Theoretical and Operational Aspects of Optimal Airport Arrival Trajectories
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Proefschrift

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Current routing procedures near airports are based on sets of published standard routes. In practice, however, air traffic controllers normally provide flight crews with instructions on a tactical basis, modifying the standard routes. This is necessary to improve efficiency and reduce environmental impact because the standard routes are the same for different situations in terms of traffic demand and weather. This cannot prevent, however, that airports occupy a bottleneck position in the air transportation system. This is indicated by growing delays, emissions, and noise disturbances.

It has been shown that it is possible to choose the shape of the arrival trajectories so that delays or environmental impact are minimised. Choosing the trajectory to minimise or maximise a certain criterion is referred to as optimising the trajectory. An example of a trajectory optimised with respect to noise production is the trajectory flown in a continuous descent approach or three-degree decelerated approach. It has been shown that such a trajectory can reduce environmental impact because a large part of the approach is flown with low thrust. However, implementing optimised trajectories such as in a continuous descent approach is at present often difficult. Operational speed and altitude constraints and ad hoc controller instructions to solve conflicts result often in deviations from the optimal trajectory. Reducing the need for tactical interventions is expected to make it easier to implement optimised trajectories. In order to reduce the need for tactical interventions more strategic control of arriving flights has been proposed.

In addition to planning trajectories more strategically, it has been proposed to make these strategically planned trajectories also flexible. Flexibility refers in this work to plan-
ning the optimal trajectory for the current situation. Such an optimal trajectory is not always the same, because the shape of it depends on the criterion used for optimisation, aircraft characteristics, and weather conditions. This is why the term flexible is used in this context. Current efforts of planning flexible trajectories, however, have been limited mainly to en-route traffic. For arriving traffic, standard trajectories have usually been maintained. It may be argued that these standard trajectories could, for example, be replaced with fixed trajectories corresponding to a continuous descent. This is, however, difficult because these trajectories depend on the situation. Allowing flexible arrival trajectories may allow more extensive use of continuous descents because the trajectory can be adapted to a particular situation. Flexible arrival trajectories may therefore result in reduced noise production. Planning flexible arrival trajectories may also allow increased runway throughput because optimisation of arrival sequences and times can be done more strategically. Optimising in an earlier stage generally results in a wider range of possibilities that can be considered and hence a better final solution. In addition, allowing flexible trajectories may reduce environmental impact by adapting the lateral trajectory profiles more strategically to current conditions so as to minimise impact on the environment.

Earlier research has shown that optimal arrival trajectories may become more complex than trajectories currently used. The usual interpretation of a trajectory becoming more complex is that the shape of the trajectory becomes less structured. The reason that flexible trajectories for arrival traffic have been studied less extensively than for en-route traffic is related to the effects of the shape of the trajectory on the tasks of pilots and air traffic controllers. In general, the effort required for executing a task is referred to as the task demand load. It is generally thought that making the trajectory more complex, or less structured, increases the task demand load for the pilot and for the air traffic controller. The tasks of pilots and air traffic controllers are usually more complicated and more extensive in the arrival phase than in the en-route phase. Hence, the task demand load is generally higher in the arrival phase. It is therefore thought that especially introducing flexible trajectories in the arrival phase may result in higher, possibly unacceptable, task demand load. However, there is only very limited theory about the influence of the shape of the trajectory on the task demand load for both pilots and air traffic controllers.

Because more accurate time-based navigation is anticipated for the future, modern guidance displays have been developed for assisting pilots in minimising deviations from planned trajectories, both in space and time. These displays may also allow for more complex arrival trajectories while retaining acceptable task demand load. These displays may therefore be an important enabler for flexible arrival trajectories.

This study has three main objectives. First, to demonstrate that performance can be increased in terms of throughput, the degree to which continuous descents are applied, and environmental impact by using flexible arrival trajectories instead of trajectories typically used at present. Second, to determine which factors in the shape of the trajectory contribute to task demand load for pilots, to determine whether the task demand load is higher for
flexible arrival trajectories than for currently used trajectories, and to determine if guidance displays currently being developed can reduce the task demand load. Third, to determine how and to what extent introducing flexible arrival trajectories increases the task demand load for air traffic controllers.

The benefits of flexible arrival trajectories are demonstrated in an off-line analysis. The currently used arrival trajectories are compared with trajectories that are optimised for a particular situation in terms of the altitude profile, speed profile, and lateral profile. The criteria used for optimisation are throughput, the degree to which continuous descents are applied, and environmental impact. The algorithms that have been used previously for trajectory optimisation typically solve a single-objective problem, even if multiple objectives are considered. It has been suggested, however, that this may result in undesirable solutions. Truly multi-objective optimisation may yield better solutions in terms of acceptable performance on multiple objectives, which is important for the problem considered. Recently, algorithms called genetic algorithms have been developed. Genetic algorithms are stochastic search methods modeled on the process of natural Darwinian evolution. They have been considered to be more suitable for multi-objective optimisation than classical optimisation methods. In addition, genetic algorithms are generally suitable for adapting solutions quickly to changing circumstances. For these reasons, a multi-objective trajectory optimisation method based on a genetic algorithm is used here. The analysis is done for Amsterdam Airport Schiphol in The Netherlands. The analysis shows that using flexible arrival trajectories can increase throughput, enables scheduling trajectories closer to continuous descent approaches, and results in routing flights less often over residential areas.

A number of metrics for describing the task demand load of the pilot’s task of guiding the aircraft along the trajectory are identified in an off-line analysis. These metrics are subsequently validated experimentally in a flight simulator. The experiments confirm that the shape of the reference trajectory influences task demand load. It was mainly influenced by the longitudinal shape of the trajectory. Changing the lateral shape of the trajectory could not be shown to influence the task demand load. It is recommended to study if these metrics can be combined into a single prediction of task demand load and if acceptable limits can be established. The experiments also indicated that guidance displays currently under development that give information related to reference position, reference speed, and acceleration can reduce the task demand load. This relates especially to control of position along the trajectory. It was indicated in the off-line analysis that task demand load relating to longitudinal motion increased when flexible arrival trajectories were used. This is mainly caused by the necessity of more manoeuvres to achieve flight profiles closer to those of a continuous descent approach while still meeting all the constraints. There were no indications found that the task demand load relating to lateral motion was increased.

The effects of flexible arrival trajectories on the task demand load for air traffic controllers are also assessed with a number of metrics. These metrics describe if the traffic situation as a whole becomes less structured and if it becomes more sensitive to non-conformance
to planned trajectories. This has been referred to as an increase in *airspace complexity*. An increase in airspace complexity is generally thought to increase task demand load for controllers. Mainly metrics identified in earlier research were used that describe geometric properties of the traffic flows. The traffic density generally became lower for flexible arrival trajectories than for conventional trajectories because more airspace could be used. The flexible trajectories could, however, result in more crossing points between arrival and departure traffic, higher vertical closure rates, and lower horizontal separation distances between aircraft. Although for flexible arrival trajectories that were optimised in terms of the lateral profiles a decrease in horizontal separation distances could be prevented, it is concluded that flexible arrival trajectories may increase airspace complexity. It is therefore also concluded that task demand load for air traffic controllers may increase. Similar to the pilot’s task, improvements in human-machine interfaces in air traffic control may help to reduce task demand load.
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1 INTRODUCTION

1.1 The Air Transportation System

The volume of air traffic has been growing over the last couple of decades to cope with the steadily increasing need for transportation around the globe (Eurocontrol, 2005). In Europe, traffic volume is expected to keep increasing by 3-4% every year, see Figure 1.1. The air transportation system, however, has not evolved with the growing volume of air traffic and has, in essence, not changed since the 1950s. It is becoming clear now that the air transportation system was not designed for current traffic loads. It is also becoming clear that airports occupy a bottleneck position in the air transportation system.

This can be seen for example in delay figures. The European Organisation for the Safety of Air Navigation (Eurocontrol) typically studies the evolution of delays by considering the delays imposed on a flight before departure due to flow restrictions requested by en-route centres or by the origin/destination airport. These delays are referred to as en-route and airport air traffic flow management (ATFM) delays, respectively. In Figure 1.2 the ATFM delays are shown for the summer period, because Eurocontrol defines delay targets for this period. En-route ATFM delays have decreased significantly in recent years. This is mainly due to better co-operation between the different parties involved. On the other hand, airport ATFM delays have not improved significantly in absolute value and are currently representing a larger part of the total ATFM delays than in the past. In summer 2004, airport ATFM delays constituted 38% of all ATFM delays (Eurocontrol, 2005). The majority of these delays were applied to arrival traffic. In addition, the constraints that airports have to operate within are growing. Social issues such as noise and pollution are becoming severely limiting factors in operating the airspace around airports (Meeus & Wagendorp, 2003; de Boer, 2001). These are all indications of the bottleneck position of airports in the current air transportation system.
Current air traffic management (ATM) is based on published sets of standard arrival routes (STARs) and standard instrument departures (SIDs). In practice, however, air traffic controllers normally provide flight crews with instructions on a tactical basis, modifying the standard routes. This is referred to as vectoring. In tactical control a look ahead time of about 5 minutes is normally considered. Vectoring is necessary to improve efficiency and reduce environmental impact because the standard routes are the same for different situations in terms of traffic demand and weather.

![Figure 1.1](image1.png) Actual and forecasted traffic in Europe (Eurocontrol, 2005).

![Figure 1.2](image2.png) En-route and airport ATFM delay during the summer (Eurocontrol, 2005).

It has been shown that it is possible to choose the shape of the arrival trajectory so that delays or environmental impact are minimised. Choosing the trajectory to minimise or maximise a certain criterion is referred to as optimising the trajectory. An example of a trajectory optimised with respect to noise production is the trajectory flown in a continuous descent approach or three-degree decelerated approach (Erkelens, 2000; Clarke, 2000; Clarke et al., 2004). The SIDs and STARs have often been designed as low noise routings in lateral sense. However, it has been shown that optimising the trajectory, such as in a continuous descent approach, can reduce environmental impact (Visser & Wijnen, 2001a, 2001b). The reason for this is that a large part of the approach is flown with low thrust. However, implementing optimised trajectories such as in a continuous descent approach is at present often difficult. Operational speed and altitude constraints and ad hoc controller instructions to solve conflicts result often in deviations from the optimal trajectory. This results in more
noise than theoretically necessary (Kershaw, Rhodes, & Smith, 2000). Reducing the need for tactical interventions is expected to make it easier to implement optimised trajectories.

The tools for communication, navigation, and surveillance (CNS) that enable the implementation of optimised trajectories are already largely available or under development (Kayton & Fried, 1997; Galotti Jr., 1997). The introduction of navigation based on satellite measurements in general and navigation based on differential global positioning system (GPS) technology in particular has allowed very high navigation accuracy, also during the arrival procedure. Curved instead of straight-in approaches may be flown in the future with the help of the microwave landing system (MLS). In addition, most modern aircraft are equipped with a flight management system (FMS) that supports area navigation (RNAV). The RNAV function removes the necessity to follow ground-based navigation fixes. In addition, modern FMS systems are capable of predicting the flight path accurately. The increased navigation accuracy of on-board systems and the increased capability of avionics systems allow modern aircraft to not only have access to detailed information on the state of the aircraft but also to express the airline’s business strategy through specifying user preferences (Green, Goka, & Williams, 1997). Using the FMS, formulating these preferences can be as detailed as defining an entire optimal flight trajectory. Communication based on data link is expected to become operational shortly. It will allow sending much more extensive sets of data between aircraft and ground stations, including eventually the entire trajectory.

1.2 Directions of Research

1.2.1 From Tactical to Strategic Control

More strategic ATM has been proposed in order to reduce the need for tactical interventions. Strategic in this sense means a look ahead time that can vary from about 5-20 minutes for improved sector traffic planning to longer than the flight time for longer-term concepts. This can be achieved with the assistance of automated decision support tools because they make more reliable predictions available to air traffic controllers. In addition, most of these tools employ centralised trajectory optimisation algorithms and are capable of advising controllers on actions that optimise performance. This usually refers to minimising the amount of delays. Examples of such tools are the Dutch “Amsterdam Advanced ATC System” (AAA), the German “Computer Oriented Metering Planning and Advisory System” (COMPAS), and the French “Means to Aid Expedition and Sequencing of Traffic with Research of Optimisation” (MAESTRO) system (Petre, 1994). Recently, centralised trajectory optimisation has been further studied in the context of the “Center TRACON Automation System” (CTAS) at NASA in the U.S. (Prevot, Crane, Palmer, & Smith, 2000) and in the context of the “Programme for Harmonised Air Traffic Management Research in Euro-control” (PHARE) in Europe (Fairclough & McKeever, 2000). These two programs are described in more detail in Chapter 2.
1.2.2 From Fixed to Flexible Trajectories

In addition to planning trajectories more strategically, it has been proposed to make these strategically planned trajectories also flexible. The term flexibility in this context has been used differently. Flexibility may refer to offering a choice between standard trajectories. Flexibility has also been taken to mean that trajectories are adapted while they are being flown. In the last meaning, currently used arrival trajectories are flexible because of vectoring. Flexibility refers in this work to planning the optimal trajectory for the current situation. Such an optimal trajectory is not always the same, because the shape of it depends on the criterion used for optimisation, aircraft characteristics, and weather conditions. This is why the term flexible is used here.

As discussed above, trajectories may be optimised with respect to noise production. Other criteria for optimisation include flight time and fuel consumption. In an attempt to make maximum use of the increased aircraft’s capabilities and to apply flexible trajectories for a large portion of the flight, the concept of free flight was introduced (Minnick, 1981; RTCA Task Force 3, 1995; Hoekstra, 2001; Krozel & Mogford, 2001). In the most radical interpretation of free flight, aircraft are allowed to fly essentially any trajectory they consider to be optimal for the current situation. In addition, the task of separation assurance is shifted from air traffic control (ATC) to the aircraft, thus changing from a system of centralised control to de-centralised control. This is also referred to as distributed control. The characteristics of these systems are being investigated widely, where special attention is given to how potential conflicts between aircraft should be solved (Paielli & Erzberger, 1997; Blin, Akian, Bonnans, Hoffman, & Zeghal, 2000; Tomlin, Pappas, & Sastry, 1997; Hoekstra, Ruigrok, & van Gent, 2000). The financial benefits of free flight due to flying shorter trajectories, burning less fuel, and better exploiting the airborne capabilities have been estimated in the U.S. at several billions of dollars annually (Barnett, 2000). Both Eurocontrol and the Federal Aviation Administration (FAA) are undertaking efforts to be able to adapt trajectories and traffic flows more to the situation at hand (Eurocontrol, 2003; FAA, 2005).

1.2.3 Four-Dimensional Guidance

Aircraft navigate normally within vertical and lateral path constraints and speed constraints. It has been argued though that more accurate time-based navigation enables higher efficiency in the ATM system, especially for arrival traffic (Adam & Lechner, 1982). This can be achieved by controlling the along-track position of the aircraft more accurately. The desire for controlling along-track position more accurately has resulted in putting limits on the aircraft’s along-track positions through time. Limits on along-track position in addition to limits on vertical and lateral position are called four-dimensional (4-D) constraints (van Gool & Schröter, 1999).

Earlier research has shown that optimal arrival trajectories may become more complex than trajectories currently used (Visser & Wijnen, 2001b). The usual interpretation of
a trajectory becoming more complex is that the shape of the trajectory becomes less structured. In general, the effort required for executing a task is referred to as the task demand load or TDL (Stassen, Johannsen, & Moray, 1990). It is generally thought that making the trajectory more complex, or less structured, increases the task demand load for the pilot. Using, in addition, stricter path constraints may result in the currently operational human-machine interfaces not being adequate any more (Garteur, 1990).

Research has studied new human-machine interfaces such as the tunnel-in-the-sky display (Grunwald, Robertson, & Hatfield, 1981; Mulder, 1999). This type of display provides a three-dimensional or perspective view of the flight path. It promises to allow flying more complex trajectories with even higher navigation performance. It is also thought to support the pilot in understanding current and future states of the environment. This ability has been referred to as situation awareness (Endsley, 1995). For a pilot, the environment includes elements such as the aircraft, mountains, and warning lights.

The growing importance of meeting time constraints better was one of the reasons for studying extensions to tunnel-in-the-sky displays. These extensions were designed to enable control of the aircraft’s along-track position. Control of the aircraft’s along-track position, in addition to control of lateral and vertical position, is generally referred to as 4-D guidance. Several designs have been made for a perspective display that allows 4-D guidance (Watler, Jr. & Mulley, 1978; Grunwald, 1984; Hoover, Shelley, Cronauer, & Filarsky, 1984; Reising et al., 1998; Otten, 2001).

1.3 Thesis Motivation

The arrival trajectories considered in most previous work are similar to STARs. This is the case in programs such as CTAS, PHARE, and most programs on free flight. The lateral, vertical, and speed profiles of these trajectories are constrained significantly due to ATC considerations and the final part of the approach is flown along the straight path defined by the instrument landing system (ILS).

It may be argued that these standard trajectories could be replaced with fixed optimised trajectories. This is, however, difficult because the shape of these trajectories depends on the situation, meaning the criterion used for optimisation, aircraft characteristics, and weather conditions. If, on the other hand, the arrival trajectory is not fixed, the trajectory optimal for the current situation may be implemented. Allowing arrival trajectories to be optimised for the current situation is referred to in this work as allowing flexible arrival trajectories.

There are different aspects of the shape of the arrival trajectory that may be optimised so that a flexible arrival trajectory is obtained. It has been shown that allowing flexibility in the altitude, speed, and lateral profiles may allow a greater portion of the arrival to be carried out as a continuous descent, may reduce environmental impact, and may increase throughput (Erkelens, 2000; Visser & Wijnen, 2001b; Clarke et al., 2004; Vormer, Mulder, 2001).
It is believed that reducing the length of the straight final leg of the approach is a feasible way of optimising lateral profiles (Erkelens, 2000; Funabiki, Muraoka, Terui, Harigae, & Ono, 1999). The new length of the final leg may also be adapted to the local situation. The studies mentioned here, however, did mainly study individual flights and did not show improved throughput and reduced environmental impact simultaneously.

Flexible trajectories have so far been studied less extensively for arrival traffic than for en-route traffic. The reason for this relates to the effects of the shape of the trajectory on the tasks of pilots and air traffic controllers. As mentioned above, flexible trajectories may become more complex than currently used trajectories. It is generally thought that making the trajectory more complex, or less structured, increases the task demand load for the pilot and for the air traffic controller. The tasks of pilots and air traffic controllers are usually more complicated and more extensive in the arrival phase than in the en-route phase. Hence, the task demand load is generally higher in the arrival phase. It is therefore thought that especially introducing flexible trajectories in the arrival phase may result in higher, possibly unacceptable, task demand load. However, there is only very limited theory about the influence of the shape of the trajectory on the task demand load for pilots and air traffic controllers.

With respect to pilots, the issue was addressed only in a few earlier studies (Funabiki et al., 1999). It is not clear which factors in the shape of the trajectory influence task demand load. In addition, it is not clear how and to what extent introducing more complex arrival trajectories influences task demand load. Requiring, besides more complex trajectories, higher 4-D navigation performance is expected to increase task demand load even further (Mulder, 1999). Newly developed instrumentation in the form of a 4-D guidance display may, however, allow for more complex trajectories with still acceptable task demand load. These displays may therefore be an important enabler for flexible arrival trajectories.

With respect to air traffic controllers, a number of metrics have been proposed to assess the influence of the shape of the trajectories on what is in this work referred to as task demand load (Masalonis, Callaham, & Wanke, 2003; Delahaye & Puechmorel, 2000; Histon, Aigoin, Delahaye, Hansman, & Puechmorel, 2001). These metrics describe if the traffic situation as a whole becomes less structured and if it becomes more sensitive to non-conformance to planned trajectories. This has been referred to as an increase in airspace complexity (Masalonis et al., 2003). Although several other terms have also been used, such as “dynamic density” and “air traffic complexity”, airspace complexity is considered the most general term and is therefore used here. An increase in airspace complexity is thought to result in an increase in what is here referred to as task demand load for air traffic controllers (RTCA Task Force 3, 1995). It is not clear though if flexible arrival trajectories do result in higher task demand load than conventional trajectories.
1.4 Objectives

This study has three main objectives. The first objective is to demonstrate that performance in terms of runway throughput, the degree to which continuous descents are applied (relating to noise production and fuel costs), and environmental impact can be increased by using flexible arrival trajectories instead of trajectories currently used. This is done for the case that flexible trajectories are applied for all arriving traffic in the terminal area. The second objective is to determine which factors in the shape of the 4-D trajectory contribute to task demand load for flight crews, to determine if flexible arrival trajectories introduce additional task demand load for pilots when compared to currently used trajectories, and to determine if a 4-D guidance display can reduce the task demand load. The third objective is to determine how and to what extent introducing flexible arrival trajectories increases task demand load for air traffic controllers.

1.5 Methods

The benefits of flexible arrival trajectories are demonstrated in an off-line analysis. The currently used arrival trajectories are compared with trajectories that are optimised in terms of the altitude profile, speed profile, lateral profile, and location of the final intercept point for a particular situation. The criteria used for optimisation are throughput, the degree to which continuous descents are applied, and environmental impact.

The algorithms that have been used previously for trajectory optimisation typically solve a single-objective problem, even if multiple objectives are considered. It has been suggested, however, that this may result in undesirable solutions. Truly multi-objective optimisation may yield better solutions in terms of acceptable performance on multiple objectives (Vormer, Boer, van Paassen, Mulder, & Davison, 2003). This is important for the problem considered here.

Recently, algorithms called genetic algorithms have been developed. Genetic algorithms are stochastic search methods modeled on the process of natural Darwinian evolution. They have been considered to be more suitable for multi-objective optimisation than classical optimisation methods. In addition, genetic algorithms are generally suitable for adapting solutions quickly to changing circumstances. For these reasons, a multi-objective trajectory optimisation method based on a genetic algorithm is used here. The analysis is done for Amsterdam Airport Schiphol in The Netherlands. In the analysis aircraft performance models and data recorded from operational practice are used.

Metrics that contribute to task demand load for the pilot’s task of following a 4-D flight path are identified through considering the task load index (TLX) rating method (Hart & Staveland, 1988). Only manual aircraft control is considered because it normally results in more task demand load than flying with an automatic flight control system (AFCS). Other pilot tasks, such as communicating with ATC, are not considered. The metrics are validated experimentally through trials in a flight simulator, assuming that all CNS tools mentioned
in Section 1.1 are available.

The values of these metrics are calculated for current and flexible trajectories. This allows to address task demand load for pilots. In addition, the values of metrics that describe airspace complexity are calculated for current and flexible trajectories also. These metrics are mainly taken from literature. This allows to address task demand load for air traffic controllers.

1.6 Outline

The thesis is roughly structured as follows. The first part of the thesis focuses on developing a method for scheduling flexible arrival trajectories with the aim of increasing ATM performance. The attention is then shifted towards TDL for pilots. Metrics for TDL are identified and validated experimentally. In the last part of the thesis the off-line analysis is discussed in which ATM performance, TDL for pilots, and TDL for air traffic controllers are calculated and compared for current and flexible arrival trajectories. The structure of the thesis is illustrated graphically in more detail in Figure 1.3.

Figure 1.3 Structure of the thesis. The three objectives are grouped vertically and the topics horizontally. The numbers in the squares indicate the chapters in which the topics are discussed. The symbols in the circles refer to the appendices.

The individual chapters discuss the following topics. Chapter 2 discusses in more detail recent research on arrival trajectory scheduling in the context of CTAS and PHARE. Chapter 3 presents the design of a method for scheduling flexible arrival trajectories. The method is based on genetic optimisation of runway throughput, the degree to which continuous descents are applied, and environmental impact.

In Chapter 4 metrics are identified to describe the influence of the shape of a 4-D arrival trajectory on the task demand load of guiding the aircraft along the trajectory. Off-
line analyses are carried out to validate important properties of these metrics.

Chapter 5 discusses several designs for a 4-D guidance display that may allow for more complex arrival trajectories. Based on a control-theoretical analysis, it is discussed how each display influences the task demand load of controlling the along-track position. This is the new task introduced if pilots are required to conduct 4-D guidance.

