exercise in a series of three PHARE Demonstrations of an advanced concept which was jointly developed by research organisations from four European nations.

The PD/2 system was demonstrated on DLR's real-time simulator ATMOS (Air Traffic Management and Operations Simulator), using 32 controllers from 7 European countries. The system incorporated advanced controller assistance tools developed by the PHARE Advanced Tools project, with an associated ground human-machine interface (GHMI) designed in the PHARE GHMI project. The DLR Advanced Technologies Testing Aircraft System (ATTAS) Experimental Cockpit, simulated air-ground datalink and 4D experimental flight management systems (EFMS) were integrated into this System. Six pilots participated in an evaluation of the PD/2 on-board components developed in the PHARE airborne human-machine interface (AHMI) project.

A PD/2 airborne demonstration programme using DLR's ATTAS Aircraft, with the ATTAS Experimental Cockpit integrated, was successfully accomplished. The ability of an aircraft to fly, in a routine manner, negotiated trajectories while operating on its inbound route down to the Approach Gate within continuous 4D constraints was convincingly demonstrated.

All participating controllers completed a controllers' training programme of one week that enabled them to work according to their roles in PD/2. They worked both in reference baseline mode with paper strips, similar to current environments, as well as in the PHARE advanced tools mode.

The controllers considered the training as being adequate and sufficient and they appreciated the simulation set-up as being realistic and valid. The PD/2 GHMI gained a high degree of controller approval including significant acceptance of display principles such as colour coding of aircraft labels, and an equally high acceptance of the interaction principles such as using the mouse for on-screen interaction with aircraft labels and pop-up menus.

Although the fundamental PD/2 concept was unanimously well accepted, some details of the operational concept which related to particular properties of the computer assistance tools and functions, received a mixed degree of controller approval. The controllers identified a need for developing individual tools and functions further, to better support controller work under this concept. Particular areas addressed in that context were the support provided by the tools to detect and solve conflicts, the introduction of trajectory update capability, and the capability to adapt better to personal work styles. A similar situation applied to the findings from the on-board components demonstration: a high degree of pilot approval of the demonstrated 4D FMS/datalink concept emerged, while at the same time valuable comments from pilots, to optimise generation, negotiation, and monitoring of 4D trajectories, were obtained. This requirement to develop tools and functions further was to be expected, since the PD/2 system was experimental rather than pre-operational.

The quantitative analysis of system performance data revealed various gains of the PD/2 PATs and GHMI introduction, in terms of traffic throughput and quality of service. Particularly under high traffic-load overall benefits were achieved for the number of landings per time unit, average flight time of aircraft, inbound delays, and time precision of delivery. An analysis of the wake vortex categories separations measured at the Approach Gate suggested that the above benefits were *not* achieved at the expense of closer separation.

Another general point was that, in parallel to the improvements gained with the advanced system, the variability of the measurements was considerably reduced. The controller team performances and work styles became more consistent, and thus more predictable.

It is concluded that improvements in traffic throughput and quality of service were achievable with the advanced system alone. The 4D FMS/datalink aircraft that automatically followed their negotiated trajectories were introduced in two steps of 30 % and 70 % of aircraft in the traffic samples. Their introduction resulted in considerably higher percentages of aircraft being delivered at the Approach Gate exactly on their planned time.

Statistical analysis of controller workload revealed, as an effect of the PD/2 PATs and GHMI introduction, some re-distribution of workload between tactical controller positions. Important to note is an observed decrease of workload at the Approach Pickup controller position which under reference baseline condition was the position with the relatively highest workload.. Furthermore, the introduction of 30 % and 70 % 4D FMS/datalink aircraft in the traffic sample produced a stepwise reduction of workload for all tactical controller positions.

The effect of releasing the controllers from the duty of transferring ATC instructions showed significant reductions in all objective workload measures at all controller working positions irrespective of traffic volume. We can therefore conclude that workload regarding the mere traffic guidance was strongly reduced by increasing proportion of 4D FMS/datalink equipped aircraft.

In summary, PD/2 was a major, successful demonstration of the integration of air and ground air traffic management using advanced tools, 4D FMS, and datalink, in an extended terminal area airspace. Experimental evidence suggests that the PHARE concept of trajectory-based traffic guidance provided by the advanced tools and human/machine interfaces was approved by the controllers and pilots, and that it has the potential for improving traffic throughput and quality of service, at acceptable levels of controller workload.