Chapter 6 describes the set-up and results of experimental evaluations carried out to demonstrate the importance of the metrics identified in Chapter 4 for task demand load of the pilot’s task. The experiments are conducted using different formats for the primary flight display (PFD) to validate the findings from Chapter 5.

In Chapter 7 an off-line analysis is carried out with the scheduling method from Chapter 3 to demonstrate the benefits of flexible arrival trajectories. The effects of using flexible arrival trajectories instead of current trajectories on task demand load for pilots are assessed using the metrics from Chapter 4. The effects on task demand load for air traffic controllers are assessed using metrics that describe airspace complexity.

Chapter 8 draws conclusions on the results obtained and provides recommendations for further research.
BACKGROUND AND RELATED RESEARCH

This chapter discusses research that has been carried out with respect to scheduling arrival trajectories. Section 2.1 discusses the work carried out at NASA in the context of the Center TRACON Automation System (CTAS); Section 2.2 discusses the results of a Eurocontrol program called the Programme for Harmonised Air Traffic Management Research in Eurocontrol (PHARE). These two programs can be seen as representative of the U.S. and the European approach to improving arrival trajectory scheduling. They are described and compared in terms of long-term planning and optimisation, short-term planning and optimisation, and the type of arrival trajectories that are used.

2.1 The CTAS Approach

2.1.1 Overview

The Center TRACON Automation System (CTAS) is developed to help air traffic controllers increase safety and efficiency (Erzberger, Davis, & Green, 1993). The system is particularly interesting, because it combines new route optimisation techniques with tools well-tested in operational practice. The tools that together form CTAS are being developed at the NASA Ames Research Center in Moffett Field, California in the U.S. The CTAS tools help en-route and terminal area controllers manage and control arrival traffic efficiently by providing computer-generated advisories. The system has been tested at the Dallas/Fort Worth airport to evaluate it in an operational environment and to get feedback from controllers using the system in real-life practice. Evaluations have shown that CTAS can increase airport throughput by 9-13% (Davis et al., 1997).
Figure 2.1 The U.S. airspace is divided into air route traffic control centers (ARTCCs), also known as 'Centers'. The position of the terminal radar approach control (TRACON) and the standard routes in both areas are indicated, although the STARs are normally adjusted using vectoring. The triangles indicate the locations of the meter fixes.

The functions of CTAS can be divided into planning and control functions. For these functions three different tools have been developed. The CTAS planning function is implemented in the first tool: the Traffic Management Advisor (TMA). This tool generates runway assignments, landing sequences, and landing times for all arriving traffic. The control functions of CTAS are implemented in the En Route Descent Advisor (EDA) and the Final Approach Spacing Tool (FAST). The EDA is used by en-route sector controllers and assists them in directing flows of arrival traffic to meter fixes at specified times in a fuel-efficient and conflict-free way before hand-off into the TRACON (Figure 2.1).

FAST is a tool which provides heading and speed advisories in the TRACON and is used by TRACON controllers. It assists in obtaining an accurately spaced flow of traffic that meets the schedule at the runway threshold as it was generated by the TMA. However, once an aircraft enters the TRACON airspace FAST may overrule the runway assignments and the times assigned by the TMA.

2.1.2 Long-Term Planning and Optimisation

Sequencing and Scheduling
The component of most interest is the TMA since it is the CTAS component responsible for long-term sequencing and scheduling of arrival aircraft. Sequencing is concerned with establishing a landing order for a group of aircraft, scheduling assigns a specific landing time to each individual aircraft. The process of sequencing and scheduling starts when the aircraft is approximately 200 nmi or 45 minutes flying time away from the airport, when it enters the Center sector from another Center sector or when it departs from an airport within the Center.
The TMA calculates for each aircraft the estimated time of arrival (ETA) and uses a sequencing and scheduling algorithm to transform this into a scheduled time of arrival (STA). The first step in this process is sequencing and scheduling at the meter fixes. When the TMA has finished determining the STAs for the meter fixes, the STAs at other reference points such as the runway threshold are calculated by using estimates of the time needed to fly between the reference points. Scheduling the meter fix STAs is done by an optimisation algorithm. A variant of the binary implicit enumeration branch and bound technique (Brinton, 1992) is used.

**Determining the Quality of Solutions**

The cost function considered by the optimisation algorithm consists of a weighted combination of delays and fuel consumption. To evaluate the cost of a candidate sequence it is necessary to first schedule all aircraft in the best possible way for this sequence. To do this the STA of the first aircraft is set to its ETA. If doing the same thing for the next aircraft would violate separation requirements, the STA of this aircraft is set to the STA of the previous aircraft plus the required separation. In case there is no violation, this aircraft is also scheduled for its ETA. This process is repeated until all aircraft are scheduled. After the meter fix schedules have been optimised in this way, the scheduled times of arrival at the other reference points can be calculated. This makes it possible to calculate the cost of choosing this solution.

**Searching for Solutions**

The simplest way to determine the sequence that minimises the objective function is generating all possible sequences and evaluating them all with respect to the objective function. However, such an approach was not considered feasible for use in real-time automation systems with current computer performance. The implicit enumeration branch and bound technique is based on finding a bound on the objective function quickly. This severely limits the number of possible solutions to be evaluated. Branch and bound techniques search the solution space (i.e., all possible sequences) by creating a sequence development tree. This tree is created by branching form the first aircraft to the next one in all possible ways until all aircraft are sequenced. To find a near optimum bound on the objective function quickly, the algorithm starts with branching to the next aircraft every time in the first come first serve (FCFS) order, or to the next aircraft if a schedule was already made. When a next aircraft is added to the sequence, the value of the aircraft individual cost function is added to the objective function value of all aircraft already scheduled.

Several methods are used to limit the length of the search for the best solution. If the objective function value can only increase when a new aircraft is added to the sequence, it is possible to discard a partially developed sequence in an early stage. If the objective function value of a partially developed sequence reaches the upper bound at some point in the development tree, this sequence and all possible branches after it cannot possibly result
in a lower objective function value than the one already determined. The partially developed
sequence can thus be discarded.

**Update Process**
The TMA continuously updates the sequences, schedules, and runway assignments in order
to adapt to changes in the traffic situation and the environment or in response to inputs by
controllers. An aircraft’s STA is constantly updated until the aircraft’s meter fix ETA is
less than or equal to 19 minutes in the future. After this point the STA is frozen.

**2.1.3 Short-Term Planning and Optimisation**
Short-term modifications to the arrival plan can be implemented by Center controllers through
the use of the EDA and by TRACON controllers through the use of FAST.

**Center Airspace**
While the airplane is in the Center, the EDA continuously gives speed, altitude, and head-
ing advisories. These advisories are generated to meet the meter fix schedules, to provide
high fuel efficiency, and to be as close as possible to the flight crew’s or airline’s prefer-
ences. These preferences could be given in many different forms, including preferred
descent speed, route, altitude or entire 4-D trajectory (Green & Vivona, 1996).

**TRACON Airspace**
Once an airplane enters the TRACON airspace, FAST may overrule the schedules and
runway assignments originally assigned by the TMA. When FAST was being designed,
it appeared that the algorithms used in the TMA did not account enough for factors like
efficiency, controller workload, and adaptability in the TRACON (Robinson III, Davis, &
Isaacson, 1997). Although useful for strategic decision support, they were less effective
for tactical decision support. Therefore, a scheduling algorithm was used in FAST that
was based on a different algorithm called the knowledge-based sequencing algorithm. This
algorithm makes extensive use of fuzzy logic techniques. It splits the traffic merging prob-
lem into merges at multiple points. At every trajectory segment intersection the sequencing
problem is identified and resolved. This results in traffic being scheduled at more points
than those considered by the TMA. It also results in using arrival trajectories that air traffic
controllers are familiar with since FAST essentially mimics the controller’s actions.

Optimisation is carried out in the sense that aircraft can be switched to alternative
runways if this is found to reduce delays. However, the aircraft’s runway assignment was
in most CTAS applications frozen when the remaining flight time to the runway was less
than twelve minutes. In addition, FAST will not switch the aircraft back to the original
runway when an aircraft has been switched to a different runway, since this was found to be
unacceptable to controllers. This approach yields an arrival schedule that works well within
the current ATM system but which is not necessarily the most optimal one.
2.1.4 Arrival Trajectories

The arrival trajectories used in the TRACON by CTAS consist of the standard traffic pattern segments used at most airports. In the work described in (Robinson III & Isaacson, 2000) the speed and altitude profiles used were typical terminal area profiles. Descents were flown at a fixed flight path angle. In addition, published altitude restrictions and standard altitude clearances were met.

Recent work with CTAS also considered adapting the trajectories towards trajectories as they were preferred by flight crews (Prevot et al., 2000; Callantine, Prevot, Smith, & Palmer, 2001). In that work, traffic started on more or less free flight routes towards the meter fix. Flight crews could request their most efficient flight path by using the FMS. Controllers then used CTAS to generate conflict-free schedules for the meter fixes and assigned modified cruise and descent speeds or routing instructions when necessary. Within the TRACON, controllers could allow aircraft to follow an FMS transition path stored in the FMS database, which is essentially a STAR and which includes altitude limits or other specifics. Controllers had the possibility though of applying route modifications to the FMS transition via data link or voice connection. The last part of the approach consisted of the standard ILS path. This concept was received well, but in some runs the controllers abandoned the usage of FMS routes. Especially more complex scenarios with deviations from the planned trajectories or with altitude changes while also traffic was passing each other could cause the FMS schedule to fall apart. Controllers would then revert back to tactical vectoring. It was also concluded that a main problem with FMS arrivals is compression. This refers to the fact that the altitudes and speeds can vary significantly for different aircraft. This can cause separation problems and add four-dimensional complexity to the scheduling problem.

2.2 The PHARE Approach

2.2.1 Overview

The Programme for Harmonised Air Traffic Management Research in Eurocontrol (PHARE) was started in 1989 and investigated a future air traffic management concept based on air-ground integration (van Gool & Schröter, 1999; Post, 2000). In this concept 4-D trajectories are negotiated between ground and airborne systems using data link.

Three main series of experiments were carried out to demonstrate the potential of the concept. The first series of experiments was conducted in 1995 in Malvern, United Kingdom in the context of the first PHARE demonstration (PD/1), where en-route flight was considered. Experiments were subsequently carried out in 1996/1997 at the German Aerospace Center (DLR) site in Braunschweig, Germany in the context of the second PHARE demonstration (PD/2), where terminal area traffic was considered. In 1998 experiments were done in the framework of the third demonstration (PD/3) at a number of sites including the Eurocontrol Experimental Centre (EEC) in Brétigny-sur-Orge, France and the National Aerospace Laboratory (NLR) in Amsterdam, The Netherlands. In these experiments both
en-route and terminal traffic were considered; in PD/3 terminal traffic for Schiphol airport was considered (Figure 2.2).

The PHARE concept was shown to be feasible and to yield significant benefits in terms of more capacity, better conformance to user-preferred trajectories, less delays, less fuel costs, less pollution and less noise. However, no clear estimates were made of the size of these benefits. It also remains unclear to what degree the benefits mentioned are competitive, i.e., whether or not a trade-off has to be made between obtaining different benefits.

Figure 2.2  The terminal area of Schiphol airport was considered in PD/3. Because controllers commonly separate traffic for different runways by using more meter fixes than only Sugol, Artip, and River (Appendix A), in PD/3 a larger number of meter fixes was implemented. From these fixes STARs were followed, although they could be tuned by flight crews or controllers.
2.2 THE PHARE APPROACH

2.2.2 Long-Term Planning and Optimisation

Sequencing and Scheduling
Whereas CTAS starts with sequencing and scheduling at the metering fixes, PHARE starts with sequencing and scheduling at a point called the approach gate by checking arrival times proposed by flight crews for conflicts. The approach gate is located 10 nmi from the runway threshold.

In the PD/3 demonstration sequencing and scheduling was done in an iterative fashion throughout the flight over multiple sectors and could start as early as pre-departure. Aircraft could submit an optimised 4-D trajectory to the ground station using an experimental flight management system (EFMS). This trajectory could be based on any criteria the flight crew or airline considers important. In the terminal area, however, the fixed route structure was maintained (Section 2.2.4). Based on the submitted 4-D trajectories, an arrival time planner generated runway assignments, sequences, and arrival times that minimise the delays for all aircraft involved (Fairclough, 1999). This was done by scheduling at the approach gate with a branch and bound algorithm.

Air-Ground Coordination
The result of the scheduling process is a constraint that specifies the approach gate that has to be overflown and the time at which that should be done for each aircraft. The trajectories are constructed as follows. If the subject aircraft is equipped with a 4-D EFMS, the constraints are up linked to the aircraft, which triggers the EFMS to generate a new trajectory. The strategies applied by the EFMS to meet time constraints are speed control, path stretching, and holding. The new trajectory is then down linked to the ground. If the down linked trajectory constructed by the EFMS does not conflict with the existing flight paths, the trajectory calculated previously is replaced by the down linked trajectory and a clearance message is send to the aircraft. A 4-D tube is then also up linked by ATC, which defines the amount of space and time the aircraft is cleared for. If the subject aircraft is not equipped with a 4-D EFMS or ATC does not agree with the EFMS trajectory, ATC employs a trajectory predictor to specify a 4-D flight path for that aircraft.

2.2.3 Short-Term Planning and Optimisation
The arrival planner re-optimises the schedules when a new arrival is detected, when a preferred time of arrival of an existing flight is changed, or when a manual change to an arrival time or landing runway is made. Aircraft that are outside a configurable planning horizon around the airport are subject to automatic re-scheduling. As soon as an aircraft reaches the planning horizon, the 4-D constraints are issued and the communication process with the aircraft is started in order to agree on a trajectory that meets these constraints. In PD/2, three different planning horizons were used: the time at which the descent was started (corresponding to the top of descent), 20 minutes prior to reaching the meter fix, and 10 minutes
prior to reaching the meter fix. In PD/3, a planning horizon of 5 and 10 minutes prior to reaching the top of descent was used. Any further optimisation of the schedules is carried out manually by the controllers.

### 2.2.4 Arrival Trajectories

While in en-route airspace, trajectories could be generated without the need to follow a standard route network (Post, 2000). The sector structure, however, was kept in place. The fixed arrival route structure was also kept in place (Fairclough & McKeever, 2000). This meant that aircraft had to enter the terminal area through one of the meter fixes. From there a STAR was followed which included meeting any associated level and speed constraints (Wilson, 1999). After reaching the approach gate the aircraft intercepted the ILS beams and started the final approach along the conventional ILS path. It was concluded from the PHARE work though that for future systems the assumptions regarding the route system and the presence of fixed points in the arrival trajectory should be minimised, since these are applicable to the current system and not necessarily to future systems.

### 2.3 Conclusions

Scheduling and optimisation is in both the CTAS and PHARE approach achieved by generating schedules at fixed reference points. The objective function in PHARE consists of the delays of all aircraft; in CTAS it is a weighted combination of delays and fuel costs. In both approaches the scheduling process is mathematically single-objective. However, a truly multi-objective scheduling process may result in more desirable trade-offs, as discussed in Chapter 3.

Both CTAS and PHARE make use of STARs. In recent work with CTAS these STARs were flown with the use of the FMS in the TRACON. The FMS contained standard lateral and vertical profiles, which included altitude or other type of specific limits for each trajectory. Controllers used FAST to issue speeds or to tactically modify the STARs.

In PHARE, STARs were used inside the terminal area. It was recommended though in PHARE that for future systems the assumptions regarding the fixed route system and the presence of fixed points in the arrival trajectory should be minimised. They are considered applicable to the current system but not necessarily to future systems.

The design of an algorithm for scheduling flexible arrival trajectories as opposed to STARs is discussed in the next chapter. This algorithm is used in Chapter 7 in order to demonstrate the benefits that flexible trajectories can offer.
This chapter discusses the design of an algorithm to generate flexible arrival trajectories. The approach taken is that an objective function is defined for a set of arrival trajectories. In addition, constraints are defined. The algorithm optimises the objective function by changing the shape of the trajectories while meeting the constraints. Section 3.1 describes the problem that is to be solved by the algorithm. Section 3.2 describes why and how a genetic algorithm is used. The implementation of the genetic algorithm is described in Section 3.3.

3.1 Problem Statement

3.1.1 Airspace Considered

The airspace considered is the terminal area of Amsterdam Airport Schiphol. Traffic starts the approach for Schiphol normally from one of the meter fixes Artip, Sugol, or River, through which the terminal area is entered, see Appendix A. Only the runways 18C and 27 are considered, because historical data that was used (Section 7.1.1) related to these two runways only.

To accommodate departure traffic, SIDs have been defined, as also shown in Appendix A. When departure and arrival flows need to cross, this is done at more or less standard points. These points are here referred to as crossing points.

3.1.2 Objectives

The objectives discussed below are considered.
Throughput

The runway throughput $T$ is one of the most important objectives in any traffic planning system. The realised runway throughput $T$ in arrivals per hour can be calculated with:

$$ T = N \left( \frac{3600}{\Delta T} \right), $$  \hspace{1cm} (3.1)

where $\Delta T$ (in seconds) is the time interval between the first and last flight that landed and $N$ the number of flights.

Continuous Descents

Optimising the degree to which continuous descents or three-degree decelerated approaches at idle power are applied can help to reduce noise production, see Chapter 1. For this reason, the deviation from altitude and speed profiles belonging to such an approach is considered.

The deviation from a three-degree decelerated approach is taken into account by considering the maximum deviation $\Delta h$ from a three-degree descent path and the maximum deviation $\Delta V$ from a speed profile (in CAS) in such a procedure. A speed profile with a constant deceleration of 0.2 m/s$^2$ was considered for all traffic. Although the speed profile will be different for different aircraft in a three-degree idle descent, this deceleration is in the order of decelerations typically seen in this procedure for large aircraft, see, e.g., (in ‘t Veld, 2003). Since the goal was to obtain a first assessment of how well this type of procedure can be applied when simultaneously other objectives are optimised, this was considered a reasonable starting point.

Noise Load on Community

The issue of noise production and emissions was incorporated in the objectives discussed above through incorporating continuous decelerated descents. It was, however, desired to determine to what degree aircraft were routed over residential areas, since this is also an important part of the disturbance put on the environment. An additional measure describing noise ‘load’ on community was therefore used. It is denoted as $L$:

$$ L = \begin{cases} 0 & \text{if } (x, y) \notin A \\ \Delta t/h^2 & \text{if } (x, y) \in A, \end{cases} $$  \hspace{1cm} (3.2)

with the area $A$ an approximation of the residential areas around the airport, see Figure 3.1(a), $(x, y)$ the aircraft position in the horizontal plane, and $\Delta t$ and $h$ the time and altitude flown over $A$ respectively. It is unrealistic to not include altitude in this measure, because traffic passing at very high altitudes will cause negligible disturbance. The quadratic term for altitude was used since sound intensity decreases quadratically with increasing distance between source and observer (Ruijgrok, 1993). The time interval $\Delta t$ was added to incorporate the effect that more time spent over an area also yields more impact on the community.
3.1 PROBLEM STATEMENT

3.1.3 Objective Function

Multi-Objective Optimisation

In multi-objective optimisation objectives may exist that are conflicting. Multi-objective optimisation is usually defined as looking for solutions that cannot be improved in any of the objectives without degrading the performance in at least one other objective. These solutions are called non-dominated and the collection of these solutions is referred to as the Pareto front. The solutions in the Pareto front score mathematically equally well. Only a decision maker with more knowledge than the optimisation algorithm can determine which solution is most desirable.

It is possible to incorporate the score on only one objective in the objective function. This, however, does not allow looking for solutions that score well on multiple objectives. It is also possible to combine the contributions from different objectives into one objective function value by using weight factors (Bagchi, 1999). Using the approach of weight factors may, however, result in solutions that score well on one objective but that have very low scores on other objectives. With this type of optimisation, decision making in terms of

Figure 3.1  Approximation of residential areas (left) and the terminal area (right).
determining the relative importance of objectives is done before searching (Zitzler, 1999). Because the weight factors have to be chosen a priori, it is not possible to obtain the set of solutions belonging to the Pareto front.

**Satisficing Decision Making**

It is doubtful that knowledge about the entire Pareto front is needed by the operator: the Pareto front contains the solutions that score mathematically equally well but that may not be equally desirable in practice. In fact, in most decision making processes human operators are merely interested in solutions that meet the demands and that do not violate performance constraints, which may depend on the situation. This also applies to ATC, where controllers look for acceptable solutions. Finding the most ‘optimal’ solution, if it exists, is of secondary importance.

The term ‘satisficing’ was introduced by Herbert Simon in the 1960s to describe this strategy. Satisficing refers to decision methods that look for good or satisfactory solutions instead of optimal solutions (Simon, 1996). The theory of satisficing decision making (SDM) was later extended and applied to problems in decision-making (Charny & Sheridan, 1986; Goodrich, Stirling, & Boer, 2000). An aspiration level, usually denoted as $\rho$, may be defined (Goodrich et al., 2000). This level prescribes a minimum performance that is to be met. The search process is continued until this aspiration level is met, if possible. When using multiple objectives, a solution is only considered acceptable if all aspirations are met.

**Definition of Objective Function**

The approach followed here is to look for solutions that meet all chosen aspiration levels as close as possible. This should result in obtaining the part of the Pareto front that is interesting for the operator. This is achieved by first normalising the score on each of the objectives throughput $T$, altitude deviation $\Delta_h$, speed deviation $\Delta_V$, and noise load on community $L$ with respect to their aspiration levels $\rho_T$, $\rho_h$, $\rho_V$, and $\rho_L$, respectively. The objective function value $F$ which is to be minimised is then taken as the maximum value of these normalised scores. The result of this is that the algorithm will try to improve the score on the objective which is least met according to the specified aspiration level. In this way it tries to find solutions that meet all aspiration levels (Figure 3.2). Mathematically $F$ is defined as:

$$F = \max \left( \frac{\rho_T}{T}, \frac{\Delta_h}{\rho_h}, \frac{\Delta_V}{\rho_V}, \frac{L}{\rho_L} \right). \quad (3.3)$$

In (Vormer et al., 2003) the results of using an objective function similar to Equation (3.3) were compared with results of using an objective function based on weight factors. This is the basis of most classical optimisation methods, as used for instance in CTAS and PHARE. It consists of finding the optimal solution by generating a range of options, calculating the performance scores (by using weight factors), and selecting the option with the highest score (Klein, 1997). It was shown that for this approach solutions exist that
have a lower quality with respect to the objective function but that have better scores on individual performance factors. These solutions may in fact be more desirable than the optimal solution.

For the problem considered here, this means that the optimal solution found using weight factors may result in, for example, throughput being lower than considered acceptable, or in environmental impact being higher than considered acceptable. Using the satisficing approach that selects solutions that meet required performance values, on the other hand, leads to acceptable solutions. In addition, it offers the controller the possibility to continue looking for better solutions only if it is possible to allocate the additional efforts involved\(^1\).

### 3.1.4 Constraints

The constraints considered are aircraft performance constraints, separation constraints, and trajectory acceptability constraints imposed by pilots and air traffic controllers.

**Aircraft Performance Constraints**

The aircraft performance constraints considered are that the calibrated airspeed should be above the minimum approach speed \(V_{\text{app}}\) and below the reference descent speed \(V_{\text{des}}\) for each aircraft. Additionally, it is required that the energy rates prescribed can be attained

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\(^1\)The potential of integrating data from different sources has been studied in the context of a program called collaborative decision making (CDM), see (Ball, Hoffman, Knorr, Wetherly, & Wambsganss, 2000). The approach taken in this chapter of starting with constraints offers the possibility to let required performance values be established by the parties who are in the best position to formulate these constraints, supporting the implementation of CDM.
by the aircraft. This is done by considering the total energy $E$, which is composed of the potential and the kinetic energy (Ruijgrok, 1994), with $m$ aircraft mass, $g$ gravitational acceleration, $h$ altitude, $W$ aircraft weight, and $V_g$ ground speed:

$$E = mgh + \frac{1}{2}mV_g^2,$$

and the total energy rate $\dot{E}_{cmd}$ commanded implicitly by the reference trajectory, which is given by:

$$\dot{E}_{cmd} = V_g W (\sin \gamma + \dot{V}_g/g).$$

Considering the equation of motion in the direction of flight, the energy rate can also be written (with $T$ thrust and $D$ drag) as:

$$\dot{E} = V_g (T - D).$$

The minimum energy rate that can be attained by the aircraft is approximated by using the thrust during descent $T_d$ and the maximum drag when speed brakes are deployed (denoted as $D_{max}$):

$$\dot{E}_{\text{min,sbr}} = V_g (T_d - D_{max}).$$

In order to be able to compare the energy rate commanded in the trajectory with the capabilities of the subject aircraft, the ratio between the two rates is considered. This ratio is called the energy rate demand $\dot{E}_{sbr}$:

$$\dot{E}_{sbr} = \frac{\dot{E}_{cmd}}{\dot{E}_{\text{min,sbr}}}.$$

The energy rate demand is required to be below 1. The energy rate demand may also be calculated without the use of speed brakes\textsuperscript{2}, in which case it is denoted as $\dot{E}$.

**Separation Constraints**

A minimum vertical separation of 1,000 ft is here required, because this is the vertical separation minimum currently used in radar-controlled environments in Europe \textsuperscript{3}. A minimum horizontal separation of 3 nmi is also required because it is the minimum radar separation distance used in the terminal area at Schiphol for arriving and departing traffic. In the control zone, which is the area of 10 nmi radius around the tower up to 3,000 ft, the minimum separation is reduced to 2 nmi horizontally and 400 ft vertically. It is assumed that the two runways are operated independently. It is therefore considered appropriate to only apply this separation to two aircraft arriving on the same runway. This is only the case though

\textsuperscript{2}This is needed in Chapter 6.

\textsuperscript{3}This separation was in the past only applied up to FL 290 (29,000 ft), but it became the standard separation up to FL 410 (41,000 ft) on 24 January 2002 when Eurocontrol activated the Reduced Vertical Separation Minimum (RVSM) programme.
if STARs are used in their conventional form. On the other hand, not using STARs or reducing the final intercept distance may make this assumption obsolete. In that case, it was considered necessary to apply the separation also to traffic arriving on different runways.

On final approach the final approach wake vortex separation minima need to be respected. Wake vortex separation is needed to make sure that the tip vortex formed by the wing tip of a preceding aircraft is sufficiently decayed before another aircraft is cleared for approach or departure. The separation distance is dependent on the weight classes of the aircraft involved (Table 3.1). Three weight classes have been defined by ICAO: heavy, for aircraft with maximum take-off weight of or above 136,000 kg, medium, for aircraft with a maximum take-off weight between 7,000 and 136,000 kg, and light, for aircraft with maximum take-off weight of or below 7,000 kg.

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<thead>
<tr>
<th>Table 3.1</th>
<th>The ICAO wake vortex spacing minima in nautical miles (CAA, 1999).</th>
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<tr>
<td></td>
<td>Trailing Aircraft</td>
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<tr>
<td></td>
<td>Leading Aircraft</td>
</tr>
<tr>
<td>Heavy</td>
<td>4</td>
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<tr>
<td>Medium</td>
<td>3</td>
</tr>
<tr>
<td>Light</td>
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**Constraints Imposed by Air Traffic Control**

The airspace structure in terms of the fixed positions of the meter fixes through which arrivals enter the terminal area is not changed. Traffic was therefore required to enter the terminal area at a meter fix.

In general, turns longer than 180 degrees would direct aircraft away from the airport and were not allowed. In accordance with current practice, a maximum altitude of 10,000 ft, a maximum calibrated airspeed of 250 kts, and a minimum altitude for leveling off of 2,000 ft were prescribed. The minimum final intercept distance, the distance between the runway threshold and the point where the aircraft intercepts the ILS glide slope, was set at 3.0 nmi, as recommended for curved approaches (Erkelens, 1997)\(^4\).

In order to prevent routes extending to outside the terminal area, it was also required that solutions are contained inside the terminal area. It was for this purpose approximated as a circle with a diameter of 70 nmi around the tower. A circle of this size includes all three meter fixes, see Figure 3.1(b).

Increasing the number of crossing points between arrival and departure traffic may

\(^4\)At Schiphol airport the outer marker is for runways 18C and 27 located at 4.0 and 3.9 nmi from the threshold, respectively, which may explain why intercepting much closer to the threshold is not recommended.
well affect airspace complexity. This suggests that an upper limit is needed to keep solutions feasible and realistic with respect to air traffic control. Exactly how many additional crossing points are allowed or desired is not clear though. This is discussed further below (Section 3.2.5) using results from applying the optimisation algorithm.

**Constraints Imposed by Aircraft Operators**

The bank angle is limited to 30 degrees, because this limit is usually also applied in current practice for passenger comfort. The minimum bank angle used is 5 degrees, which prevents annoyingly slow turns.

The flight path angle is limited at -6 degrees since this is already considered a steep descent. In addition, most airlines require a minimum stabilization altitude of about 500 ft, which means that at this altitude the aircraft should be stabilized and at a steady approach speed. This is incorporated by requiring a minimum stabilization distance from the runway threshold of 2 nmi and a flight path angle of -3 degrees during the final approach.

![Figure 3.3 The standard working scheme of a genetic algorithm.](image)

### 3.2 Solution Methodology

#### 3.2.1 Genetic Algorithms

**Foundations**

The recent advent of the use of evolutionary optimisation techniques has provided ways of obtaining the Pareto front for multi-objective problems by processing multiple trade-offs in
3.2 SOLUTION METHODOLOGY

Figure 3.4 Illustration of the optimisation process using a genetic algorithm. The dots (connected to the ground plane with an altitude line) indicate how the 30 random initial solutions climb onto the highest peak of the landscape over successive generations, where (a) shows the first generation of solutions and (b) the tenth generation. This example optimises the objective function $z = 10 + 3 \cdot (1 - x)^2 + e^{-x^2 - (y+1)^2} - 10 \cdot (x/5 - x^3 - y^5) \cdot e^{-x^2 - y^2} - 1/3 \cdot e^{-(x+1)^2 - y^2}$ (Haataja, 1999).

one optimisation run (Bagchi, 1999). The most widely used of these algorithms are genetic algorithms. They are suitable for handling large and complex search spaces (Zitzler, 1999). Because a number of solutions can be processed simultaneously, a priori decision making about the relative importance of objectives can be prevented and the Pareto front can be approximated\(^5\). They have therefore been considered to be more suitable for multi-objective optimisation than classical optimisation methods.

A disadvantage of using genetic algorithms is that it cannot be guaranteed that a better solution does not exist. In this work, however, we are only interested in finding acceptable solutions. Another disadvantage is that because of its random nature, different solutions may result every time the same problem is solved. This is an important issue to be taken into account when it is considered how a scheduling system based on a genetic algorithm should be implemented in practice. It may be necessary to let such a system consider only those solutions that result in substantial improvements over the actual schedule. Schedules that are radically different but yield only limited improvements may need to be discarded.

A genetic algorithm (GA) qualifies as a stochastic search method modeled on the process of natural Darwinian evolution (Gen & Cheng, 1997). Possible solutions are encoded into strings of data, referred to as chromosomes. A solution described by a chromosome is called an individual. Each individual is assigned a fitness value $f$ that determines

\(^5\)Using weight factors for this particular problem was studied in (Vormer, Mulder, van Paassen, & Mulder, 2002).
its chance of survival.

The genetic algorithm starts by generating a set of individuals called an initial population (Figure 3.3). They can be either randomly selected individuals or individuals that are expected to be of high-quality based on knowledge about the system. During the process of genetic optimisation, a new population is created over and over again. These new populations are created by applying genetic operators on the existing individuals in the population. Well-known genetic operators are selection and crossover, which preserve knowledge about good solutions, and mutation, which explores new areas of the solution space. An example of a genetic algorithm applied to an optimisation problem is shown in Figure 3.4.

**Selection, Crossover, and Mutation**

The selection operator reproduces more copies of individuals with high fitness values by assigning individuals with a higher fitness value a proportionally higher probability of selection. The crossover operator creates two new individuals from two original individuals that were selected from the current population by the selection operator. The original chromosomes are cut at either one or two points and the separate pieces of genetic information are swapped and connected again, forming two new individuals (Figure 3.5).

When using only the crossover operator to preserve knowledge in the population on good properties of the solutions, only different combinations of those properties are
explored. The diversity of the population will then generally decrease. For this reason a mutation operator is also applied. This operator changes randomly one or more values in the chromosome (Figure 3.6) with a certain mutation probability. In this way, new genetic information is added to the population. This promotes new search directions and which helps to avoid premature convergence.

**Fitness Scaling**

Using only standard probabilistic selection where the fitness of a chromosome is proportional to probability of selection can have some disadvantages (Gen & Cheng, 1997). Early in the genetic evolution process a small number of solutions can quickly become to dominate the selection process and limit the directions of search. At the same time, later on in the process the solutions in the population can become so similar that competition is not really possible any more and the solution search process will only consist of making random changes. A technique called fitness scaling has been developed to counteract these problems. This technique translates the fitness \( f \) (following from the objective function value) into the scaled fitness \( f' \), which is used instead to determine the individual’s survival change. A widely applied method of fitness scaling called *sigma truncation* was proposed in the following form by Goldberg (1989):

\[
f' = f - (\bar{f} - c \cdot \sigma), \quad (3.9)
\]

with \( c \) a problem-dependent small integer, \( \sigma \) the standard deviation of the fitness in the population, and \( \bar{f} \) the average fitness. Negative values for \( f' \) are set to zero. This type of scaling mechanism is often used to prevent negative fitness values and to promote higher diversity further in the evolution process.

**Repairing Strategies**

Although the values of the chromosomes may be chosen within certain limits to satisfy constraints, for most problems it cannot be prevented that the solution proposed by the genetic algorithm violates one or more constraints. When these solutions are simply destroyed, the genetic solution search process will not be very efficient. For this reason, domain-specific strategies are often used that apply deterministic rules to proposal solutions to overcome the constraint violation. These strategies are called repairing strategies (Gen & Cheng, 1997).

### 3.2.2 Previous Applications in ATM

Several earlier studies addressed the use of genetic algorithms for route planning in air traffic management. For example, genetic algorithms were applied in an attempt to reduce airspace congestion (Oussedik, Delahaye, & Schoenauer, 1998), where the congestion was described in terms of air traffic controller workload. In that work, the coded chromosomes contained the assigned delay time to the departure slot and the assigned route number for each aircraft, where for each aircraft there were a number of pre-defined routes to choose.
The traffic situation considered was based on recorded data from all traffic crossing the French airspace on one day (a total of over 6,000 flights over 89 sectors). The initial result was a decrease in congestion by a factor of 2.

The use of genetic algorithms was also studied for on-line real-time flight path optimisation (Hu, Wu, & Jiang, 2001). It was argued that this path optimisation problem was nearly impossible to be solved by more conventional algorithms within tolerable time and the use of genetic algorithms was suggested. Two different models were studied. In the first, the focus was on following fixed ground stations and the chromosome format consisted of a list of ground station numbers, which were subsequently connected during flight. The chromosome was fixed-length (containing all stations). As soon as the destination station was reached, the remaining string did not have a meaning anymore. The algorithm was able to find solutions quickly and this type of fixed-route optimisation was concluded to be suitable for real-time application. Similar studies obtained also positive results (Gerdes, 1997).

The second approach abandoned the concept of fixed ground stations and, instead, operated with a chromosome of variable length that summed all planned path coordinates. Trajectories could be optimised, but the length of the chromosomes and the computational time increased quickly. Further assumptions and heuristic rules were recommended for application to real-time problem solving.

In similar work, the trajectories were also coded as collections of points (Akker, Kemeneade, & Kok, 1998). In that work, mutations could change the flight level and the heading at some point in the trajectory. Favourable results were obtained, but it was emphasized that incorporating domain-specific knowledge was important for obtaining feasible solutions.

A different kind of coding studied included the flight path angle \( \gamma \) directly in the chromosome format (Yokoyama & Suzuki, 2003). The genetic algorithm developed in this way was used to find shortest-time flight trajectories and worked well. A similar approach defined the trajectory as a collection of parameterised manoeuvres, where a manoeuvre was described by either a straight line, a curve, an acceleration, or an altitude change (Hesselink & Basjes, 1998). The initial solution consisted of straight trajectories from an airspace entry to an exit point. A customized mutation operator was applied at positions in the solution where conflicts were found that generated manoeuvres that could avoid the conflict.

### 3.2.3 Trajectory Definition

In this work flight paths are represented as sets of straight and curved trajectory segments. The main reason for this is that humans generally also process trajectories in terms of segments (Delahaye, Puechmorel, Hansman, & Histon, 2003). This approach was also taken in other applications (McConnell, Jr., 1976; Chen & Pritchett, 2001; Hesselink & Basjes, 1998). Other reasons for using segments include the facts that segments are a common way of describing trajectories both in ATC and in the flight management system and that an efficient communication or negotiation process between controllers and pilots can be supported (Barrer, 1999).
Segments
The parameters to describe a segment \( j \) for a flight \( i \) are chosen as:

\[
\begin{align*}
\text{Segment type } T_{i,j}, \\
\text{Radius } R_{i,j}, \\
\text{Length } L_{i,j}, \\
\text{Absolute flight path angle } |\gamma_{i,j}|, \\
\text{Absolute acceleration } |a_{i,j}|. 
\end{align*}
\]  

A straight segment is denoted as a segment of type 1, whereas types 2 and 3 are used to describe segments with left and right turns respectively. The acceleration \( a \) is defined as the time derivative of \( V_C \), because un accelerated flight refers in practice to constant \( V_C \).

The reason for also specifying a value of \( R \) for straight segments is to prevent the generation of chromosomes that do not represent a solution to the problem (regardless of whether or not constraints are satisfied). These chromosomes are normally called illegal chromosomes. Because \( R \) is always defined, mutating one value of the segment to a new value always results in a legal solution.

The reason for using the absolute signs was related to the possibility of including departure traffic and optimising departure and arrival flights simultaneously. This coding is advantageous when a genetic algorithm is applied because an arrival trajectory can be changed to a departure trajectory without the need to change the segment’s parameters. If the absolute signs are not used, additional repairing strategies will be necessary which may deteriorate the algorithm’s efficiency. The smallest part of the chromosome, referred to in GA terminology as a codon, contains the segment data as shown in Figure 3.7.

Trajectories
A trajectory is described by connecting \( M \) segments. There is, however, a potential problem for \( M \). If no fixed value of \( M \) is prescribed, chromosomes may be formed that contain different numbers of codons (i.e., segments). In this case crossover may generate illegal solutions because the number of trajectories described in the offspring may not be equal to the number of flights, or segments may be formed that do not contain all five parameters \((T, R, L, \gamma, \text{ and } a)\). For this reason, every trajectory is composed of a fixed number of segments. The number of segments in the standard approach routes used at the airport considered is typically about 9 (Appendix A). The number of segments \( M \) is therefore set to 9.

Each set of segments for a flight \( i \) is extended with the following parameters:

\[
\begin{align*}
\text{Flight identification code } ID_i, \\
\text{Runway assignment } RA_i, \\
\text{Arrival time deviation } d_i. 
\end{align*}
\]
The genetic algorithm can change the scheduled time of arrival \( STA_i \) by changing the deviation \( d_i \) with respect to a nominal time of arrival \( NTA_i \):

\[
STA_i = NTA_i + d_i.
\]  

(3.12)

The form of a gene giving a trajectory description for one flight is indicated in Figure 3.8. The different genes are combined into a chromosome as shown in Figure 3.9, with \( N \) the number of flights.

An example of a standard arrival trajectory from a meter fix coded in segments is given in Figure 3.10. The final approach is always coded in two segments: segment 1 and
2. Segment 1 contains the un accelerated part and segment 2 the part where the speed is reduced to approach speed. Coding standard arrival trajectories in segments is elaborated on in Chapter 7.

**The Lamarckian Property**

An important aspect of chromosome design is the *Lamarckian property*. It considers the question whether or not a chromosome can pass on its desirable properties or its ‘goodness’ to future chromosomes when applying genetic modifications. Such a property is generally desired since knowledge about good solutions is to be preserved. When a chromosome does not have the Lamarckian property, it means that what a specific part of the chromosome refers to in the solution space depends on other values in the chromosome. The coding format used here is partly Lamarckian, because a part of the chromosome has this property (e.g., the runway assignments and times) whereas another part does not (e.g., the segment lengths). The fact that part of the chromosome does not have the Lamarckian property is a general disadvantage of the approach of using segments.

**Genetic Operators**

A standard single-point crossover operator can be used. A customized mutation operator, however, has to be applied. This is because the flight identification code in one gene cannot be changed without changing the flight identification codes of the other genes. This is necessary to maintain legality. If they would not be changed, one flight might be linked to more than one trajectory. This was solved by allowing the mutation operator to change every parameter except *ID*.

### 3.2.4 Inputs and Outputs

The inputs to the optimisation problem that the genetic algorithm is looking for are the 4-D trajectories for all flights. The trajectories are described with the parameters contained
in the chromosome as shown in Figure 3.9. These parameters are the flight identification codes $ID_{1..N}$, runway assignments $RA_{1..N}$, arrival time deviations $d_{1..N}$, segment types $T_{1..N,1..M}$, radii $R_{1..N,1..M}$, lengths $L_{1..N,1..M}$, flight path angles $\gamma_{1..N,1..M}$, and accelerations $a_{1..N,1..M}$.

The outputs determine the quality of the solution. They consist of the scores on the objectives: the throughput $T$, maximum deviation $\Delta h$ from a three-degree descent path, maximum speed deviation $\Delta V$ from a continuously decreasing speed profile, and noise load on community $L$.

### 3.2.5 Meeting the Objectives and Constraints

When the genetic algorithm has generated a set of chromosomes, trajectory profiles can be generated for all aircraft. This is necessary to calculate the scores on the objectives and to determine if constraints are met. For each trajectory a 4-D profile is therefore generated by calculating aircraft states along the trajectory. The following aircraft states are calculated: horizontal position $x$ and $y$ (with the origin of the axis system at the location of the tower), altitude $h$, track angle $\chi$, flight path angle $\gamma$, bank angle $\Phi$, calibrated airspeed $V_C$ and ground speed $V_g$. The time step was tuned to 2 seconds so that for every segment a number of aircraft states were generated, even if very small segments were required (see Section 6.2).

The constraints are expressed mathematically in Tables 3.2 and 3.3, where both $i = 1..N$ and $n = 1..N$ refer to the arriving flights. In the tables, $\Delta T_{sep}$ is the required time separation between two aircraft with weight classes $WC_i$ and $WC_n$ (Brinton, 1992), $td$ refers to the prescribed touch down point (300 m from the threshold), $final$ to the actual touch down point, $entry$ to the entry point into the terminal area, and $mf$ to the meter fix that is used. The constraints related to the touch down point are met by starting the generation of the profiles from $x_{final} = x_{td}$, $y_{final} = y_{td}$, $h_{final} = 0$, $\chi_{final} = \chi_{td}$, $V_{C,final} = V_{app}$. The wake vortex minima are met by choosing the scheduled time of arrival at the touch down point for each aircraft with enough time separation from that of the preceding aircraft. It is assumed that this results in wake vortex separation throughout the entire approach.

The constraints that apply to parameters contained in the chromosome are applied directly by limiting these parameters to the range allowed. The constraints that apply to parameters not contained in the chromosome, however, require repairing strategies. These are summarized also in the tables where applicable. The values involved in the repairing strategies are very problem-dependent and have been found to function well for this application. For calculation of aircraft performance parameters the data from the Eurocontrol Base of Aircraft Data (BADA) is used (Eurocontrol, 2000). This database contains operation performance parameters, airline procedure parameters and performance summary tables for a large number of aircraft types.

If higher bank angles than 30 degrees occur, the radius is selected for 29 degrees of bank. If lower bank angles than 5 degrees occur, the radius of turn is set for a turn at 10
### Table 3.2  Constraints and repairing strategies (1).

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Repairing strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T \in [1, 2, 3], \ a \leq 0 )</td>
<td>Set ( a ) so that maximum speed is not exceeded</td>
</tr>
<tr>
<td>( V_C \leq \min(V_{des}, 250 \text{ kts}) )</td>
<td>If ( a &lt; 0 ), increase ( a ) with 0.02 m/s(^2)</td>
</tr>
<tr>
<td>( \dot{E}_{sbr} \leq 1 )</td>
<td>If ( a = 0 ), increase ( \gamma ) with 0.25 deg</td>
</tr>
<tr>
<td>(</td>
<td>\sqrt{(x_i - x_n)^2 + (y_i - y_n)^2} - h_i - h_n</td>
</tr>
<tr>
<td>Conventional STARs:</td>
<td></td>
</tr>
<tr>
<td>(</td>
<td>\sqrt{(x_i - x_n)^2 + (y_i - y_n)^2} - h_i - h_n</td>
</tr>
<tr>
<td>No conventional STARs:</td>
<td></td>
</tr>
<tr>
<td>(</td>
<td>\sqrt{(x_i - x_n)^2 + (y_i - y_n)^2} - h_i - h_n</td>
</tr>
<tr>
<td>( STA_i \geq STA_n + \Delta T_{sep}(WC_i, WC_n) \lor )</td>
<td></td>
</tr>
<tr>
<td>( STA_i \leq STA_n - \Delta T_{sep}(WC_i, WC_n) \forall i \neq n )</td>
<td></td>
</tr>
<tr>
<td>5 \text{ deg} \leq \Phi \leq 30 \text{ deg} \lor )</td>
<td>Set ( R ) so that bank angle limits are not exceeded</td>
</tr>
<tr>
<td>(-6 \text{ deg} \leq \gamma \leq 0 \text{ deg} )</td>
<td></td>
</tr>
<tr>
<td>first segment from runway: ( T = 1, L \geq 2 \text{ nmi}, )</td>
<td></td>
</tr>
<tr>
<td>( \gamma = -3 \text{ deg, } a = 0 )</td>
<td></td>
</tr>
<tr>
<td>( x_{final} = x_{td}, y_{final} = y_{td}, h_{final} = 0, \chi_{final} = \chi_{td}, V_{C,final} = V_{app} )</td>
<td></td>
</tr>
</tbody>
</table>
Table 3.3  Constraints and repairing strategies (2).

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Repairing strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\sqrt{(x_{\text{entry}} - x_{mf})^2 + (y_{\text{entry}} - y_{mf})^2}</td>
</tr>
<tr>
<td>$h \leq 10,000 \text{ ft}$</td>
<td>$\gamma = 0$</td>
</tr>
<tr>
<td>$\gamma \leq -3 \text{ deg if } h &lt; 2,000 \text{ ft}$</td>
<td>$\gamma = -3 \text{ deg}$</td>
</tr>
<tr>
<td>second segment from runway: $L \geq 1 \text{ nmi}$</td>
<td></td>
</tr>
<tr>
<td>$L \cos \gamma / R \leq 180 \text{ deg}$</td>
<td>Set segment type to straight ($T = 1$)</td>
</tr>
<tr>
<td>$</td>
<td>\sqrt{x^2 + y^2}</td>
</tr>
<tr>
<td>$N_C \leq 11$</td>
<td>Use same route for more aircraft</td>
</tr>
</tbody>
</table>

degrees of bank. The values for the new bank angles were tuned to work satisfactory with the genetic algorithm. The new bank angles were selected not too close to the old values, because in one cycle of the optimisation algorithm more parameters of the trajectories could change. When the new bank angles were selected closer to the original bank angles this resulted often in violations of bank angle limits in the next cycle.

The constraint on meeting the prescribed meter fix position is met by connecting the trajectory defined by the first five segments from the runway to the meter fix. This is done by adding to these five segments one curved segment and three straight segments that result in reaching the meter fix. Three straight segments were used instead of one to prevent that one segment would be much larger than the other segments in the trajectory.

The number of crossing points allowed between arriving and departing traffic has so far not been specified. In simulations carried out in this work that modeled current operational practice, the number of crossing points was generally found to be about 4. On the other hand, most of the initial solutions generated with the genetic algorithm for a system where the STAR structure was not in place had a minimum of 11 crossing points. Since this is already a large number compared to the 4 crossing points for current practice, it was used as an upper limit. In case that candidate solutions were found with a higher number of crossings than allowed, the arrival trajectory that caused the violation was removed and replaced by a trajectory that was already scheduled for another aircraft. In this way two aircraft used the same trajectory and the number of crossing points was reduced.