## 9 ACKNOWLEDGEMENTS

A collaborative work programme like PHARE PD/2 would not be possible without the close co-operation of the PHARE partners in the research establishments: CENA of France, DLR of Germany, EUROCONTROL, NATS of the UK and NLR of the Netherlands. Everyone who contributed in the execution of the PD/2 project shares in its success.

Special acknowledgements go to:

- all the controllers and pilots who participated. It was a great pleasure to co-operate with such qualified and highly motivated personnel.
- the authorities and organisations who supported the PD/2 trials.
- the Flugabteilung of DLR for their participation in the ATTAS flight programme.
- the PHARE cell members for their co-ordination effort.

A special thank is addressed to the British controllers Alison Rhodes, Roger Goodwyn and Terry Symmans for their constructive comments and effective support during the pilot phases, and for their assistance in the demonstration phases of PD/2.

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## 10 GLOSSARY

25L	Runway 25 Left
25R	Runway 25 Right
4D	Four Dimensional (latitude, longitude, altitude, and time)
4D FMS	Four Dimensional Flight Management System
a/c	Aircraft
ACC	Area Control Centre
ADP	Aéroports de Paris
AHMI	Airborne Human-Machine Interface
AMD	Arrival Management Display
ANOVA	Analysis of Variance
API	Application Interface
ATC	Air Traffic Control
ATMOS	Air Traffic Management and Operations Simulator
ATS	Air Traffic Services
ATTAS	Advanced Technologies Testing Aircraft System
CAS	Calibrated Airspeed
CDU	Control Display Unit
CENA	Centre d'Etudes de la Navigation Aérienne
CLASS A	Aircraft in <b>A</b> utomatic guidance mode (4D FMS/datalink equipped aircraft with clearance to implement its own trajectory)
CLASS B	Aircraft guided via R/T, ground system support through conflict-free trajectory and advisories
CLASS M	Aircraft in <b>M</b> anual guidance mode (via R/T) without a valid trajectory
CMS	Common Modular Simulator
COMPAS	Computer Oriented Metering, Planning and Advisory System
CP	Conflict Probe
CRD	Conflict Risk Display
d.f.	Degrees of Freedom
DFS	Deutsche Flugsicherung GmbH
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V.
EEC	EUROCONTROL Experimental Centre
EFMS	Experimental Flight Management System
ETMA	Extended Terminal Manoeuvring Area
FL	Flight Level

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FMS	Flight Management System
FPM	Flight Path Monitor
GED	Metering Fix Gedern
GHMI	Ground Human-Machine Interface
H0	Null Hypothesis
H1	Alternative Hypothesis
ILS	Instrument Landing System
LFV	Lufftartsverket (Swedish Civil Aviation Administration)
MilATCC	Military Air Traffic Control Centre
n	Number of Subjects
n.s.	Not Significant
NATS	National Air Traffic Services
ND	Navigation Display
NLR	Nationaal Lucht- en Ruimtevaartlaboratorium
NM	Negotiation Manager
NM	Nautical Mile
ORG	Organisation
PATs	PHARE Advanced Tools
PD/2	PHARE Demonstration 2
PHARE	Programme for Harmonised Air traffic management Research in EUROCONTROL
PSA	Metering Fix Spessart
PVD	Plan View Display
R/T	Radio Telephony
RMS	Root Mean Square
ROMATSA	Romanian Air Traffic Services Administration
RUD	Metering Fix Rüdeshheim
RWY	Runway
SICTA	Sistemi Innovativi per il Controllo del Traffico Aereo
STAR	Standard Arrival Route
SWAT	Subjective Workload Assessment Technique
TLX	NASA Task Load Index
TMA	Terminal Manoeuvring Area

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Trajectory	A trajectory is defined as a series of profile and route points defining a 4D–path for an aircraft joined by straight or curved segments ( 4D or 4 Dimensional is used to denote positions in space defined relative to earth and time. These points can be considered as being latitude, longitude, altitude and time).
Trajectory Predictor	Trajectory Predictor
VAL	Validation Tools Project
VVD	Vertical View Display

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## 11 REFERENCES

Within PHARE numerous documents have been produced in preparation of the PHARE Demonstration 2, that represent sources for the PD/2 Final Report.

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