When solutions are found, the fitness $f$ can be calculated. It is defined as $f = 1/F$, with $F$ from Equation (3.3). The inverse of $F$ is used because the genetic algorithm maximises fitness, whereas $F$ needs to be minimised.
3.3 Implementation

3.3.1 Genetic Algorithm Parameters

The genetic algorithm was implemented using the GAlib genetic algorithm package, which was developed at the Massachusetts Institute of Technology (Wall, 1996). The initial solution was obtained by filling in random values for the inputs within the range allowed. The genetic algorithm that was applied used a standard single-point crossover operator. For mutations a modified mutation operator was used that could modify all parameters except the flight assignments ($ID$). The crossover probability was set to 0.7 and the mutation probability to 0.1. These are within the range of typically used values (Bagchi, 1999) and allowed initial solutions to be improved for this problem.

It may be beneficial to replace only a part of the population each generation, because a good balance between population diversity and the tendency of high-fitness individuals to survive may allow desired solutions to be found earlier (Bagchi, 1999). In this work, in each generation 50% of the population was replaced. This was also the default value applied in the mentioned genetic algorithm package.

The number of solutions processed simultaneously was set to 5. This was based on the idea that if an air traffic controller would use a tool based on this method, 5 was considered a reasonable number of solutions that could also be processed simultaneously by an operator. Fitness scaling based on a technique called sigma truncation (Goldberg, 1989), see Section 3.2, was also applied as this was found to yield faster improvement of the solutions. In case that constraints were not met, a maximum of 40 attempts were made to satisfy the constraints by using repairing strategies before discarding the solution.

3.3.2 Software Design

This section shows the main parts of the design of the software needed to implement the scheduling algorithm.

Static Modeling

The system that is modeled in the software is divided in two subsystems:

- a planning computer, and
- a set of research equipment.

The top-level class diagram is shown in Figure 3.11. In this figure the design of the class structure and the associations between different classes are shown to give an overview of the software architecture used.

The main part of the system is constituted by the subsystem of the Planning Computer. Within this subsystem, a candidate for a traffic planning solution is represented by an instant of the class Planning, which is known as an object. In general, the number 1 next
Figure 3.11  Top-level class diagram.
3.3 IMPLEMENTATION

**Figure 3.12** Sequence diagram.
to a class refers to only one object, whereas the indication 1..* refers to multiple objects of that class. A Planning object consists of a number of Flight objects, representing all the flights contained in the proposed planning. The 4-D profile data is stored in the Flight objects. These Flight objects also each contain one Aircraft object and a number of Segment objects.

Each Aircraft objects receives data from one Aircraft Data object, which contains the data that cannot be changed in the planning process: performance data, operator preferences data, and operationally recorded data. The performance data is contained in the Bada Flight Model objects. These objects contain the data for the particular aircraft involved from the BADA database.

The environmental properties are contained in an Environment object, which consists of Runway, Geometry, and Wind objects. The Genetics object contains the genetic functions and performs genetic operations on the set of Planning objects.

The Research Equipment subsystem provided the analyst with functions to control the analyses (e.g., starting, stopping, and specifying a scenario that was to be analysed).

### Dynamic Modeling

The main data flows in the software are illustrated through a sequence diagram in Figure 3.12. It shows the chronological structure of solution searching and evaluating: the sequence diagram shows the actions through time between objects (not between classes). This is indicated with an underline in the object name box. Time flows from the top to the bottom.

The sequence diagram shows how the Genetics object updates all Planning objects with the appropriate chromosome in its current state in the genetic modification process, after which the Planning object updates all Flight objects with the genes, contained in the chromosome, and the Flight object updates all Segment objects with the codon, contained in the gene. The Genetics object then commands that the constraints are to be imposed from the level of the Planning to the level of the Segment.

Finally, when the planning is considered feasible the Genetics object requests an evaluation of the performance of the Planning object. This also requires evaluation procedures at the Flight level (since it contains the 4-D trajectory profile), but not at the Segment level since none of the segment parameters are needed to calculate the ATM performance in terms of the objectives.

### 3.4 Conclusions

A multi-objective scheduling algorithm was developed that provides a way to optimise arrival trajectories. The scheduling algorithm considers four objectives: throughput, deviation from altitude and speed profiles of a three-degree decelerated approach, and noise load on community. In order to prevent finding solutions that score high on one objective but low on others, the approach of meeting performance levels on multiple objectives is followed.
Solutions are looked for in a sequential fashion using a genetic algorithm. The genetic algorithm is expected to be able to approximate the Pareto front. By taking into account the required performance levels for the different objectives, it is expected that the algorithm is able to approximate the part of the Pareto front that is useful for a decision maker.

In Chapter 7 the developed algorithm will be applied in order to compare the ATM performance that can be obtained for flexible arrival trajectories and for conventional trajectories. Besides ATM performance, in Chapter 7 the pilot task demand load for flexible arrival trajectories and conventional trajectories will be compared also. It is, however, necessary to determine first which factors need to be considered for describing the task demand load for the pilot. This is done in the next chapter.
The algorithm designed in Chapter 3 may be used to generate flexible arrival trajectories that increase ATM performance. These trajectories may, however, become more complex than those used today. In addition, 4-D constraints may become more stringent (Chapter 1). This may result in the task of flying the assigned trajectory becoming more difficult.

The difficulty of a task may affect both operator performance and mental effort. Since in aviation performance is often prescribed, the focus is here on mental effort. A distinction is usually made between task demand load and mental load (Stassen et al., 1990). Task demand load (TDL) is the mental effort required to accomplish a task. Mental load, also often referred to as workload, is the mental effort actually experienced by the operator. The reason for the difference is that for the same task demand load different operators may choose to operate at different levels of mental load. It is here important to determine how the trajectory influences the task; it is thus necessary to determine TDL.

In this thesis only manual flight is considered (Section 1.5). A number of metrics that may be important for TDL of this task are identified in Section 4.1. These metrics are only useful if they are sensitive to variations in trajectory shape. On the other hand, they should not be sensitive to pilot control behaviour. Pilot control behaviour may differ significantly between pilots and may influence the values of the metrics. These two aspects are considered in Section 4.2.

### 4.1 Identification of Metrics

One of the most commonly used methods in aviation for workload assessment is the NASA task load index (TLX) method (Hart & Staveland, 1988). It is a subjective rating scale.
The TLX method defines six categories of sources of workload: physical, mental, temporal, performance, effort, and frustration. The physical, mental, and temporal workload levels are primarily a function of the task, thus relating to task demand load. On the other hand, the performance, effort, and frustration levels are heavily influenced by the operator. The categories of physical, mental, and temporal workload are therefore used as a starting point to identify factors in the task that influence task demand load.

4.1.1 Physical Aspects

For guiding the aircraft along the trajectory, the physical component of task demand load is very dependent on other influences besides the task definition. Examples of these influences are aircraft type and type of controls used (e.g., control column, side stick, or autopilot). It was therefore not considered an appropriate category to reveal basic properties of the trajectory that allow general assessment of task demand load. No attempts have been made to estimate physical aspects of task demand load.

4.1.2 Influence of Manoeuvres

It is hypothesized that temporal and mental pressure are influenced by the trajectory primarily through the amount and type of manoeuvres that are prescribed in the trajectory. Four factors may be identified to estimate the mental and temporal pressure:

- the number of manoeuvres,
- the amount of time necessary to complete the commanded manoeuvres in relation to the time available,
- the size of the commanded changes, and
- the rate of change, i.e., rate at which the pilot has to transfer from one state to another.

Since any change of flight condition requires appropriate action, a manoeuvre generates task demand load. The total number of commanded manoeuvres is therefore hypothesized to be an important metric when assessing task demand load. It is denoted as $N_M$.

The amount of time involved in carrying out these changes is denoted as $T_M$. The ratio between time necessary for carrying out the task and time available has been shown to be an important factor for temporal load (Wei, 1997). The ratio between $T_M$ and the flight time $T$ is therefore expected to be an important metric as well. For convenience, the ratio $T_M/T$ is referred to as manoeuvre time in the rest of the thesis.

The size of the changes is considered important because with large changes more mental processing may be required. For example, with larger changes of track angle present predicting future states may be more complicated because a larger part of the trajectory is curved.
Higher rates of change between aircraft states may require the aircraft to be pulled out of the nominal condition to a larger extent than for lower rates of change. This, in effect, may require more effort. Higher rates of changes are therefore expected to contribute to task demand load. The rate is also introduced as an additional variable for a second reason. A quickly changing situation may result in more task demand load because it becomes harder to predict future aircraft states. An example of this is that prediction of future aircraft position is easier if speed is constant than if speed is changing.

The number of manoeuvres $N_M$ and manoeuvre time $T_M/T$ are applicable to all manoeuvres. However, the variables that have to be considered to describe the rate of change and size of change are different depending on the manoeuvre that is considered. Therefore, the following four types of common aircraft manoeuvres are considered separately:

- vertical flight path change (referred to as P),
- speed change (referred to as S),
- combined vertical flight path and speed change (referred to as PS), and
- track change (referred to as T).

**Vertical Flight Path Change (P)**

Vertical flight path changes can be described by a change in flight path angle $\Delta \gamma$. To obtain the total commanded change for a trajectory, the contributions from all $N_P$ vertical path manoeuvres over the trajectory are summed. This yields $\Sigma_{i=1}^{N_P} |\Delta \gamma_i|$, which is abbreviated for convenience to $\Sigma |\Delta \gamma|$. This parameter is used to describe the size of vertical flight path changes. It is denoted as $(\Sigma |\Delta \gamma|)_P$ to indicate that it refers to only commanded vertical flight path changes (where speed remains constant).

Both the vertical speed and the vertical acceleration may be used to describe the rate of change in the vertical plane. However, increasing the flight path angle increases also the vertical speed. The size of the path change used above and the vertical speed are therefore not independent. This makes vertical speed less suitable as a metric. The vertical acceleration $a_z$ is therefore used instead to describe the rate of change during vertical flight path changes. The maximum value of the absolute vertical acceleration is used as a metric because it describes the fastest changing situation.

**Speed Change (S)**

Analogous to the path changes, it may seem that summing the size of the speed changes from all speed manoeuvres in a trajectory is useful. This is, however, not the case. This is because the total change in airspeed in an arrival trajectory is for a specific aircraft generally not influenced by the arrival trajectory. Therefore, the maximum value of the required increase or decrease in speed is used instead. To describe the commanded rate of change the maximum commanded acceleration or deceleration is used. This describes the fastest changing situation.
Table 4.1 The variables of manoeuvre-related properties of the trajectory that contribute to task demand load. The indications P, S, PS, and T refer to vertical path changes, speed changes, combined vertical path and speed changes, and track changes, respectively.

<table>
<thead>
<tr>
<th>Manoeuvre</th>
<th>Number</th>
<th>Manoeuvre time</th>
<th>Size of change</th>
<th>Rate of change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Path</td>
<td>N_P</td>
<td>(T_M / T)_P</td>
<td>(Σ</td>
<td>Δγ</td>
</tr>
<tr>
<td>Speed</td>
<td>N_S</td>
<td>(T_M / T)_S</td>
<td>(</td>
<td>ΔV_C</td>
</tr>
<tr>
<td>Path and speed</td>
<td>N_PS</td>
<td>(T_M / T)_PS</td>
<td>(Σ</td>
<td>Δγ</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(</td>
<td>ΔV_C</td>
</tr>
<tr>
<td>Track</td>
<td>N_T</td>
<td>(T_M / T)_{lat}</td>
<td>Σ</td>
<td>Δχ</td>
</tr>
</tbody>
</table>

Combined Vertical Flight Path and Speed Change (PS)
For combined vertical flight path and speed changes the separate contributions from vertical flight path change and speed change manoeuvres are combined.

Track Change (T)
The manoeuvre time for track changes is denoted as the lateral manoeuvre time (T_M / T)_{lat} since there are no other lateral manoeuvres. The cumulative size of all track changes Σ|Δχ| is used to represent the change size. The same abbreviated notation as for the flight path changes is used. The rate of change is for lateral manoeuvres normally described by the turn rate Ω,

Ω = \frac{V_{at}}{R}, \qquad (4.1)

with V_{at} along-track speed and R turn radius. However, Funabiki et al. (1999) used the nominal bank angle required and showed that it affects workload. The maximum value of the turn rate is used here instead because it describes the situation that is changing most quickly. The turn rate and bank angle Φ are related in a true banked turn in level flight without wind through Ω = (g \tan Φ)/V (Ruijgrok, 1994). The absolute value of the turn rate is used because there is no reason to make a distinction between left and right turns.

For all manoeuvres the relevant variables are given in Table 4.1.

4.1.3 Influence of Aircraft Performance Limits
The reference trajectory is also thought to affect the task demand load through effects related to aircraft performance (Funabiki et al., 1999). The effects meant here refer to ‘the
closeness to aircraft performance limits’, i.e., to how close the trajectory forces the pilot to approach the aircraft’s performance limits.

It is hypothesized that an important factor to describe these effects is the type of energy conversions implied by the trajectory. This is because for fixed-wing aircraft the rate at which energy can be dissipated is normally limited. This is a result of aircraft being designed for high lift and low drag. The standard descent thrust usually applied is only a small portion of the thrust available and a large part of the arrival route is often flown at a power level close to idle. When the throttle has been set to idle, dissipating energy faster requires the speed brakes to be deployed. This, however, is not always desirable. Flaps or gear may also be set, but this is not always possible. This means that the options to reduce energy at a higher rate than normally during the arrival phase are very limited. Aircraft are thus often operating close to this performance limit.

The energy rate demand with speed brakes deployed $\dot{E}_{sbr}$, as defined in Equation (3.8), is the ratio between the energy rate commanded in the reference trajectory and the minimum energy rate that can be realised by the subject aircraft. The maximum value of it during the arrival describes the most demanding situation for the aircraft. The maximum value during the arrival is therefore used to serve as a measure of task demand load:

$$\dot{E}_{max} = \max_t (\dot{E}_{sbr}),$$

where the time $t$ covers the time from the start to the end of the trajectory.

### 4.1.4 The Set of TDL Metrics

As discussed above, a list of parameters can be assembled that are hypothesized to be important factors for the task demand load. The number of manoeuvres and the manoeuvre times have so far been considered for all manoeuvres separately. It is, however, worth studying if the list of metrics can be reduced by making combinations of the metrics. A shorter list may make TDL estimation easier. It is therefore studied if the total number of manoeuvres $N_M = N_P + N_S + N_{PS} + N_T$ can be used instead of $N_P$, $N_S$, $N_{PS}$, and $N_T$ separately. The total longitudinal manoeuvre time $(T_M/T)_\text{lon} = (T_M/T)_P + (T_M/T)_S + (T_M/T)_PS$ and total manoeuvre time $(T_M/T)_\text{tot} = (T_M/T)_\text{lon} + (T_M/T)_\text{lat}$ are studied for the same reason. The entire list of metrics studied is given in Table 4.2.
Table 4.2  Metrics studied for estimating task demand load. The indications P, S, PS, and T refer to vertical path changes, speed changes, combined vertical path and speed changes, and track changes, respectively.

<table>
<thead>
<tr>
<th>Nr</th>
<th>Metric</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$N_P$</td>
<td>number of vertical path changes</td>
</tr>
<tr>
<td>2</td>
<td>$(T_M/T)_P$</td>
<td>manoeuvre time for vertical path changes</td>
</tr>
<tr>
<td>3</td>
<td>$(\Sigma</td>
<td>\Delta\gamma</td>
</tr>
<tr>
<td>4</td>
<td>$(</td>
<td>a_z</td>
</tr>
<tr>
<td>5</td>
<td>$N_S$</td>
<td>number of speed changes</td>
</tr>
<tr>
<td>6</td>
<td>$(T_M/T)_S$</td>
<td>manoeuvre time for speed changes</td>
</tr>
<tr>
<td>7</td>
<td>$(</td>
<td>\Delta V_C</td>
</tr>
<tr>
<td>8</td>
<td>$(</td>
<td>\dot{V}_C</td>
</tr>
<tr>
<td>9</td>
<td>$N_{PS}$</td>
<td>number of combined vertical path and speed changes</td>
</tr>
<tr>
<td>10</td>
<td>$(T_M/T)_{PS}$</td>
<td>manoeuvre time for path-speed changes</td>
</tr>
<tr>
<td>11</td>
<td>$(\Sigma</td>
<td>\Delta\gamma</td>
</tr>
<tr>
<td>12</td>
<td>$(</td>
<td>\Delta V_C</td>
</tr>
<tr>
<td>13</td>
<td>$(</td>
<td>\dot{V}_C</td>
</tr>
<tr>
<td>14</td>
<td>$(</td>
<td>a_z</td>
</tr>
<tr>
<td>15</td>
<td>$N_T$</td>
<td>number of track changes</td>
</tr>
<tr>
<td>16</td>
<td>$(T_M/T)_{lat}$</td>
<td>lateral manoeuvre time</td>
</tr>
<tr>
<td>17</td>
<td>$\Sigma</td>
<td>\Delta\chi</td>
</tr>
<tr>
<td>18</td>
<td>$</td>
<td>\Omega</td>
</tr>
<tr>
<td>19</td>
<td>$\dot{E}_{max}$</td>
<td>maximum energy rate demand</td>
</tr>
<tr>
<td>20</td>
<td>$N_M$</td>
<td>total number of manoeuvres</td>
</tr>
<tr>
<td>21</td>
<td>$(T_M/T)_{lon}$</td>
<td>longitudinal manoeuvre time</td>
</tr>
<tr>
<td>22</td>
<td>$(T_M/T)_{tot}$</td>
<td>total manoeuvre time</td>
</tr>
</tbody>
</table>
4.2 Verification of Metrics

In general, any workload assessment technique must have the following properties (Stassen et al., 1990):

- sensitivity to changes in task difficulty,
- selectivity, meaning immunity to changes in other factors such as pilot behaviour,
- no interference with the variable to be determined,
- presence of cause-effect relationships,
- reliability, meaning that identical circumstances should yield identical values,
- consistency among subjects, i.e. the variation between subjects shall not exceed the workload index variation to be measured, and
- bandwidth, meaning that the workload index should be able to track the mental load variations in time.

It is assumed that these requirements apply (partly) to the TDL metrics used here also. The metrics identified in Section 4.1 can be either predicted before the trajectory is flown by the subject or calculated afterwards based on logged data. Neither interferes with any variables to be determined. The metrics used here were derived based on theory. Hence, cause-effect relationships are provided. Since the metrics depend only on the trajectory, reliability is provided. Because the task demand load is determined, the consistency criterion is not applicable. Since it is not desired to assess task demand load as a function of time, the bandwidth property is not applicable either.

The sensitivity and selectivity of the lateral and longitudinal metrics are discussed separately in the following sections. Pilot control behaviour may influence the values of the metrics used. Control behaviour may differ significantly between pilots. Selectivity is therefore addressed through determining if the metrics are insensitive to variation in pilot control behaviour.

4.2.1 Sensitivity and Selectivity of Lateral Metrics

The number of track changes and cumulative track change sizes are only functions of the trajectory. Pilot nor aircraft will influence these metrics, assuming that pilots do not carry out a different number of turns or a different total change in track angle than prescribed. Under these assumptions, $N_T$ and $\Sigma|\Delta \chi|$ are only sensitive to variations in the trajectory and not to variations in pilot behaviour.

The influence of pilot behaviour on manoeuvre time $T_M/T$ can be illustrated with an example. The time necessary to complete the turn can be determined since in this work the speed and both the radius and length of turns are prescribed (see Figure 3.8). Although
$T_M/T$ can be calculated from the properties of the turn, an error will be made since the roll transient responses are ignored. The time required to place the aircraft in a steady turn is dependent on pilot behaviour. In (Mulder, 1999) the roll-in time $T_{ri}$ needed to acquire a constant bank angle was for a stationary horizontal turn with an Airbus A300 model found to vary between about 3 and 10 seconds depending on pilot behaviour. The reference roll angle $\phi_r$ for this turn was 11.8 deg. For this condition ($V_{at} = 77 \text{ m/s, } R = 2941.2 \text{ m, } \theta = 4.8 \text{ deg}$), the reference turn rate $\Omega_r$ is obtained from Equation (4.1) as 1.5 deg/s. However, because of the roll-in this turn rate cannot be instantly be achieved. In a stationary turn $q = 0$ and the turn rate is obtained from (Ruijgrok, 1994):

$$\Omega = \frac{r \cos \phi}{\cos \theta}.$$  \tag{4.3}

For the A300 model it was observed that $r$ and $\phi$ increase linearly with time during almost the entire roll-in procedure. With $r$ and $\phi$ assumed linear functions of time, $\Omega$ can be approximated to increase with time linearly also for the value of $\phi_r$ used here (Figure 4.1). The turn rate may therefore be assumed to increase linearly to the reference value at the start of the turn and to decrease linearly to zero at the end of the turn. Then, integration of $\Omega$ with respect to $t$ yields the time needed to complete a turn as:

$$T_M = \frac{\Delta \chi}{\Omega_r} + T_{ri}.$$  \tag{4.4}

For this example a turn with $\Delta \chi = 16 \text{ deg}$ is used. This is the track angle change obtained if a slow pilot with the largest roll-in time mentioned above of $T_{ri} = 10 \text{ s}$ rolls in and immediately rolls out of the turn. When a trajectory requires for example 10 turns to be carried out, this results for $T_{ri} = 3 \text{ s}$ in $T_M = 137.0 \text{ s}$ and for $T_{ri} = 10 \text{ s}$ in $T_M = 207.0 \text{ s}$. A typical total flight time $T$ of the arrival route is 10 minutes (see Table 7.1). This results in $T_M/T$ values of 0.23 and 0.35, respectively.

Whether this is a large difference, can be determined by comparing it to the changes in $T_M/T$ due to changes in the trajectory. If, for example, the turns are made twice as long, the track changes increase to 32 degrees and $T_M/T$ increases for $T_{ri} = 3 \text{ s}$ to 0.41. The value of $T_M/T$ has thus changed by 0.18 (0.41 − 0.23) due to the trajectory change. The change in $T_M/T$ due to pilot behaviour was 0.12. It is therefore concluded that pilot behaviour affects $T_M/T$ for this case significantly.

If, on the other hand, only one turn (with the original $\Delta \chi = 16 \text{ deg}$) is carried out the values of $T_M/T$ become ten times smaller. The difference in $T_M/T$ due to pilot behaviour becomes only 0.012. It is further reduced to 0.006 if the flight time $T$ is increased to 20 minutes. The effect of pilot behaviour on $T_M/T$ is thus very dependent on the number of turns and the trajectory length.

The example shows that $T_M/T$ is sensitive to changes in the trajectory. However, the example also shows that $T_M/T$ can become sensitive to variations in pilot behaviour. The variable $T_M/T$ may therefore for lateral motion be less suitable as a metric.
The only remaining lateral metric to be discussed is the maximum turn rate. Overshoot in turns is generally very small or not present at all. This is because the bank angle determines the load factor during turns. In passenger transport pilots are not eager to apply a higher load factor than necessary. It can therefore be expected that the maximum turn rate required will not be exceeded in real flight. When assuming in addition that there is enough time to acquire the reference turn rate that the trajectory prescribes, the maximum turn rate is not likely to be influenced by variations in pilot behaviour. The maximum turn rate is inversely proportional to the turn radius and is thus sensitive to variations in the trajectory.

4.2.2 Sensitivity and Selectivity of Longitudinal Metrics

Estimating the values of the metrics by considering only the shape of the trajectory is not possible for longitudinal motion because the description of the trajectory used here does not prescribe how fast flight path changes should be carried out. It is therefore not possible to determine the load factor, the speed, and other metrics such as manoeuvre time. For this reason, the sensitivity and selectivity of the longitudinal metrics are evaluated with an aircraft and pilot model.

Description of Longitudinal Aircraft Model

The linear aircraft equations of motion as described in Appendix B are used. The stability and control derivatives used are those for the B747-100 aircraft model described in (Etkin & Reid, 1996). This model was made for the aircraft in landing configuration with flaps at 30 degrees, with landing gear down, for a speed of 131 kts (= 67.36 m/s), and for an altitude of 0 ft. The characteristics of the longitudinal eigenmodes are given in Table 4.3.
The aircraft model is augmented with engine dynamics, which are represented as a first-order time lag similar to (Blakelock, 1965):
\[ H = \frac{1}{\tau_p s + 1}. \]  
(4.5)

The time constant \( \tau_p \) represents the time required for the thrust of the jet engines to build up after a commanded thrust change. A time constant of 3 seconds was used.

**Table 4.3** Characteristics of the longitudinal eigenmodes.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Short period</th>
<th>Phugoid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eigenvalue</td>
<td>(-0.443 \pm 0.674i)</td>
<td>(-0.00622 \pm 0.142i)</td>
</tr>
<tr>
<td>Natural frequency</td>
<td>0.674 rad/s</td>
<td>0.142 rad/s</td>
</tr>
<tr>
<td>Undamped circular frequency</td>
<td>0.806 rad/s</td>
<td>0.142 rad/s</td>
</tr>
<tr>
<td>Period</td>
<td>9.322 s</td>
<td>43.036 s</td>
</tr>
<tr>
<td>Half time</td>
<td>1.456 s</td>
<td>111.438 s</td>
</tr>
<tr>
<td>Damping</td>
<td>0.549</td>
<td>0.0437</td>
</tr>
</tbody>
</table>

**Description of Pilot Model**

The human operator control constraints have been described as an effective time delay which represents human information processing (McRuer & Jex, 1967) and a neuromuscular lag time, see for instance (Kleinman, Baron, & Levison, 1970).

For the transfer function of the effective time delay \( \Delta t_e \) a first-order Padé approximation is used:
\[ H = \frac{1 - \frac{\Delta t_e}{2} s}{1 + \frac{\Delta t_e}{2} s}. \]  
(4.6)

Experiments have shown that typical values for the effective time delay \( \Delta t_e \) are between about 0.25 and 0.35 seconds, see for instance (van Paassen, 1994). Since the metrics may be sensitive to changes in effective time delay, the metrics are determined for effective time delays of 0.25, 0.30, and 0.35 seconds.

The neuromotor dynamics can be modeled as (Kleinman et al., 1970):
\[ H = \frac{1}{\tau_n s + 1}, \]  
(4.7)

where \( \tau_n \) is typically equal to about 0.1 seconds. The neuromotor lag is generally not
applied to throttle control because the aircraft response to the throttle is so slow that the
effects of neuromuscular lag are negligible.

A speed controller was designed based on PID control to track a selected velocity by
generating throttle commands. An altitude controller was designed based on PID control,
after first a PID controller had been designed to control pitch attitude. The altitude controller
generates elevator commands in order to track altitude. The controllers were designed based
on the system illustrated in Figure 4.2 to provide adequate stability margins and to meet
handling qualities criteria (Soares, 2005). They were designed for the ‘nominal’ pilot time
delay of 0.30 s. For the altitude controller, the reference altitude a number of seconds ahead
in time was considered, because pilots would also respond to a path change before it would
actually occur. This prediction time was tuned to 10 s to give desirable aircraft behaviour.
The obtained gain margins, phase margins, and open-loop crossover frequencies are shown
in Table 4.4.

**Figure 4.2** Block diagram of aircraft and pilot model.

**Table 4.4** Gain margins, phase margins, and open-loop crossover frequencies for the de-
signed control system.

<table>
<thead>
<tr>
<th>Loop</th>
<th>Gain margin, dB</th>
<th>Phase margin, deg</th>
<th>Crossover frequency, rad/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch attitude</td>
<td>8.17</td>
<td>58.1</td>
<td>0.653</td>
</tr>
<tr>
<td>Altitude</td>
<td>14.0</td>
<td>77.8</td>
<td>0.0793</td>
</tr>
<tr>
<td>Velocity</td>
<td>27.2</td>
<td>80.7</td>
<td>0.274</td>
</tr>
</tbody>
</table>
Definition of Conditions
The effect of changing the trajectory on the metrics is assessed through calculating the metrics for a number of vertical path, speed, and combined vertical path and speed manoeuvres. The standard ILS approach path prescribes a flight path angle of -3 degrees. A flight path angle of -6 degrees is normally considered a steep approach. Initial flight path angles of 0, -3 and -6 degrees were therefore selected. From these initial flight path angles, changes of -3 and -6 degrees were applied so that the final flight path angle is also equal to -3 or -6 degrees. For the speed changes, a speed change of 10 kts is studied because this is also a typical speed change in current practice.

Table 4.5 Definition of the manoeuvres. These manoeuvres are evaluated for all combinations of $V_{C0} = 140$ and 180 kts and $h_0=1,000$ and 3,000 ft.

<table>
<thead>
<tr>
<th>Manoeuvre</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_0$, deg</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-3</td>
<td>-3</td>
<td>-6</td>
<td></td>
</tr>
<tr>
<td>$\Delta \gamma$, deg</td>
<td>-3</td>
<td>-6</td>
<td>0</td>
<td>-3</td>
<td>-6</td>
<td>-3</td>
<td>-3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\Delta V_{C}$, kts</td>
<td>0</td>
<td>0</td>
<td>-10</td>
<td>-10</td>
<td>-10</td>
<td>0</td>
<td>-10</td>
<td>-10</td>
<td>-10</td>
</tr>
</tbody>
</table>

The initial speed was selected as 140 kts, so that the speed would become close to the trim speed if a speed change of -10 kts is applied. Although the aircraft model was trimmed for 0 ft altitude, the simulations were carried out at 1,000 ft to provide altitude for carrying out the manoeuvres. The metrics are also evaluated for the speed and altitude at the beginning of an ILS approach, because (besides changing the manoeuvre) changing the initial flight condition also changes the trajectory. The speed at the beginning of the ILS approach is selected as 180 kts (Appendix A) and the altitude as 3,000 ft. It is to be noted though that for this condition the deviation from the trim condition is significant.

This results in the following initial conditions to be evaluated:

$$
\gamma_0 = \begin{cases} 
0 \\
-3 \\
-6 
\end{cases} \text{ deg,} \quad V_{C0} = \begin{cases} 
140 \\
180 
\end{cases} \text{ kts,} \quad h_0 = \begin{cases} 
1,000 \\
3,000 
\end{cases} \text{ ft,}
$$

and the following changes:

$$
\Delta \gamma = \begin{cases} 
0 \\
-3 \\
-6 
\end{cases} \text{ deg,} \quad \Delta V_{C} = \begin{cases} 
0 \\
-10 
\end{cases} \text{ kts.}
$$

This yields nine different manoeuvres as shown in Table 4.5. Because the initial flight path angle determines which flight path changes can be carried out, the initial flight
4.2 VERIFICATION OF METRICS

path angle is included in the table.

\[ |\alpha_z|_{\text{max}} | \] \( \text{m/s}^2 \)

\[ |\dot{V}_C|_{\text{max}} | \] \( \text{m/s}^2 \)

\[ \hat{E}_{\text{max}} \]

\[ \frac{T_M}{T} | \] \( \text{(s)} \)

**Figure 4.3** Variation in values of the difficulty metrics due to changes in trajectory and pilot effective time delay for a B747 aircraft model. The ranges of the obtained values are shown for \( \Delta t_e = 0.25 \text{ s (bar without lines)}, \Delta t_e = 0.30 \text{ s (diagonal lines), and } \Delta t_e = 0.35 \text{ s (horizontal lines).} \)

**Results**

With the aircraft and pilot model the values of the metrics are calculated for the different manoeuvres, initial flight conditions, and effective time delays (Soares, 2005). For \( \hat{E}_{\text{max}} \) this is done with Equation (4.2) and data from BADA (Section 3.2.5). The only metrics not evaluated are those relating to the number of manoeuvres, because they depend only on
the prescribed manoeuvres. They are not influenced by any of the other factors. They are therefore sensitive and selective.

There is also a potential problem for calculating the manoeuvre times $T_M/T$. The flight time $T$ is not specified since only separate manoeuvres are considered. The time $T$ is set to 1. In this way the manoeuvre times can still be compared.

The ranges of the obtained values for the different initial conditions are shown in Figure 4.3. Some of the plots show the values of more than one difficulty metric, because the manoeuvre defines unambiguously which metric is applicable. For manoeuvre 9 the value of $\hat{E}_{max}$ becomes larger than 1, meaning that this manoeuvre cannot be performed even if speed brakes are deployed.

It can be seen that in general the variation in the values of the metrics due to a change in flight condition (represented by the size of the bar) or effective time delay is small compared to the variation due to manoeuvres. This conclusion is also drawn for a different value of $T$, because the only effect is a scale change in Figure 4.3(d). The variation due to effective time delay, however, can be large when compared to the variation due to initial flight condition. This can be seen for example in the results for $|\dot{V}_C|_{max}$. The studied metrics are therefore concluded to be only more sensitive to the trajectory than to pilot behaviour when the trajectory is varied in the sense of changing the manoeuvres present in the trajectory. Changing, on the other hand, the altitude and speed with which the manoeuvres have to be carried out can result in the metrics being equally sensitive to pilot behaviour as to the trajectory.

### 4.3 Conclusions

A number of metrics were identified that are hypothesized to describe properties of the trajectory that contribute to the task demand load of guiding the aircraft along the trajectory. They describe the number of manoeuvres in the trajectory, the time needed to complete the manoeuvres in relation to the time available, the size of the flight path angle, speed, and track changes, the vertical and longitudinal accelerations, the turn rate, and the energy reductions defined in the trajectory in relation to the aircraft’s capabilities. It was shown that the metrics are sensitive to the manoeuvres in the trajectory. It was also shown that they are unsensitive to variation in pilot behaviour. This confirms that the variables selected are suitable as metrics. The only exception is the ratio between time needed to complete lateral manoeuvres and the flight time $T$, which may therefore be less suitable as a metric.

In Chapter 6 experimental data is obtained with the objective of supporting the hypothesis that the identified metrics are related to task demand load. However, recently developed formats for a primary flight display that supports 4-D guidance may influence task demand load also. The experimental evaluations therefore make use of different primary flight displays. The displays used in the experiments and the reasons for expecting that the display influences the task demand load are first discussed in the next chapter.
The combination of more complex arrival trajectories and stricter 4-D navigation requirements may prove to require new aircraft instrumentation and display systems for manual control. It has been suggested that the introduction of a new primary flight display in the form of a 4-D guidance display as opposed to the currently used primary flight display may allow much more complicated flight paths to be followed. This may even be done with higher accuracy and higher situation awareness (Chapter 1). Such a different primary flight display may therefore allow a more complex arrival trajectory.

This chapter discusses several formats for a 4-D guidance display that have been developed. These displays will be used in the experiments in Chapter 6. Section 5.1 starts with discussing the pilot’s task of controlling the aircraft’s along-track position, which is the task that 4-D guidance displays particularly support. A control-theoretical analysis of velocity control and longitudinal (i.e., along-track) position control is carried out in Section 5.2. Section 5.3 reviews a number of designs for an integrated 4-D guidance display and discusses how the display influences the task demand load of guiding the aircraft along the trajectory based on the results of the theoretical analysis.

5.1 The Four-Dimensional Guidance Task

When guiding the aircraft along a 4-D trajectory, the pilot’s task can be described as minimizing the lateral, vertical, and longitudinal or along-track position errors. Applying vertical and lateral constraints to the flight path results in the definition of a tunnel (Figure 5.1). The four-dimensional constraints that may result for example from ATC restrictions can be represented through what is essentially a 3-D box or ‘bubble’ (Wilson, 1996) moving with its own velocity along the flight path.
5.2 Control-Oriented Analysis of Velocity Control

In order to be able to compare the task demand load of guiding the aircraft along the trajectory with different 4-D guidance displays (Section 5.3), a frequency domain analysis of the aircraft velocity response is first carried out. This allows to determine which information
the pilot needs to control along-track velocity and position in a stable way. It then becomes possible to determine how well this information is provided by the different displays.

Controlling the aircraft’s position in the bubble can be accomplished using a combination of throttle and elevator. In large aircraft the pilot normally controls speed primarily with the throttle. Throttle control was here considered as the only means for the pilot to control velocity and an altitude-hold controller was used to keep altitude constant as shown in Figure 5.3.

![Figure 5.3](image)

**Figure 5.3** The aircraft block from Figure 5.2 consists of engine dynamics and aircraft dynamics augmented with an altitude-hold controller. The velocity is controlled using only the throttle.

### 5.2.1 Design of Altitude-Hold Controller

The aircraft models used in the analysis consists of the linearised symmetrical equations of motion given in Appendix B. Models of two different aircraft, a Cessna Citation 500 and a Boeing B747, in several configurations were used. The design of the altitude-hold controller is illustrated using the stability and control derivatives of the Cessna Citation 500 in cruise configuration at 128.2 m/s. The values of the stability and control derivatives for all aircraft models can be found in Appendix C.

![Figure 5.4](image)

**Figure 5.4** Block diagram of the aircraft with altitude-hold controller.

The altitude-hold controller is designed following the same steps and using the same system blocks as in (Blakelock, 1965). The altitude-hold controller holds the aircraft in straight and level flight by feeding back altitude and pitch rate to increase the damping of the short-period.
The altitude-hold controller is shown in Figure 5.4. The rate gyro is modeled as a pure gain $K_q$. The elevator servo is modeled as a first-order time lag with a time constant of 0.1 s:

$$\frac{\delta_e}{\delta_{e,cmd}} = \frac{-10}{s + 10}. \tag{5.1}$$

The pitch rate feedback gain $K_q$ is selected based on a root locus analysis of the inner loop, as shown in Figure 5.5. A gain of $K_q = 0.1$ was selected to provide additional damping of the short period and the phugoid.

Using the pitch rate feedback the inner loop can be closed. A second root locus analysis is carried out to select the outer loop gain $K_h$, as shown in Figure 5.6. The outer loop gain $K_h$ was chosen as 0.02, which provides good damping of the phugoid and places the natural frequency of this mode further away from the eigenfrequency of 0.2 rad/s belonging to the engine dynamics, as discussed in the next section.

For the B747 aircraft the feedback gains were determined in a similar way and were selected as $K_q = 8$ and $K_h = 0.04$.

### 5.2.2 Throttle Servo and Engine Dynamics

In order to obtain the system in Figure 5.3, the aircraft dynamics with the altitude-hold controller are augmented with a throttle servo and with engine dynamics (Figure 5.7). The throttle servo is modeled as a first-order time lag (Blakelock, 1965):
5.2 CONTROL-ORIENTED ANALYSIS OF VELOCITY CONTROL

The engine dynamics are represented as a first-order time lag in the same way as in Section 4.2.2:

\[
\frac{\delta_T}{T_p} = \frac{1}{3s + 1}.
\]  

(5.3)

5.2.3 Velocity Control

The dynamics of the system shown in Figure 5.7 are studied in more detail, where of particular interest is the form of the transfer function \( H_{\delta T_{cmd}}^V \), which describes the velocity response due to a throttle input. The magnitude of this transfer function is shown in Figure 5.8 for the different aircraft as a function of frequency.

According to the crossover model, the pilot-aircraft system should behave like a single integrator near the cross-over region (McRuer & Jex, 1967). The Bode plot of \( H_{\delta T_{cmd}}^V \) (Figure 5.8) shows that the system under control of the pilot behaves like two lags in series for a wide range of frequencies. For this type of control task, it has been found that pilots typically place the cross-over frequency of the open loop pilot-aircraft system between about 1 and 5 rad/s (McRuer & Jex, 1967). The similarity of the aircraft response to that of two lags in series is found for all aircraft models for frequencies that lie within the expected
Figure 5.7  The aircraft with altitude-hold controller and engine dynamics.

Figure 5.8  The frequency response of the velocity due to throttle lever position for several aircraft models augmented with an altitude-hold controller. The system dynamics show great resemblance with a system containing two lags in series for a wide range of frequencies.

cross-over region. This means that when velocity control with manual throttle control is considered, the pilot has to compensate for one lag by introducing a lead in his control behaviour.
5.3 ANALYSIS OF 4-D GUIDANCE DISPLAYS

Position control introduces another integration in the system under control. The conclusion is therefore drawn that the pilot has to control a system with two lags and one integrator when following a four-dimensional path, if there is only information about the reference or ‘bubble’ position available. A system of increasing order is increasingly difficult to control though (Kelley, 1968). If the system under control consists of two lags and one integrator it is in fact a third-order system. According to the crossover model, the pilot is then required to apply double-derivative control to maintain stability (Wickens, 1992). This means that the pilot should respond to accelerations of the bubble. The human abilities to perceive accelerations are, however, limited (McRuer, 1980). It is therefore expected that this results in velocity being controlled with a low bandwidth or at the cost of a high workload. This may be prevented by giving information about derivatives, e.g. related to velocity differences or accelerations. This will provide additional differentiators in the system to be controlled, which can reduce the order and make the system easier to be controlled (Wickens, 1992).

From the foregoing, it is clear that for controlling along-track position it may be necessary to aid the pilot via the display with feedback of derivative information. This means showing information about speed differences and possibly also accelerations. With this in mind, the design of 4-D guidance displays is considered in the next section.

5.3 Analysis of 4-D Guidance Displays

From the theoretical analysis of the previous section it is concluded that feedback of speed difference and possibly also acceleration may be necessary for stable manual velocity and longitudinal position control. In this section, an overview is given of existing and recently designed formats for the primary flight display that support control of along-track position. Displays with this capability are here called 4-D guidance displays. Besides a description of the displays, a task analysis for longitudinal position control is given for each display on the basis of the task analysis from Sections 5.1 and 5.2. The analysis is used to judge the suitability of the different displays for 4-D guidance.

5.3.1 The 4-D Flight Director Display

Most current cockpits are equipped with a primary flight display with a flight director (FD) for vertical and lateral guidance. Although the FMS usually can provide velocity guidance, there is no 4-D guidance in the sense of time-based position control along the trajectory. This can be incorporated though by pointing the speed bug (Figure 5.9) on the speed tape to a guidance speed that closes the position loop. This commanded speed is termed the ‘bubble capture speed’ \( V_{BCS} \). The speed tape then shows the velocity difference \( V_e \) between \( V_{BCS} \) and \( V_{IAS} \):\n
\[
V_e = V_{BCS} - V_{IAS},
\]  

(5.4)
where

\[ V_e = \Delta V_{pc} + \Delta V_{vc}, \]  \hspace{1cm} (5.5)

with \( v_c \) referring to velocity control. The speed indicated by the speed bug is normally also shown in digits above the speed tape.

**Figure 5.9**  The 4-D flight director display, with ① the bubble capture speed \( V_{BCS} \) in digits, ② the speed bug indicating the \( V_{BCS} \) and ③ the flight director bars showing how to keep the aircraft in the tunnel.

**Figure 5.10**  Velocity control for the 4-D flight director display.

Starting from the general task analysis of longitudinal position control from Section 5.1, the pilot’s task when using the 4-D flight director display is illustrated in Figure 5.10. The size of \( V_e \) is shown by the distance between the speed bug and the indication of the current speed and the value of \( V_{BCS} \) is obtained from the digital readout. The pilot can use this information to derive a suitable control input \( \delta_{T_{cmd}} \). The indication of \( V_e \) and the bubble capture speed automate the position control and part of the velocity control (see Figure 5.2), enabling the pilot to act as an inner loop controller. The task of the pilot is thus to determine
the suitable throttle input that keeps the current aircraft speed equal to the value indicated by the speed bug. As shown in Section 5.2 the dynamics of the controlled system then resemble those of a double lag.

5.3.2 The Bubble-in-the-Sky Display

Design of the Bubble Display

The design and several preliminary experimental evaluations of a bubble-in-the-sky display were presented in (Otten, 2001; Vormer et al., 2003; Dijkhuizen, Vormer, Mulder, & van Paassen, 2004). Because this display did prove to make some elements of the pilot’s task difficult, notably the distinction between tunnel and bubble, the determination of the position in the bubble, the determination of the relative speed between aircraft and bubble, and the determination of the distance to the rear boundary of the bubble, several additional conceptual designs of a 4-D display format have been developed and evaluated (Otten, 2001). Those pilot-in-the-loop experiments had a preliminary character and real distinctions between the different designs were not found. However, several concepts seemed to be promising solutions for further study. Displays based on two of these concepts are discussed below.

The Basic Bubble Display

The ‘basic bubble display’ (Figure 5.11) is a general tunnel-in-the-sky display which is augmented with a visualization of the bubble. The bubble can be distinguished from the tunnel by the thicker lines. Halfway the box an additional bubble frame is shown to make the middle of the bubble more distinctive.
Position control is carried out by the pilot, see Figure 5.12(a). Relative position feedback \((x_e)\) is given by the size of and the distance to the bubble frames:

\[
x_e = x_{\text{bubble}} - x_{a/c}.
\]  

(5.6)

From the position error information, the pilot has to determine the velocity difference \(\Delta V_{pc}\) and this is to be compared to the actual velocity difference \(\Delta V_{act}\), see Figure 5.12(b):

\[
\Delta V_{act} = V_{\text{bubble}} - V_{a/c},
\]

(5.7)

which has to be derived by determining the rate of change of the distance to and the size of the bubble frames.

Hence, position as well as velocity control are both carried out by the pilot. Although higher situation awareness may be provided by showing the position of the aircraft with respect to the bubble, it is expected that additionally closing the position loop manually will increase task demand load.

**The Bubble Display with Speed Marks**

In the way discussed in Section 5.2, providing derivative information may reduce task demand load. In order to verify if more accurate information about difference in relative velocity leads to lower task demand load, a bubble display with so-called ‘speed marks’ was designed by Otten (2001). The visualisation shown in Figure 5.13 was based on this design. Relative speed information is provided by a number of horizontal lines on the floor and vertical lines on the sides of the bubble. The lines are only visible in the lower corners of the bubble. The vertical lines are coupled to the aircraft and appear stationary to the pilot whereas the horizontal lines are attached to the bubble. When the aircraft speed matches the bubble speed, the relative positions of the horizontal and vertical lines will be fixed. When there is a speed difference the horizontal lines will move relative to the vertical lines, specifying both the value and direction of the difference between the aircraft and bubble speed. It is expected to provide a salient cue for speed differences.
5.3 ANALYSIS OF 4-D GUIDANCE DISPLAYS

Figure 5.13  The bubble display with speed marks. The vertical lines indicated with $\circ$ are attached to the aircraft and the horizontal lines indicated with $\bullet$ are attached to the bubble.

The pilot’s task using the bubble display with speed marks remains essentially the same as with the basic bubble display (Figure 5.12). The speed difference between aircraft and bubble ($\Delta V_{act}$), however, is shown more clearly by the speed marks. This is expected to support the pilot in closing the control loops successively, thereby lowering the task demand load.

5.3.3 The Grunwald Display

The Predictor Square with Tick-Marks
The display Grunwald describes for flying 4-D aircraft approaches consists of the basic tunnel display with predictive information superimposed on it. A predictor symbol is shown a certain distance ahead of the vehicle, predicting the aircraft position a number of seconds ahead, see Figure 5.14(a). The pilot’s task is to match the predictor symbol to the reference frame. The reference frame is the tunnel cross-section at the same distance ahead as the predictor symbol, indicating the desired future aircraft position (Grunwald et al., 1981). It has been shown also in that work that the predictive information can be used to provide system damping when following curved trajectories.

This predictive information can also be utilized for controlling the forward velocity of the aircraft. For such velocity control the display was augmented with ‘tick-marks’ shown at the corners of the tunnel. The predictor symbol and the tick-marks are shown at a distance $D_{tickmarks} = T \cdot V$ (with $V$ true airspeed). The reference frame is moving at the reference velocity $V_r$ and shown at a distance $D_r = T \cdot V_r$. In this formula $T$ is a time constant of 4-7 seconds (Grunwald, 1984) and $V_r$ was constant throughout conducted experiments.

The display gives feedback about the velocity difference by the position difference
between the tunnel reference frame and the tick-marks. Hence, by matching the tick-marks with the tunnel reference frame the pilot can minimise errors in the velocity. Because the display does not give feedback about the position of the bubble, it is not possible for the pilot to know whether the aircraft is still in the bubble or not and the outer loop of Figure 5.2 cannot be closed. So, unless \( V_r \) is based on a 4-D algorithm that closes the longitudinal position loop, no 4-D guidance in the sense of position control along the entire trajectory is given. Experiments with the tunnel with tick-marks display did show that accurate velocity control was achieved with moderate throttle activity and without affecting the path-following performance (Grunwald, 1984).

**The Modified Grunwald Display**

The positive results of the experiments from Grunwald (1984) and the fact that the concept with the tick-marks is very close to the original tunnel visualization inspired the design of a modified version of the Grunwald display to provide 4-D guidance. The visualization of this concept originated from a display designed by Amelink (2002).

![Modified Grunwald Display](image)

(a) tunnel, predictor, and tick-marks with 1 the predictor symbol, 2 the tick-marks, and 3 the reference frame

(b) the modified Grunwald display with 1 the tick-marks representing the bubble capture speed \( V_{BCS} \), 2 the reference frame showing the actual velocity of the aircraft, and 3 the extraction of the reference frame showing the acceleration of the aircraft

**Figure 5.14** The tunnel-in-the-sky display with predictor and tick-marks (left) as studied in (Grunwald, 1984) and the modified Grunwald display (right).

In the modified Grunwald display shown in Figure 5.14(b) the original tick-marks are replaced by larger symbols that show \( V_{BCS} \) rather than the true airspeed \( V \). The prediction
frame is placed in the tunnel at a distance of $V_{IAS}$ times 4 seconds ahead of the aircraft. The length of the tick-marks corresponds to a difference of plus or minus 2 knots between $V_{BCS}$ and the actual aircraft speed $V_{IAS}$ (Amelink, 2002). Additionally, the frame shows the acceleration. This is done by extracting and retracting the frame.

The task of the pilot using the modified Grunwald display is illustrated in Figure 5.15. Position and velocity control (Figure 5.2) are almost entirely automated and the task of the pilot is reduced to minimizing the velocity error $V_e$ by matching the prediction frame to the middle of the tick-marks.

The visualization of the acceleration of the aircraft by the prediction frame is expected to lower the control activity of the pilot. This is because an additional differentiator in the system to control can reduce the effective order of the system and make it easier to control (Wickens, 1992). Information about the acceleration allows the pilot to close the acceleration loop and the velocity loop successively. This should permit the pilot to control the velocity with a higher bandwidth. For this reason the display may allow the same trajectory to be flown with a lower task demand load than the 4-D flight director display or the bubble-in-the-sky displays.

### 5.4 Conclusions

A frequency domain analysis of the longitudinal aircraft responses to a thrust input was conducted to show which information pilots need for control of along-track position. From this analysis it was concluded that besides relative position it may be necessary to show the pilot relative velocity information and possibly also acceleration information for stable control with acceptable workload.

Four displays were selected that will be evaluated in the experiments carried out in the next chapter: the 4-D flight director display, the basic bubble display, the bubble with speed marks display, and the modified Grunwald display. The 4-D flight director display enables continuous 4-D guidance with the smallest modification to the current primary flight display: the speed indicated by the speed bug is continuously updated. The position control loop is automated, which is expected to keep task demand load relatively low. For the basic bubble display a 3-D view of the reference trajectory is shown. The task demand load, how-
ever, is expected to be higher than for the FD display, because position and velocity control are both to be carried out by the pilot. The bubble with speed marks display is expected to allow more complex trajectories than the basic bubble display at the same task demand load level because of clearer presentation of speed differences. The modified Grunwald display additionally provides acceleration information. It is therefore expected to allow more complex trajectories than any of the other displays at the same task demand load level. These hypotheses are evaluated in the next chapter.
In Chapter 4 a number of metrics were identified that are expected to affect the task demand load of flying an arrival trajectory. Only manual flight was considered. In this chapter, a number of experimental evaluations are carried out to determine to what extent the metrics do influence TDL. However, as discussed in Chapter 5, it should be expected that the way in which information is presented on the primary flight display affects the TDL also. It is therefore additionally studied how the 4-D guidance displays from Chapter 5 influence the TDL. Although flight crews perform a variety of tasks during approaches, these experiments consider only the pilot flying in guiding the aircraft along the trajectory.

Section 6.1 discusses Experiment 1, which had a preliminary character. It was carried out on a fixed-base simulator. Experiment 2 (Section 6.2) was carried out in a moving-base simulator. Data is obtained about the effects of introducing vertical path, speed, and track manoeuvres, which the theory from Chapter 4 was largely based on. In Experiment 3 (Section 6.3) the effects of the trajectory shape are further detailed by considering the influence of the individual metrics. This is done only for the longitudinal motion because in Experiment 2 this was found to be more important for TDL than lateral motion. A number of pilots participated in the experiments (Table 6.1).

6.1 Experiment 1

6.1.1 Objectives

The first experiment conducted was a small-scale pilot experiment. The first objective was to demonstrate that the shape of the reference trajectory and the speed profile affect the TDL.
Table 6.1  General information about the subjects that participated in the experiments.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Year of birth</th>
<th>Gender</th>
<th>Vision(^1)</th>
<th>Flying hours</th>
<th>Aircraft types</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1967</td>
<td>male</td>
<td>U</td>
<td>1400</td>
<td>Single engine piston, C-550</td>
</tr>
<tr>
<td>B</td>
<td>1967</td>
<td>male</td>
<td>U</td>
<td>-</td>
<td>C-550 and B747 (both simulator only)</td>
</tr>
<tr>
<td>C</td>
<td>1972</td>
<td>male</td>
<td>U</td>
<td>2000</td>
<td>Single engine piston, B747-400</td>
</tr>
<tr>
<td>D</td>
<td>1975</td>
<td>male</td>
<td>U</td>
<td>75</td>
<td>Gliders</td>
</tr>
<tr>
<td>E</td>
<td>1973</td>
<td>male</td>
<td>C (l)</td>
<td>5000</td>
<td>J31, B767, B757, Single engine piston</td>
</tr>
<tr>
<td>F</td>
<td>1939</td>
<td>male</td>
<td>C (g)</td>
<td>13100</td>
<td>DC3, F28, DC8, B747-300, B747-400, C-550</td>
</tr>
<tr>
<td>G</td>
<td>1975</td>
<td>male</td>
<td>U</td>
<td>1000</td>
<td>PA-128, Be36A, Be58, C172, B747-300, B747-400</td>
</tr>
<tr>
<td>H</td>
<td>1966</td>
<td>male</td>
<td>U</td>
<td>4500</td>
<td>C-550, Metro II, Fokker 70/100, B767</td>
</tr>
<tr>
<td>I</td>
<td>1975</td>
<td>male</td>
<td>U</td>
<td>200</td>
<td>Single engine piston</td>
</tr>
<tr>
<td>J</td>
<td>1971</td>
<td>male</td>
<td>U</td>
<td>8000</td>
<td>Single engine piston, light multi-engine, B757, B767, B747 (classic)</td>
</tr>
<tr>
<td>K</td>
<td>1972</td>
<td>male</td>
<td>U</td>
<td>7000</td>
<td>C-500, MD-11, B767, B747-400</td>
</tr>
<tr>
<td>L</td>
<td>1980</td>
<td>male</td>
<td>U</td>
<td>1500</td>
<td>A320</td>
</tr>
<tr>
<td>M</td>
<td>1975</td>
<td>male</td>
<td>C (g)</td>
<td>1300</td>
<td>Gliders, MD-11</td>
</tr>
</tbody>
</table>

\(^1\) U = uncorrected, C (l) = corrected lenses, C (g) = corrected glasses
of guiding the aircraft along a 4-D arrival trajectory. As discussed in Chapter 1, the length of the straight final leg of the approach and shape of the speed profile are believed to influence ATM performance. In the first experiment it was only studied what the effects are of the length of the straight final leg, the presence of a deceleration, and, if there is a deceleration, the location of the deceleration. With respect to the location of the deceleration, a distinction was made between decelerating on a straight flight segment and in a turn. It was expected that demonstrating that these variations in the trajectory influence TDL would warrant further research into the effects of the trajectory shape on TDL. The second objective was to determine if a 4-D guidance display can reduce TDL.

6.1.2 Method

Subjects and Instructions
Subjects A through F participated in the experiment (Table 6.1). Their primary task was to minimise the errors in lateral, vertical and along-track position. Their secondary task was to adjust the flap settings so that the appropriate flap limit speeds were not exceeded.

Apparatus
The experiment was carried out in a fixed-base simulation laboratory (Figure 6.1). The simulator is equipped with an electro-hydraulic side stick for pitch and roll control; a single handle was used to manipulate the engine settings and two buttons could be pressed to extend or retract the flaps. Rudder control was not included in this experiment. Two 18-inch LCD screens were used. One screen showed the PFD and the navigation display (ND) while the other displayed the engine and flap settings.

Figure 6.1  Experimental setup in the Human Factors Laboratory at Delft University of Technology.

For all conditions, the ND showed the reference tunnel and bubble. Pilots were instructed to use the ND only for global reference though to prevent they would try to remain
in the tunnel based on the tunnel shown on the ND. There was no traffic present. In this experiment the (conservative) flap limit speeds from (Koeslag, 2001) were applied. These limits were applied because they had been successfully used in an automated system for the B747. This system gave pilots instructions on deployment of flaps during approaches. The list in Table 6.2 was provided to the subjects.

**Table 6.2** Flap limit speeds used in Experiment 1.

<table>
<thead>
<tr>
<th>Speed, kts</th>
<th>Flap setting, deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower</td>
<td>Nominal</td>
</tr>
<tr>
<td>215</td>
<td>230</td>
</tr>
<tr>
<td>200</td>
<td>215</td>
</tr>
<tr>
<td>180</td>
<td>200</td>
</tr>
<tr>
<td>160</td>
<td>180</td>
</tr>
<tr>
<td>140</td>
<td>160</td>
</tr>
</tbody>
</table>

**Independent Variables**

The experiment had two independent variables. The first independent variable was the trajectory type. Four trajectory types were used. The trajectories were obtained by selecting trajectories from a wide range of trajectories generated by the software described in Chapter 3. The trajectories selected (Figure 6.2) all consisted of a straight section, a turn onto final approach and a final straight section towards a single runway. The initial indicated airspeed along all trajectories was constant, but for two trajectories types there was a required deceleration to a new constant indicated airspeed. For trajectory 1 the deceleration took place on a straight section; for trajectory 3 during a turn. The reference speed of the bubble was for all trajectories constant (185 kts) on the final straight section. In current practice, the final approach intercept takes usually place between 6 and 11 nmi from the runway threshold (see Section 7.1.3). For this reason, one trajectory was selected with a final approach intercept distance within this range (8.77 nmi). For the minimum allowable final approach intercept distance a value of 3.0 nmi is generally mentioned, see Section 3.1.4. For this reason, one trajectory was selected that required an intercept distance close to this value (3.66 nmi). To address the effects on TDL of even further reducing this distance, which may be beneficial in terms of ATM performance (Chapter 1), two trajectories were selected that require a smaller final intercept distance (1.66 and 1.16 nmi). Intercepts closer than 1.0 nmi were not applied in the experiment to give the pilots some time to stabilize the aircraft before landing.

The trajectories and the wind direction were mirrored with respect to the runway centerline in order to be able to do a second independent measure for each trajectory type.
Figure 6.2 The trajectories used in Experiment 1. The small numbers show the indicated airspeed in kts on that part of the trajectory. The deceleration for trajectory 1 and 3 took place between the markers. An IAS of 185 kts was prescribed on the final segment.
Each trajectory type corresponds to the trajectory from Figure 6.2 and the same trajectory mirrored with respect to the runway centerline.

The second independent variable was the primary flight display (PFD). The 4-D flight director, the basic bubble, the bubble with speed marks, and the modified Grunwald display were used (Chapter 5). The 4-D flight director logic is detailed in Appendix D. The displays were based on a conventional B747 display and a tunnel-in-the-sky display that had been designed in earlier applications (Mulder, 1999; Amelink, 2002). It is important to note that for these displays the range of the speeds displayed on the speed tape was for the tunnel display significantly smaller (about 40 kts) than for the conventional display (about 140 kts). The tunnel width and height were fixed at 100 m. Tunnel sizes previously studied were in the order of 10-80 m for a Cessna Citation I aircraft (Mulder, 1999) and 450 ft (=137 m) for a full-scale B737 simulator (Grunwald, 1984). The compromise of 100 m allowed smooth 2-D path control for the B747 aircraft model for speeds between 250 and 140 kts. The bubble length was chosen as 500 m, because it allowed stable and smooth control of along-track position for the same speed range. It is also important to note that none of the displays showed a speed trend vector.

**Experiment Design and Procedure**

A full-factorial within-subjects design was applied, yielding 16 conditions (4x4). For each trajectory type the 2 mirrored trajectories were flown, resulting in 32 measurement runs (Appendix E). The subjects started with 12 training runs. The measurement runs were provided in a random order that was the same for all pilots. One run lasted approximately 2 minutes, of which the first and last 5 seconds were not used for analysis. Once the aircraft descended below the standard stabilization altitude of 500 ft (see Section 3.1.4) the data was not used either. This was to prevent that the landing procedure would influence the data. After each measurement run the pilot was asked to rate workload using the TLX scale, see Section 4.1. After the experiment pilots were asked to fill in a questionnaire. In the questionnaire the pilots were asked to what extent they agreed with propositions about the trajectory, the simulation, and the display formats.

**Aircraft and Weather Model**

The aircraft model used was a non-linear Boeing B747 model with the landing gear extended. In the simulations both wind and turbulence were present. The wind velocity was always equal to 19 kts and the direction was constant at 210° during each run. Light turbulence was applied based on white noise and a patchy filter.

**Dependent Measures**

Workload and performance are measured because a trajectory for which TDL is higher may result in more workload and lower performance, although humans tend to compensate for performance loss by making more effort. The following measures are considered.
6.1 EXPERIMENT 1

- The 2-D path-following performance can be expressed by the root mean square (RMS) of the aircraft 2-D position error $e_{2D} = \sqrt{e_{lat}^2 + e_v^2}$, with $e_{lat}$ the cross-track error and $e_v$ the vertical position error.

- For longitudinal performance the RMS of the longitudinal position error $e_{lon}$ is considered. It is defined as the difference between commanded along-track distance and aircraft along-track distance.

- Another indication of performance can be given by the number of times per minute that the aircraft exceeds the bubble boundaries per approach ($N_{bv}$).

- The pilot control activity, an indication of workload, is expressed by the standard deviation of the commanded elevator deflection $\delta_{e_{cmd}}$, commanded aileron deflection $\delta_{a_{cmd}}$ and throttle lever position $\delta_{T_{cmd}}$.

- Another indication considered for the pilot control activity is the total number of throttle lever deflections per minute. This is called here the throttle lever deflection count $N_{T_{cTot}}$. The throttle lever deflection count is considered because throttle inputs are often given in a discontinuous way, as opposed to the elevator and aileron commands which normally correspond more to a continuous signal. In addition to the total number of deflections, the number of throttle deflections per minute in several magnitude intervals (0-10 %, 10-20 %, 20-30 %, and more than 30 %) was used to express the control activity. These measures are indicated as $N_{T_{c0-10}}$, $N_{T_{c10-20}}$, $N_{T_{c20-30}}$, and $N_{T_{c>30}}$, respectively. They are used since pilots may use only a small portion of the throttle lever’s range; the differences between the displays or the trajectories may therefore be larger at smaller intervals.

- The pilot workload is analysed subjectively using the TLX workload rating.

- Another indication of pilot workload is the number of flap limit speed violations per minute per approach ($N_{sv}$), because it is a measure of how well the subjects were able to meet the objective of the secondary task.

6.1.3 Hypotheses

Trajectory Type
It is expected that a trajectory with deceleration results in more TDL than without deceleration, because the flight condition has to be changed more often. The deceleration in the curved section of trajectory type 3 is expected to result in more TDL than the deceleration on the straight section of trajectory type 1, because in trajectory type 3 the pilot has to carry out two manoeuvres at the same time as opposed to only one for trajectory type 1. However, it is expected that trajectory types 1 and 3 result in similar TDL, because trajectory type 1
has a shorter final approach segment than trajectory type 3. A shorter final approach segment will require a later merge onto the runway centerline, which is expected to give more time pressure with respect to stabilizing for landing. This is expected to increase TDL. Trajectory type 4 is expected to result in the lowest TDL, because the bubble moves with a constant indicated airspeed along the entire track and the intercept of the final approach course is at a distance comparable to those used in current practice. It is expected that TDL for trajectory type 2 is in between of the TDL for trajectory type 4 and trajectory type 1 and 3, because it has a short final section but no decelerations.

**PFD**

Based on the study from Chapter 5, the following hypotheses about the PFD can be stated. It is expected that the 4-D FD display yields the lowest path-following performance, because the trajectory nor the bubble is shown. For formulating hypotheses about the influence of the PFD on workload only the task of longitudinal position control is considered, because it is the main task that the 4-D displays have been designed to support. The pilot workload is for the FD display also expected to be low, because only the velocity loop has to be closed manually.

For the basic bubble display the 4-D path-following performance is expected to be higher because the 4-D position errors can be perceived directly. The workload is expected to be higher because of the same reason and because both the position and the velocity loop have to be closed manually. It is expected that the bubble with speed marks display will provide a similar path-following performance as the basic bubble display. The workload is expected to be lower because speed differences are made more explicit by the speed marks.

The modified Grunwald display is expected to result in better path-following performance than the FD display because of the visualization of the trajectory. The longitudinal path-following performance is expected to be lower than for the two bubble displays, because the bubble is not shown. Since the bubble displays and the modified Grunwald display all show the reference tunnel, the lateral and vertical path-following performance for these three displays is expected to be similar. The workload for the modified Grunwald display is expected to be lower because only the velocity loop has to be closed manually and additionally acceleration information is available.

### 6.1.4 Results

**Analysis of Variance**

A full-factorial analysis of variance (ANOVA) was conducted (Winer, Brown, & Michels, 1991; Stevens, 1999). The independent variables were the trajectory type (4 levels) and PFD (4 levels). The pilot was considered a random factor. Tables 6.3 and 6.4 and Figures 6.3 to 6.6 show the results. The figures on the left show the results clustered by the PFD; the figures on the right show the mean values over all PFDs.
Figure 6.3  The means and 95% confidence limits for the 2-D position error $e_{2D}$, the longitudinal position error $e_{lon}$, and the number of bubble limit violations per minute. The circles, boxes, crosses, and triangles represent the 4-D flight director display, the basic bubble display, the bubble with speed marks display, and the modified Grunwald display, respectively. In the figures on the right the means are shown over all displays with a diamond.
Figure 6.4 The means and 95% confidence limits for the standard deviation of $\delta_{e_{cmd}}$, $\delta_{a_{cmd}}$ and $\delta_{T_{cmd}}$. 
Figure 6.5  The means and 95% confidence limits for the numbers of thrust setting changes per minute for different magnitude intervals.
Figure 6.6 The means and 95% confidence limits for the TLX z-scores and the number of flap limit speed violations per minute.
Path-Following Performance

The trajectory type had a statistically significant effect on all performance measures \((e_{2D}: F_{3,15} = 21.517, p \leq 0.01; e_{\text{lon}}: F_{3,15} = 25.647, p \leq 0.01; N_{\text{bv}}: F_{3,15} = 11.675, p \leq 0.01)\). A Student-Newman-Keuls (SNK) test with \(\alpha = 0.05\) showed that the trajectories with a decelerated turn (trajectory type 3) resulted for all measures in the worst performance. More distinctions between the trajectory types could not be confirmed because of the different results for the different displays (causing the interactions). The effect of the PFD on the performance measures was also statistically significant \((e_{2D}: F_{3,15} = 65.097, p \leq 0.01; e_{\text{lon}}: F_{3,15} = 14.192, p \leq 0.01; N_{\text{bv}}: F_{3,15} = 5.698, p \leq 0.01)\). The SNK test showed that the 4-D flight director display yielded the worst performance for all measures, as expected, and that without the 4-D flight director display the modified Grunwald display yielded a higher 2-D position error than the bubble displays. For \(e_{\text{lon}}\) the modified Grunwald display unexpectedly provided the best performance.

Control Activity: Elevator and Aileron

Statistically significant effects were found for the control activity in terms of the elevator deflection \((\delta_{e_{\text{cmd}}}: \text{Trajectory Type}: F_{3,15} = 38.780, p \leq 0.01; \text{PFD}: F_{3,15} = 10.759, p \leq 0.01)\) and aileron deflection \((\delta_{a_{\text{cmd}}}: \text{Trajectory Type}: F_{3,15} = 38.780, p \leq 0.01; \text{PFD}: F_{3,15} = 10.759, p \leq 0.01)\). An SNK test showed that trajectory type 3 resulted in the highest elevator and aileron control activity. Trajectory type 2 and 4 resulted in the lowest values for \(\delta_{e_{\text{cmd}}}\). For the elevator, the FD display yielded the lowest control activity, as expected. For the aileron, the FD display yielded the highest control activity, which was most likely caused by the flight director being too sensitive in roll as commented by the subjects.

Control Activity: Throttle

Both independent variables had statistically significant effects on the throttle command \((\delta_{T_{\text{cmd}}}: \text{Trajectory Type}: F_{3,15} = 43.441, p \leq 0.01; \text{PFD}: F_{3,15} = 5.425, p \leq 0.01)\). Trajectory type 3 gave the highest throttle control activity; trajectory types 2 and 4 (those without

| Table 6.3 | Results of a full-factorial ANOVA of the main dependent measures. The indications ’**’, ’*’ and ’◦’ represent probability levels of \(p \leq 0.01\), \(0.01 < p \leq 0.05\), and \(0.05 < p \leq 0.10\) respectively. |
|-----------|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| main effects | \(e_{2D}\) | \(e_{\text{lon}}\) | \(\delta_{e_{\text{cmd}}}\) | \(\delta_{a_{\text{cmd}}}\) | \(\delta_{T_{\text{cmd}}}\) | \(N_{\text{bv}}\) | \(N_{sv}\) | TLX z-score |
| Trajectory Type | ** | ** | ** | ** | ** | ** | ** | ** |
| PFD | ** | ** | ** | ** | ** | ** | ** | ** |
| 2-way interactions | | | | | | | | |
| Trajectory Type x PFD | ** | ** | ** | * | * | ** | * | * |
Table 6.4  Results of a full-factorial ANOVA of the dependent measures regarding throttle lever counters. The indications ‘⋆⋆’, ‘⋆’ and ‘◦’ represent probability levels of $p \leq 0.01$, $0.01 < p \leq 0.05$, and $0.05 < p \leq 0.10$ respectively.

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a deceleration) the lowest. The throttle control activity for the FD display and modified Grunwald display was lower than for both bubble displays (SNK, $\alpha = 0.05$).

Both independent variables had statistically significant effects on the total throttle deflection count per minute ($N_{tc<10}$: Trajectory Type: $F_{3,15} = 10.117, p \leq 0.01$; PFD: $F_{3,15} = 5.131, p = 0.012$). For the total throttle lever deflection count, trajectory type 1 and 3 gave the highest control activity; trajectory type 2 and 4 the lowest (SNK, $\alpha = 0.05$). In the different magnitude intervals statistically significant differences due to the trajectory type were also found, where in all magnitude intervals trajectory type 2 and 4 were in the subset with the lowest control activity.

Post-hoc analysis of the total number of thrust inputs per minute (SNK, $\alpha = 0.05$) for the display revealed that the 4-D flight director display resulted in the lowest score. The flight director display also showed the lowest throttle count or was in the lowest throttle count subset for each of the separate magnitude intervals. The modified Grunwald display scored highest for the 10-20 % interval and was in the highest throttle count subset for the 20-30 % interval.

**TLX Workload Ratings**

A statistically significant effect was found for the trajectory type (Trajectory Type: $F_{3,15} = 22.760, p \leq 0.01$; PFD: $F_{3,15} = 2.357, p = 0.113$; Trajectory Type x PFD: $F_{9,45} = 2.419, p = 0.025$). An SNK test showed that trajectory type 3 yielded the highest workload, whereas no differences were found between the other trajectories. The SNK test also showed that the 4-D flight director display yielded higher ratings than the two bubble displays. The modified Grunwald resulted as expected in the lowest workload rating. The interaction is caused by less variation of the TLX ratings over the trajectories for the modified Grunwald display and the bubble with speed marks display.

**Flap Limit Speed Violations**

The number of flap speed violations per minute showed also a statistically significant effect
for the trajectory type (Trajectory Type: $F_{3,15} = 6.229, p \leq 0.01$). As expected, a trajectory with a deceleration resulted in a higher number of violations than a trajectory without deceleration: a post-hoc analysis for the trajectory showed that trajectory type 2 and 4 gave the lowest number of flap speed violations per minute, whereas trajectory type 1 and 3 gave the highest number of flap speed violations per minute.

**Pilot Questionnaire**

Most pilots found the trajectory with the long decelerated turn undesirable as it sometimes required a bank angle over 30 degrees. Some pilots also indicated that decelerations beyond the capabilities of the aircraft caused significant difficulty.

The flight director was generally found too sensitive in roll. It was also recommended to add turn anticipation to the flight director logic, which had not been included so far. Some pilots commented that they preferred using the official placard maximum flap speeds as opposed to the conservative maximum speeds that were prescribed.

Some pilots found it difficult to distinguish the bubble from the tunnel, because it was displayed in the same colour. They also indicated that the addition of the speed marks to the basic bubble display was only a small improvement.

**6.1.5 Concluding Remarks**

It was shown in the pilot experiment that the shape of the reference trajectory can influence the TDL of guiding the aircraft along a 4-D trajectory. Especially decelerations in the trajectory appear to increase TDL. No indication was found of the length of the final leg influencing performance or workload, which is in agreement with results from other experiments (Funabiki et al., 1999; Mulder & Mulder, 2005). It is necessary though to study the effects of trajectory shape on TDL in more detail, which will be done in the following two experiments (Sections 6.2 and 6.3).

Indications were found that visualisation of position and higher derivative information can decrease the TDL. No indications were found, however, that the addition of the speed marks reduces it.

In the experiment the bank angle exceeded 30 degrees a number of times. Also, path deviations up to about 0.5 nmi were registered, which could have resulted in conflicts with other traffic if it would have been present. A higher fidelity of the simulation environment was therefore desired.

**6.2 Experiment 2**

**6.2.1 Objectives**

The first experiment demonstrated the influence of the shape of the trajectory on TDL in a general sense. The first objective of the second experiment was to demonstrate the influence
of the shape of the reference trajectory on TDL in more detail by distinguishing between the different manoeuvres that have to be carried out. The effects of vertical path changes, speed changes, and track changes were studied, because they are the basis of the theory from Chapter 4. Similar to Experiment 1, the second objective was to determine if an advanced 4-D guidance display reduces the TDL. The experiment is conducted in a more realistic simulation environment with motion and traffic because in Experiment 1 high bank angles and high path deviations were on a number of occasions present.

6.2.2 Reference Trajectories

For each of the manoeuvres (vertical path change, speed change, and track change) several metrics were identified in Section 4.1. It is not known what the relation is between these metrics. For this reason, for each of the manoeuvres only one metric was selected to describe the TDL. For each of these metrics a value was selected that was expected to result in ‘low’ TDL and another value was selected that was expected to result in ‘high’ TDL. The TDL was denoted as TDLₚ, TDLₜ, and TDLₛ (for the vertical path, track, and speed changes, respectively). They all could have a value of either 0 or 1, corresponding to low or high TDL. This was implemented for the three different manoeuvres as follows.

**Track Changes**

There are four metrics shown in Table 4.2 that describe the TDL for track changes: \(N_T\), \((T_M/T)_{lat}\), \(\sum|\Delta \chi|\), and \(|\Omega|_{max}\). The number of track changes or turns \(N_T\) was selected, because increasing \(N_T\) increases all the other metrics, with the exception of \(|\Omega|_{max}\). This is not the case for any other metric. For TDLₜ = 0, the trajectory was generated to start at a convenient in-bound course so that only one turn is necessary to merge onto final approach. For TDLₜ = 1, the number of turns was set to 3, because this is also a typical value for standard or optimised arrival routes (see Appendix A and Chapter 7).

For all turns a minimum bank angle of 5 degrees and maximum bank angle of 30 degrees was used. This was to prevent very slow turns that may annoy the subjects and very fast turns that require uncomfortable accelerations.

**Speed Changes**

From the metrics relating to speed changes, \(\hat{E}_{max}\) was selected because Experiment 1 indicated that a commanded deceleration close to or larger than the maximum deceleration possible could result in the trajectory to be considered significantly more difficult. The number of speed changes applied in the trajectory was 3, because this is also a typical value for current approach procedures (Appendix A).

For constant-speed segments the commanded energy rate was always kept above the current aircraft minimum energy rate without speed brakes. For segments on which decelerations take place, the same was done for speed changes for TDLₛ = 0. A lower limit for the energy rate demand was used to prevent very slow energy conversions, which
would be annoying and require a lot of experiment time. This resulted in the following limits for $\hat{E}$: $0.6 \leq \hat{E} < 1$.

For TDL$_S = 1$ the segments on which decelerations take place were constructed so that $\hat{E} > 1$. However, the value of $\hat{E}_{abr}$ was always kept below 1. This means that these decelerations require the use of speed brakes.

The speed changes were always applied to bring the aircraft speed back from entry speed (220 kts) to final approach speed (148 kts). On the B747 though in-flight use of the speed brakes is generally not recommended at flap settings above 20 degrees. The lowest acceptable speed for flaps at 20 degrees is 180 kts, see Table 6.5. Therefore, the last deceleration was always scheduled from 180 kts to final approach speed without the need for speed brakes ($\hat{E} < 1$).

**Vertical Path Changes**

The parameter used to describe the TDL for vertical path changes was the number of vertical path changes $N_P$, because increasing $N_P$ also increases all the other metrics, with the exception of $(|a_z|_{max})_P$. This is not the case for any other metric.

For TDL$_P = 0$, the arrival trajectory was based on a 3-degrees continuous descent approach. Modifications to this trajectory were only made if this was necessary to comply with performance constraints (see Section 3.1.4). The flight path angle was limited at 0 and -3 degrees, so that the flight path was always descending and never became steeper than the standard 3-degrees descent. The number of vertical path changes was kept below 4. This value was chosen because when requiring fewer vertical path changes the scheduling software developed became unable to find feasible trajectories within reasonable time.

For TDL$_P = 1$ the flight path angle was limited at 0 and -4 degrees, because the trajectories that resulted from limiting the path angle at -3 degrees prescribed most flight path angle changes to be very small (e.g., in the order of less than 0.5 degree). The flight path angle was selected randomly for each segment separately. The number of vertical path changes was kept above 6, so that for TDL$_P = 1$ the flight path always had at least twice the number of vertical flight path changes as for TDL$_P = 0$.

**Generation of the Reference Trajectories**

It is assumed that the contributions from the three different manoeuvres to the total TDL are independent. In order to test the effects of the three manoeuvres on task demand load, it is then only necessary to generate trajectories of 4 different types. The following combinations were studied:

- Trajectory Type 1: TDL$_S = 0$, TDL$_T = 0$, TDL$_P = 0$
- Trajectory Type 2: TDL$_S = 1$, TDL$_T = 0$, TDL$_P = 0$
- Trajectory Type 3: TDL$_S = 1$, TDL$_T = 1$, TDL$_P = 0$
- Trajectory Type 4: TDL$_S = 1$, TDL$_T = 0$, TDL$_P = 1$
This list was determined by changing the TDL values one by one with respect to trajectory type 2. The reason for starting with this combination was that trajectories generated for $TDL_S = 0$ took more time; it was therefore desired to use $TDL_S = 0$ only once.

The scheduling software from Chapter 3 was modified so that trajectories could be generated for the four specified types. This was done by making modifications to a set of nominal trajectories. These nominal trajectories were based on a set of operationally measured traffic samples (Section 7.1.1). In total 6 different samples were used. For each sample trajectories were generated for the four specified types. In the measured data runways 18C and 27 were considered. Each sample used contained 9 aircraft. The trajectory flown by the subject was always selected so that runway 27 was used and that several aircraft were ahead. In the experiment three displays will be used (Section 6.2.3). For every combination of display and trajectory type two unique sets of trajectories are available. In this way two measurements can be conducted for every combination of display and trajectory type.

In generating the trajectories with the method described in Chapter 3, a maximum number of 23 segments was chosen instead of 9. This was needed to give enough room to vary the three values of TDL simultaneously. Also, the length of straight segments that prescribed a steady speed was fixed at 0.5 nmi to limit experiment time. This was found acceptable for recovery from a manoeuvre and initiation of the following manoeuvre. The segment length of curved segments needed to be limited to 15 nmi to prevent very long and time-consuming turns. Manoeuvres were also not allowed to be placed next to each other in order to allow stationary flight conditions between manoeuvres.

The trajectories that were generated are shown in Figure F.1 to F.24 in Appendix F. In these figures, the top figure shows a plan view of all trajectories, with the thick line representing the trajectory that is to be flown by the subject and the other lines representing the trajectories of the surrounding traffic. The middle figure shows the altitude, speed, and bank angle profile of the subject’s trajectory; the bottom figure shows the properties of the segments of this trajectory.

6.2.3 Method

Subjects and Instructions
Seven pilots (subjects F, G, E, H, I, J, and K from Table 6.1) participated in the experiment. The subjects were instructed that the primary task was to minimise the errors in lateral, vertical, and longitudinal or along-track position of the aircraft with respect to the tunnel and bubble. The secondary task was to adjust the flap settings so that the appropriate flap speed limits are not exceeded.

The flaps maximum speeds from Experiment 1 were replaced by the flap placard speeds (the official upper limits) for the B747-400. A list of the flap limit speeds (Table 6.5) was provided to the subjects.
Table 6.5  Flap limit speeds for Experiment 2.

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Apparatus
The experiment was carried out in the SIMONA Research Simulator (SRS), see Figure 6.7. The simulator is equipped with a six-degree-of-freedom motion system. The motion system can realise a maximum heave acceleration of $1.5g$ and a minimum of $0.02g$ and is designed for a bandwidth of up to 15 Hz. Only the left seat was used, which is equipped with an hydraulically-loaded control column, wheel, and pedal system. A light-weight outside world display system provides a collimated 180-degree horizontal by 40-degree vertical field of view. Three LCD projectors project high-resolution computer-generated images onto a rear projection screen, which are then displayed on the large shell around the shuttle. The shell functions as a mirror.

The aircraft instrumentation system consisted of the PFD, the ND, and a display showing engine and flap settings. The ND was based on the EFIS in the B747-400. It showed the surrounding traffic, a top view of the reference trajectory, and the middle of the bubble as a diamond moving along the reference trajectory (Figure 6.8).

The following controls were present: control column and wheel for pitch and roll control, rudder pedals for yaw control, trim up and trim down switches on the control column, throttle lever, flap lever, speed brake lever, and buttons to increase and decrease the range of the ND. The gear could be put in the down position by giving a voice command over the intercom to the experiment controller.

Independent Variables
The experiment had two independent variables: the trajectory type and PFD. Four trajectory types are used (Section 6.2.2). The same conventional primary flight display with flight director as in Experiment 1 was used. Three modifications to the flight director had been made though: the control laws for roll were changed, the sensitivity of the roll bar was reduced, and turn anticipation was added (Appendix D). A prediction time of 7 seconds was needed with this aircraft to allow smooth intercept of turns. The basic bubble display was
also used again, although in this experiment the bubble was displayed in black as opposed to in white. The same modified Grunwald display as in Experiment 1 was used.

**Experiment Design and Procedure**

A similar experiment design was employed as in Experiment 1. The number of experimental conditions here was 12 though (4 trajectory types and 3 displays). Each pilot flew each condition twice, using different trajectories. This resulted in 24 measurement runs (Appendix E). Each run lasted about 5-10 minutes. The total experiment time was about 7 hours.

Of each run the first 5 seconds were discarded. The data was discarded also after the aircraft descended below 500 ft to remove the influence of carrying out the landing. The run stopped as soon as the aircraft touched the ground, after which the subject was asked to fill in a TLX form.

The different trajectories and display formats were provided in a random order that was different for each subject. Before the measurements started, a couple of training runs were carried out. After the experiment, subjects were asked to fill in a questionnaire.

**Aircraft and Weather Model**

The aircraft model used was the same non-linear B747 model as in Experiment 1. However, this time the entire model including controls was validated qualitatively with a retired B747
pilot in the simulator. The gains for the control loading system in the simulator on the pitch and roll channels were selected so that an acceptable response was obtained.

The wind velocity and direction was constant during each run, but changed over the various runs. The direction varied between 210° and 250°, and the speed varied between 4.4 and 10.8 m/s. These directions and speeds correspond to the winds that were present in the original situations on which the trajectories were based (Section 7.1.1). There were not found any indications during the experiment that wind speed and direction affected performance or workload. Also, wind is particularly labour-intensive during the landing, which is a phase of flight not considered here. The turbulence level was tuned in the simulator to give light turbulence.

**Dependent Measures**

The path-following performance measures were the same as in Experiment 1. The lateral and vertical position error $e_{\text{lat}}$ and $e_v$ were considered separately though since this distinction was also made in the definition of the trajectories. For control activity three additional measures were considered:

- the number of times per minute that speed brakes were deployed per approach ($N_{\text{sbr}}$),
- the number of times per minute that the trim up switch was used per approach ($N_{\text{tr}_u}$), and
- the number of times per minute that the trim down switch was used per approach ($N_{\text{tr}_d}$).

**Figure 6.8** The navigation display, with 0 showing the middle of the bubble as a diamond moving along the reference trajectory.
6.2.4 Hypotheses

Trajectory Type
It was expected that changing TDL from 0 to 1 for one of the manoeuvres has the effect of increasing the workload and decreasing the path-following performance in the appropriate dimension (lateral for track changes, vertical for vertical path changes, and longitudinal for speed changes).

PFD
For the 4-D flight director display the hypothesis is the same as in Experiment 1: it is expected to yield relatively low 4-D path-following performance and low workload. The hypothesis for the bubble display is also the same as in Experiment 1: the 4-D path-following performance and workload are higher than with the 4-D flight director display. Because Experiment 1 indicated that with the modified Grunwald display 2-D path-following performance was exchanged for longitudinal performance, the longitudinal path-following performance with the modified Grunwald display is expected to be higher than for the bubble display. In the lateral and vertical dimension it is expected to be lower than for the bubble display. The workload is expected to be lower than for either of the other two displays (as in Experiment 1).

6.2.5 Results

Analysis of Variance
A full-factorial ANOVA was conducted with the trajectory type (4 levels) and the PFD (3 levels) as the independent variables. The pilot was included as a random factor. The results are shown in Tables 6.6 to 6.8 and Figures 6.9 to 6.14.

Path-Following Performance
For all performance measures a statistically significant effect was found only for the display ($e_{lat}$: $F_{2,12} = 23.044, p \leq 0.01$; $e_{v}$: $F_{2,12} = 49.689, p \leq 0.01$; $e_{lon}$: $F_{2,12} = 4.852, p = 0.029$; $N_{bn}$: $F_{2,12} = 4.043, p = 0.045$). An SNK test ($\alpha = 0.05$) did, however, show that trajectory type 1 gave higher vertical position errors than trajectory type 2 and 3, an unexpected result. It may be an indication that trajectory type 1 was so easy that subjects concentrated less on minimising errors. The conventional FD display resulted in the lowest performance according to all measures, as expected. The lateral position error was lowest for the bubble display, whereas the longitudinal position error was lowest for the modified Grunwald display.

Control Activity: Elevator and Aileron
The display had a statistically significant effect on the control activity in terms of the com-
Table 6.6  Results of an ANOVA of the dependent measures regarding performance and workload. The indications ‘⋆⋆’, ‘⋆’ and ‘◦’ represent probability levels of $p \leq 0.01$, $0.01 < p \leq 0.05$, and $0.05 < p \leq 0.10$ respectively.

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Table 6.7  Results of an ANOVA of dependent measures regarding control activity. The indications ‘⋆⋆’, ‘⋆’ and ‘◦’ represent probability levels of $p \leq 0.01$, $0.01 < p \leq 0.05$, and $0.05 < p \leq 0.10$ respectively.

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Table 6.8  Results of an ANOVA of the dependent measures regarding the number of throttle lever changes. The indications ‘⋆⋆’, ‘⋆’ and ‘◦’ represent probability levels of $p \leq 0.01$, $0.01 < p \leq 0.05$, and $0.05 < p \leq 0.10$ respectively.

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manded elevator deflection (PFD: $F_{2.12} = 27.113, p \leq 0.01$; Trajectory Type x PFD: $F_{6.36} = 4.467, p \leq 0.01$). The 2-way interaction is caused by differences when the displays are considered separately: for the FD display trajectory type 3 and 4 resulted in the highest control activity, for the modified Grunwald display trajectory type 1.

Statistically significant effects on the commanded aileron deflection were found for both the trajectory type and the display (Trajectory Type: $F_{3.18} = 35.323, p \leq 0.01$; PFD: $F_{2.12} = 30.076, p \leq 0.01$; Trajectory Type x PFD: $F_{6.36} = 4.104, p \leq 0.01$). The 2-way interaction is caused by the fact that for the modified Grunwald display the differences between the trajectory types become smaller.

For both elevator and aileron, the flight director display yielded the lowest control activity and the basic bubble display resulted in the highest control activity.

Control Activity: Throttle
The trajectory type and display both had statistically significant effects on the throttle lever position ($\delta_{\text{cmd}}$: Trajectory Type: $F_{3.18} = 7.407, p \leq 0.01$; PFD: $F_{2.12} = 7.484, p \leq 0.01$; Trajectory Type x PFD: $F_{6.36} = 3.560, p \leq 0.01$). Trajectory type 4 (the only trajectory type with TDL$^T$=1) resulted in higher throttle control activity than the other trajectory types (SNK, $\alpha = 0.05$). The 2-way interaction was caused by the size of the increase in control activity for trajectory type 4 being dependent on the display; the difference was most distinct for the FD display. The throttle control activity was lowest for the modified Grunwald display and highest for the bubble display.

For the total throttle deflection count per minute a statistically significant effect was only found for the display ($N_{\text{tc}_{\text{tot}}}$: PFD: $F_{2.12} = 7.303, p \leq 0.01$). Several statistically significant effects were found for the different intervals ($N_{\text{tc}_{10-20}}$: $F_{3.18} = 9.269, p \leq 0.01$; $N_{\text{tc}_{20-30}}$: $F_{3.18} = 3.177, p = 0.049$), where trajectory type 4 scored highest in both intervals. Although no interactions were found, for $N_{\text{tc}_{10-20}}$, $N_{\text{tc}_{20-30}}$, and $N_{\text{tc}_{>30}}$ it can be seen that the increase in number of changes for trajectory type 4 is most distinct for the FD display. For the PFD, the flight director display showed the lowest value of the total number of throttle lever changes (SNK, $\alpha = 0.05$). Several statistically significant effects were found for the different intervals ($N_{\text{tc}_{10-20}}$: $F_{2.12} = 8.412, p \leq 0.01$; $N_{\text{tc}_{20-30}}$: $F_{2.12} = 7.435, p \leq 0.01$; $N_{\text{tc}_{>30}}$: $F_{2.12} = 6.111, p = 0.015$). In the 0-10 % interval the modified Grunwald display resulted in the highest number of changes, whereas in the >30% interval the bubble display gave the highest number of changes. In the 10-20 % interval and the 20-30 % intervals the flight director display was confirmed to result in the lowest number of changes.

Control Activity: Speed Brakes and Trim
Trajectory type 2 resulted in the highest number of times speed brakes were deployed, but the increase was not statistically significant. However, further analyses showed that a num-
Figure 6.9 The means and 95% confidence limits for the position errors. The circles, boxes, and crosses represent the 4-D flight director display, the basic bubble display, and the modified Grunwald display, respectively. In the figures on the right the mean values over all displays are shown.
ber of measurements resulted in values outside the 95% confidence intervals, where 1 was located very far outside. With this measurement removed, the same SNK test showed that trajectory type 2 (with TDL_S = 1) did result in a higher number of times that speed brakes were deployed than trajectory type 1 (the only trajectory type with TDL_S = 0). This means that more control actions are needed, which may contribute to workload. The SNK test also showed that the modified Grunwald display resulted in the lowest number of times speed brakes were deployed and the bubble display in the highest.

For the number of times per minute the trim up switch was used, a statistically significant effect was found for the trajectory type (Trajectory Type: $F_{3,18} = 3.221$, $p = 0.047$; Trajectory Type x PFD: $F_{6,36} = 4.669$, $p \leq 0.01$). The SNK test showed that trajectory type 1 and 3 resulted in more trim up usage than trajectory type 2 and 4. The 2-way interaction is caused by the fact that for the FD display the trim up usage was for trajectory 1 lowest instead of highest. The SNK test also showed that the bubble display resulted in more usage of the trim up switch than the flight director display.

No statistically significant effects were found for the number of times the trim down switch was used, although the SNK test showed that with the bubble display the trim down switch was used more often than with the other displays. The differences are very small though.

**TLX Workload Ratings and Flap Limit Speed Violations**

For the TLX ratings, only the display resulted in statistically significant differences ($F_{2,12} = 11.410$, $p \leq 0.01$). However, further analyses showed that 1 measurement resulted in a value outside the 95% confidence interval. This was a rating given by the least experienced pilot that participated in this experiment. When this measurement is removed, the differences due to the trajectory type are statistically significant as well ($F_{3,18,114} = 3.311$, $p = 0.044$),
Figure 6.11  The means and 95% confidence limits for the standard deviation of $\delta_{\text{cmd}}$, $\delta_{\text{a,cmd}}$, and $\delta_{\text{T,cmd}}$.
Figure 6.12  The means and 95% confidence limits for the number of throttle lever changes.
Figure 6.13  The means and 95% confidence limits for the number of times speed brakes were deployed and the number of times trim switches were used.
Figure 6.14  The means and 95% confidence limits for the number of flap limit speed violations and the TLX $z$-scores.
indicated in Table 6.6 with the parenthesis. Post-hoc tests (SNK and Tukey) did not detect differences though. From the trend that can be observed in Figure 6.14(d), it seems that trajectory type 4 (the only trajectory type with $\text{TDL}_P = 1$) results in higher values of the TLX ratings. Lateral manoeuvres did not appear to be important for workload. Even though the number of turns became three times higher for trajectory type 3 when compared to the other trajectories and on a number of occasions the bank angle was between 25 and 30 degrees, the TLX ratings for trajectory type 3 were the lowest given. This may be different when more turns are used; however, it has not been shown that composing the trajectory of a larger number of turns is desired from an ATM point of view (e.g., Section 7.2).

For the number of flap limit speed violations, a statistically significant effect was only found for the display ($F_{2,12} = 9.566, p \leq 0.01$). Trajectory type 1 (the only trajectory type with $\text{TDL}_S = 0$) did result in the lowest number of speed limit violations, but this difference was not statistically significant.

An SNK test showed that the modified Grunwald display resulted in the lowest number of violations and the bubble display in the highest. Together with the lower usage of speed brakes and smaller throttle lever displacements this indicates speed and longitudinal position control was easier with the modified Grunwald display. The FD display, however, resulted in the lowest TLX ratings (SNK, $\alpha=0.05$). It is possible that the flight director system (which was improved based on the recommendations from Experiment 1) made lateral and vertical position control so much easier that it compensated for the more difficult longitudinal position control. It is also possible that pilots associate the flight director concept with low workload because they are less familiar with the new display systems. Although no interaction effects were found, the modified Grunwald display resulted in less variation of the TLX ratings over the trajectories.

**Pilot Questionnaire**

The aircraft model was considered realistic, although some subjects found the aircraft too sensitive, especially in roll.

With respect to the trajectories, it was recommended to remove trajectories that required leveling at low altitudes since this is also unusual in practice. Manual flight with the basic bubble display was generally found difficult and it was also commented that for some combinations of manoeuvres the workload for this display was too high.

Most subjects recommended the addition of a speed trend vector and indications of the limit speeds on the speed tape. The modified Grunwald display was found difficult to read: some pilots thought a better colour combination could be used, had difficulty in distinguishing between accelerations and decelerations, and found that at high speeds the tick marks were placed too far away.
6.2.6 Concluding Remarks

It was shown that the characteristics of the manoeuvres present in the trajectory can influence the TDL. For speed changes, it is concluded that faster energy reductions may increase the TDL of following the trajectory, although this could not be supported by statistically significant differences. For vertical path changes, it is concluded that more path changes and, therefore, a more diverse shape of the vertical profile can increase the TDL. Lateral manoeuvres did not seem to contribute to TDL.

Although the importance of manoeuvres for TDL has been shown, the importance of the different metrics identified in Section 4.1 that are used to describe the characteristics of these manoeuvres has not been studied. This is considered in the next experiment (Section 6.3).

In Experiment 2, like in Experiment 1, indications were found that visualisation of position, speed, and acceleration information can reduce the TDL of following the arrival trajectory. This relates especially to control of along-track position.

For a number of the dependent variables used in this experiment the differences due to changing the trajectory were not statistically significant. This may be related to the fact that the nature of the task, 4-D position control, is a new concept, which makes the differences between the trajectories harder to detect. It is therefore recommended to conduct further experiments with controlling speed instead of along-track position, which pilots are more familiar with.

6.3 Experiment 3

6.3.1 Objectives

The second experiment indicated that path and speed manoeuvres may affect TDL. It considered, however, the influence of only one metric for each manoeuvre. In Section 4.1 a larger number of metrics were identified. The first objective of the third experiment was, therefore, to address the influence of all metrics on TDL. Because Experiment 2 indicated that the longitudinal shape of the trajectory may be more important for TDL than the lateral shape, the third experiment considers only the longitudinal shape of the trajectory. This was done by comparing the subjects’ response to a number of commanded vertical flight path and speed manoeuvres. The manoeuvres used were the manoeuvres that were analysed off-line in Section 4.2 so that the results from the off-line analyses can be compared to the experimental results.

Similar to Experiment 1 and 2, the second objective was to determine if advanced guidance displays can help to decrease TDL. The pilot task is changed from 4-D position control to lateral and vertical position control and speed control (which pilots are more familiar with). This may make differences in TDL between trajectories more distinct. For the same reason, it was decided to study only the current display system and the advanced guidance display that was most analogous to the current display. The displays used in this
experiment were therefore the conventional flight director display and a tunnel-in-the-sky display which did not show a bubble or Grunwald prediction frame.

6.3.2 Method

Subjects and Instructions
Seven pilots (subjects L, C, M, E, J, A, and F from Table 6.1) participated in the experiment. The subjects were instructed to minimise the deviation from the reference flight path and reference speed.

Apparatus
The experiment was carried out in the SRS and the setup was the same as in Experiment 2.

Independent Variables
The experiment had two independent variables. The first independent variable was the trajectory type. Nine trajectory types were defined, accommodating the nine manoeuvres from Table 4.5. Each trajectory was a straight trajectory towards runway 27. In Experiment 2 not all the dependent variables did show a statistically significant influence of the trajectory type. Each trajectory type here is defined so that the pilot has to carry out the same manoeuvre twice. It was expected that carrying out two of the same manoeuvres as opposed to only one would make differences in the dependent variables more distinct.

The flight path angle at the beginning of the manoeuvre may influence the TDL of the manoeuvre. The trajectory was therefore generated so that the pilot was required to return to the original flight path angle after the first manoeuvre was ended. Although initial speed and altitude may also influence the TDL, speed and altitude were not brought back to their original values. This is not done because it is not part of a normal approach procedure either. This means that for speed manoeuvres the speed is simply changed two times. For vertical path manoeuvres, the first flight path angle change is made, the flight path angle is brought back to the original flight path angle, the second flight path angle change is made, and the flight path angle is again brought back to the original flight path angle. For combined vertical path and speed manoeuvres the procedure is the same as for the vertical path manoeuvres, only while the flight path angle is changed from the initial to the new value, the speed is reduced at the same time. The speed is kept constant when the flight path angle is brought back to the original flight path angle.

The trajectories all ended at interception of the ILS glide slope, because path changes are normally not carried out later. The trajectories were defined as a set of segments, where each segment prescribed a different flight path angle, a different speed, or both. The length of the segments was chosen so that with the scheduled speed 45 seconds were needed for each segment. This was found enough to allow the manoeuvres to be carried out separately.

The predicted values of the metrics for the nine trajectory types are shown in Table
Table 6.9  Predicted values of the metrics (listed vertically) for the nine trajectory types (listed horizontally). Each trajectory type is defined to carry out the corresponding manoeuvre from Table 4.5 twice. Some trajectories require manoeuvres to return to the original flight path angle in between the two manoeuvres.

| N_T | (T_M/T)_P | (Σ|Δθ|)_P, deg | (a_{z_{max}})_P, m/s² | (T_M/T)_S | (ΔV_C|_{max})_S, m/s | (|V_C|_{max})_S, m/s² | (T_M/T)_{PS} | (Σ|Δθ|)_{PS}, deg | (ΔV_C|_{max})_{PS}, m/s | (|V_C|_{max})_{PS}, m/s² | (a_{z_{max}})_{PS}, m/s² | E_{max} | N_M | (T_M/T)_{ion} |
|-----|----------|----------------|-----------------|----------|-----------------|----------------|----------|----------------|-----------------|----------------|----------------|----------------|-----------|----------|----------|
| 1   | 4        | 92.9           | 12              | 0.042    | 0               | 0              | 0        | 0               | 12              | 0               | 0              | 0.042         | 4         | 92.9     |
| 2   | 4        | 93.6           | 24              | 0.084    | 0               | 0              | 0        | 0               | 5.144           | 0               | 0              | 0.141         | 4         | 93.6     |
| 3   | 0        | 46.5           | 6               | 0.042    | 0               | 0              | 0        | 0               | 5.144           | 0               | 0              | 0.141         | 2         | 46.5     |
| 4   | 2        | 46.8           | 12              | 0.042    | 0               | 0              | 0        | 0               | 5.144           | 0               | 0              | 0.141         | 2         | 46.8     |
| 5   | 4        | 81.3           | 12              | 0.042    | 0               | 0              | 0        | 0               | 5.144           | 0               | 0              | 0.141         | 2         | 81.3     |
| 6   | 2        | 40.6           | 6               | 0.042    | 0               | 0              | 0        | 0               | 5.144           | 0               | 0              | 0.141         | 2         | 40.6     |
| 7   | 0        | 0              | 0               | 0.141    | 0               | 0              | 0        | 0               | 5.144           | 0               | 0              | 0.141         | 2         | 0        |
| 8   | 0        | 0              | 0               | 0.141    | 0               | 0              | 0        | 0               | 5.144           | 0               | 0              | 0.141         | 2         | 0        |
| 9   | 2        | 4              | 2               | 0.141    | 0               | 0              | 0        | 0               | 5.144           | 0               | 0              | 0.141         | 2         | 2        |

6.9. Only the metrics relating to longitudinal motion are shown because all metrics relating to lateral motion are equal to zero. The values shown are based on the values obtained for the linear aircraft and pilot model in the off-line analysis in Section 4.2. The values belonging to the condition V_{C0} = 140 kts and h_0 = 1,000 ft are used because this condition is closest to the trim condition of the aircraft model.

The flight time T (denoted in seconds) was extracted from the experimental data, because it was not specified in the off-line analysis. Since T is different for each trajectory, T_M/T had to be calculated for each trajectory separately. The ranges obtained were: 0 ≤ (T_M/T)_P ≤ 0.48, 0 ≤ (T_M/T)_S ≤ 0.40, 0 ≤ (T_M/T)_{PS} ≤ 0.54, and 0.34 ≤ (T_M/T)_{ion} ≤ 0.78.

In order to be able to do a second measurement for each experimental condition, 4 trajectories were generated for each trajectory type. These trajectories all contained the appropriate manoeuvres from Table 6.9. However, the manoeuvres were carried out at different altitudes by choosing different ILS interception altitudes. This was to prevent that pilots were flying exactly the same trajectory multiple times. Interception of the ILS glide
slopes normally take place between 2,000 and 3,000 ft. For this reason, the interception altitudes were chosen as

- 2,000 ft,
- 2,300 ft,
- 2,600 ft, and
- 3,000 ft.

The second independent variable was the PFD: the FD display and a tunnel-in-the-sky display were used. The FD display was the same as in Experiment 2; however, vertical flight path anticipation with 10 seconds of prediction time was added to the flight director logic (Appendix D). This was also done in the off-line analyses (Section 4.2). The speed bug showed in this experiment the reference speed instead of the bubble capture speed that was shown in Experiment 2. The tunnel-in-the-sky display was based on the basic bubble display from Experiment 2 but did not show a bubble; it did show a speed bug that pointed to the reference speed. Because of the subjects’ comments from Experiment 2, in this experiment both displays showed the flap limit speeds and a speed trend vector.

**Experiment Design and Procedure**
A similar design was employed as in the other experiments. The number of conditions was 18 (9 trajectory types and 2 displays). Each condition was flown twice. The interception altitudes were provided randomly for each trajectory type (Appendix E). Each run lasted about 3 minutes and the experiment took about 4 hours.

Of each run the first 5 seconds were discarded. The experimental run stopped when the aircraft started to intercept the ILS glide path, after which the subject was asked to fill in a TLX form.

The different trajectories and display formats were provided in a random order that was different for each subject. Before the measurements started, a couple of training runs were carried out to get familiar with the simulator system and the display formats. After the entire experiment was finished, subjects were asked to fill in a questionnaire.

**Aircraft and Weather Model**
The aircraft model used was the same non-linear B747 model as in Experiment 2. However, the control wheel stiffness was increased because the subjects commented in Experiment 2 that the aircraft was too sensitive in roll. Wind was not present and the turbulence was the same as in Experiment 2.

**Dependent Measures**
The following measures were used.
• For lateral and vertical performance the same measures were used as in Experiment 2 except for the measure $N_{bv}$, which is not applicable.

• The longitudinal path-following performance was expressed by the RMS of the speed error $e_{IAS}$. It is defined as the difference between the actual IAS and the reference IAS, because speed instead of longitudinal position control is considered.

• The pilot control activity and workload were expressed with the same measures as in Experiment 2 except for $N_{sv}$, which is not applicable.

6.3.3 Hypotheses

Trajectory Type
It was expected that changing the trajectory type affects path-following performance and workload. It is not known how much importance the pilot attributes to the different metrics. It therefore cannot be specified how the trajectory types compare to each other.

PFD
It is expected that lateral and vertical position errors with the tunnel display are smaller than with the flight director display. It is also expected that the speed errors for the tunnel display will be smaller because of the higher resolution of the speed tape on the tunnel display. It is expected that the view of the reference trajectory with the tunnel-in-the-sky display yields lower workload.

6.3.4 Results

The results from an ANOVA are shown below. As discussed in Section 6.3.2, each trajectory type was associated with different values for the metrics. It is therefore difficult to interpret the results of for example an SNK test if statistically significant differences are found with an ANOVA between the trajectory types. The effects of the trajectory type on performance and workload are therefore instead assessed in more detail by determining the suitability of each of the metrics for predicting TDL. This is done after discussing the ANOVA.

Analysis of Variance
A full-factorial ANOVA was conducted with the trajectory type (9 levels) and the display (2 levels) as the independent variables. The pilot was included as a random factor. The results are shown in Tables 6.10 to 6.12. The means and 95% confidence limits of the dependent variables are shown in Figures 6.15 to 6.19.

Path-Following Performance
Statistically significant differences between the trajectory types were found only for $e_v$ and
Table 6.10  Results of an ANOVA of the dependent measures regarding performance. The indications ‘⋆⋆’, ‘⋆’ and ‘◦’ represent probability levels of $p \leq 0.01$, $0.01 < p \leq 0.05$, and $0.05 < p \leq 0.10$ respectively.

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Table 6.11  Results of an ANOVA of dependent measures regarding control activity and workload. The indications ‘⋆⋆’, ‘⋆’ and ‘◦’ represent probability levels of $p \leq 0.01$, $0.01 < p \leq 0.05$, and $0.05 < p \leq 0.10$ respectively.

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<tr>
<td>2-way interactions</td>
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<tr>
<td>Trajectory Type x PFD</td>
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<td>o</td>
<td>o</td>
<td>⋆⋆</td>
</tr>
</tbody>
</table>

Table 6.12  Results of an ANOVA of the dependent measures regarding the number of throttle lever changes. The indications ‘⋆⋆’, ‘⋆’ and ‘◦’ represent probability levels of $p \leq 0.01$, $0.01 < p \leq 0.05$, and $0.05 < p \leq 0.10$ respectively.

<table>
<thead>
<tr>
<th></th>
<th>$N_{tc_{tost}}$</th>
<th>$N_{tc_{0-10}}$</th>
<th>$N_{tc_{10-20}}$</th>
<th>$N_{tc_{20-30}}$</th>
<th>$N_{tc_{&gt;30}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>main effects</td>
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<tr>
<td>Trajectory Type</td>
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<tr>
<td>PFD</td>
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<td>2-way interactions</td>
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<td>Trajectory Type x PFD</td>
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<td>⋆⋆</td>
</tr>
</tbody>
</table>
\( e_{IAS} \) (\( e_v \): Trajectory Type: \( F_{8,48} = 5.175, p \leq 0.01; \( e_v \): Trajectory Type x PFD: \( F_{8,48} = 5.386, p \leq 0.01; \) \( e_{IAS} \): Trajectory Type: \( F_{8,48} = 33.821, p \leq 0.01 \)). For the displays, the tunnel display resulted in statistically significant lower lateral position, vertical position, and speed error than the FD display, as expected (\( e_{lat} \): \( F_{1,6} = 17.313, p \leq 0.01; e_v \): \( F_{1,6} = 21.395, p \leq 0.01; e_{IAS} \): \( F_{1,6} = 7.111, p = 0.037 \)).

Control Activity: Elevator and Aileron
Statistically significant differences were found in the control activity in terms of the elevator deflection due to both independent variables (Trajectory Type: \( F_{8,48} = 26.698, p \leq 0.01; \) PFD: \( F_{1,6} = 33.003, p \leq 0.01 \)). For the commanded aileron deflection only the display resulted in statistically significant differences (\( F_{1,6} = 101.803, p \leq 0.01 \)); the effect of the trajectory type was borderline statistically significant (\( F_{8,48} = 2.079, p = 0.057 \)). The elevator and aileron control activity were higher for the tunnel display.

Control Activity: Throttle
The trajectory type and display both showed statistically significant effects on the throttle lever position (\( \delta T_{cmd} \): Trajectory Type: \( F_{8,48} = 91.758, p \leq 0.01; \) PFD: \( F_{1,6} = 16.662, p \leq 0.01 \); Trajectory Type x PFD: \( F_{8,48} = 4.139, p \leq 0.01 \)). The throttle control activity was generally higher for the tunnel display. For some trajectories the control activity was lower for the tunnel display. This causes the interaction effect. In general, the variation over the trajectories was larger with the FD display.

The differences in the total throttle deflection count per minute were only statistically significant with respect to the trajectory type (\( N_{tc_{tot}} \): \( F_{8,48} = 30.216, p \leq 0.01 \)). Statistically significant effects were found in all magnitude intervals (\( N_{tc_{0-10}} \): \( F_{8,48} = 26.091, p \leq 0.01 \); \( N_{tc_{10-20}} \): \( F_{8,48} = 4.829, p \leq 0.01 \); \( N_{tc_{20-30}} \): \( F_{8,48} = 4.520, p \leq 0.01 \); \( N_{tc_{>30}} \): \( F_{8,48} = 6.281, p \leq 0.01 \)). Statistically significant interactions between trajectory type and PFD were found in the 20-30 % and larger than 30 % intervals, caused by a larger variation over the trajectory for the tunnel display.

For the display, several statistically significant effects were found (\( N_{tc_{10-20}} \): \( F_{1,6} = 7.267, p = 0.036 \); \( N_{tc_{20-30}} \): \( F_{1,6} = 5.982, p = 0.05 \); \( N_{tc_{>30}} \): \( F_{1,6} = 13.885, p \leq 0.01 \)). The control activity was generally higher for the tunnel display, although for several trajectories the tunnel display resulted in lower throttle deflection count.

Control Activity: Speed Brakes and Trim
Differences in the number of times speed brakes were deployed were statistically significant with respect to only the trajectory type (\( F_{8,48} = 33.389, p \leq 0.01 \)). Also for the number of times per minute the trim up switch was used, a statistically significant effect was found only for the trajectory type (\( F_{8,48} = 16.429, p \leq 0.01 \)).
Figure 6.15  The means and 95% confidence limits for the position and speed errors. The circles and boxes represent the flight director display and the tunnel display, respectively. In the figures on the right the mean values over all displays are shown.
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Figure 6.16 The means and 95% confidence limits for the standard deviation of $\delta_{e\text{cmd}}$, $\delta_{a\text{cmd}}$ and $\delta_{T\text{cmd}}$. 
Figure 6.17  The means and 95% confidence limits for the number of times speed brakes were deployed and trim switches were used.
Figure 6.18 The means and 95% confidence limits for the number of throttle lever changes.
TLX Workload Ratings

Statistically significant differences between the trajectory types were only found when the tunnel-in-the-sky display was considered separately ($F_{8,48} = 2.353, p = 0.032$). For the display, a statistically significant effect was found when all trajectory types were considered (PFD: $F_{1,6} = 9.897, p = 0.02$; Trajectory Type x PFD: $F_{8,48} = 3.060, p \leq 0.01$). The tunnel display generally resulted in higher workload ratings than the flight director display. For trajectory types 1 and 6 the tunnel display resulted in a lower TLX rating, see Figure 6.19(a). This causes the interaction. For these trajectories, only a path change of -3 degrees is applied. With the exception of trajectory type 2, all the other trajectory types require speed changes. It is possible that workload was higher with the tunnel display for the trajectories with speed changes because of the different speed scales on the displays. In general, the variation of the TLX ratings over the trajectories was larger for the tunnel display.

Regression Analysis

The effects of the values of the metrics on performance and workload are assessed by carrying out a linear regression analysis for all dependent measures. A commonly used procedure called the stepwise selection procedure was used (Stevens, 1999). This procedure tries to make a linear model of a given dependent variable by adding metrics to and removing metrics from the model.

The results are shown in Tables 6.13, 6.14, and 6.15 where it is indicated which of the metrics were found to be of enough importance for entering the linear regression function for each of the dependent variables. In the theory discussed in Section 4.1 an increase in the value of a metric is associated with an increase in TDL. It is therefore only meaningful to consider metrics for which an increase corresponds to an increase in the dependent variable. These entries are printed in boldface. The values of $R^2$ shown in the tables are a measure
Table 6.13  Results of a linear regression analysis (1). The metrics from Table 4.2 relating to longitudinal motion are listed vertically and a number of the dependent measures are listed horizontally. The other dependent measures are shown horizontally in Tables 6.14 and 6.15. The entries show the number of the step (in parenthesis) at which the metric indicated was added. The value listed after the number of the step shows the value of $R^2$ obtained.

<table>
<thead>
<tr>
<th></th>
<th>$e_{lat}$</th>
<th>$e_v$</th>
<th>$e_{IAS}$</th>
<th>$\delta_{\text{cmd}}$</th>
<th>$\delta_{n_{cmd}}$</th>
<th>$\delta_{T_{cmd}}$</th>
<th>$N_{\text{shr}}$</th>
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<tbody>
<tr>
<td>$N_P$</td>
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<td>$(T_M/T)_P$</td>
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<td>$E_{\text{max}}$</td>
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<td>$N_M$</td>
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<td>$(T_M/T)_{Ion}$</td>
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of the amount of variance in the dependent variable that the model accounts for.

For the TLX $z$-score no metrics were added to the regression model. In order to be able to study if the metrics can be used to predict very specific aspects of TDL, the TLX $z$-scores relating to only mental (TLX$_m$), physical (TLX$_ph$), temporal (TLX$_t$), performance (TLX$_p$), effort (TLX$_e$), and frustration (TLX$_f$) aspects have been added to the list of dependent variables.

The metrics that were included and for which an increase is associated with an increase in TDL are summarized in Table 6.16. The other metrics were found to be of less importance for describing TDL: $N_P$, $(T_M/T)_P$, $N_S$, $(|\Delta V_C|_{\text{max}})_S$, $N_{PS}$, $(T_M/T)_{PS}$, $(|\Delta V_C|_{\text{max}})_{PS}$, and $N_M$.

There are no clear acceptable values for $R^2$; however, in data describing human behaviour an $R^2$ value of 0.70 is generally considered high (Myers, 1986). It can therefore be concluded that the metric $(|a_z|_{\text{max}})_P$ is particularly effective in predicting STD $\delta_{T_{cmd}}$ and $E_{\text{max}}$ in predicting $N_{\text{shr}}$. The measured values of STD $\delta_{T_{cmd}}$ and the prediction errors
Table 6.14  Results of a linear regression analysis (2). For the metric $(\Sigma|\Delta \gamma|)_{PS}$ two values are given, which indicates that the metric was first added (in step 1) and later removed (in step 6).

<table>
<thead>
<tr>
<th>$N_{tr_u}$</th>
<th>$N_{tr_d}$</th>
<th>$N_{tc_{tot}}$</th>
<th>$N_{tc_{0-10}}$</th>
<th>$N_{tc_{10-20}}$</th>
<th>$N_{tc_{20-30}}$</th>
<th>$N_{tc_{&gt;30}}$</th>
</tr>
</thead>
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<tr>
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<tr>
<td>$(T_M/T)_P$</td>
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<tr>
<td>$(\Sigma</td>
<td>\Delta \gamma</td>
<td>)_P$</td>
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<td>·</td>
<td>·</td>
</tr>
<tr>
<td>$(a_{z_{max}})_P$</td>
<td>(1) 0.202</td>
<td>(2) 0.309</td>
<td>(2) 0.267</td>
<td>·</td>
<td>·</td>
<td></td>
</tr>
<tr>
<td>$N_S$</td>
<td>·</td>
<td>·</td>
<td>·</td>
<td>·</td>
<td>·</td>
<td></td>
</tr>
<tr>
<td>$(T_M/T)_S$</td>
<td>·</td>
<td>·</td>
<td>·</td>
<td>·</td>
<td>·</td>
<td>(4) 0.117</td>
</tr>
<tr>
<td>$(</td>
<td>V_C</td>
<td>_{max})_S$</td>
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<tr>
<td>$(\Sigma</td>
<td>\Delta \gamma</td>
<td>)_S$</td>
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<tr>
<td>$N_{PS}$</td>
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</tr>
<tr>
<td>$(T_M/T)_{PS}$</td>
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<td>·</td>
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</tr>
<tr>
<td>$(\Sigma</td>
<td>\Delta \gamma</td>
<td>)_{PS}$</td>
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<td>·</td>
<td>·</td>
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</tr>
<tr>
<td>$(</td>
<td>V_C</td>
<td><em>{max})</em>{PS}$</td>
<td>·</td>
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<td>·</td>
</tr>
<tr>
<td>$(a_{z_{max}})_{PS}$</td>
<td>·</td>
<td>·</td>
<td>·</td>
<td>·</td>
<td>·</td>
<td>(5) 0.133</td>
</tr>
<tr>
<td>$\hat{E}_{max}$</td>
<td>(2) 0.040</td>
<td>(1) 0.229</td>
<td>(1) 0.204</td>
<td>·</td>
<td>·</td>
<td></td>
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<tr>
<td>$N_M$</td>
<td>·</td>
<td>·</td>
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</tr>
<tr>
<td>$(T_M/T)_{Ion}$</td>
<td>·</td>
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</tr>
</tbody>
</table>

Made by predicting STD $\delta T_{cmd}$ based on $(|a_{z_{max}}|)_P$ only are shown in Figure 6.20. The measured values of $N_{sbr}$ and the prediction errors made by predicting $N_{sbr}$ based on $\hat{E}_{max}$ only are shown in Figure 6.21. A clear trend of STD $\delta T_{cmd}$ increasing with $(|a_{z_{max}}|)_P$ and $N_{sbr}$ increasing with $\hat{E}_{max}$ can be observed. However, predicting values seems to require a much more extensive function than a linear function of just one metric.
### Table 6.15  Results of a linear regression analysis (3).

<table>
<thead>
<tr>
<th></th>
<th>TLX</th>
<th>TLX&lt;sub&gt;mf&lt;/sub&gt;</th>
<th>TLX&lt;sub&gt;p&lt;/sub&gt;</th>
<th>TLX&lt;sub&gt;t&lt;/sub&gt;</th>
<th>TLX&lt;sub&gt;pe&lt;/sub&gt;</th>
<th>TLX&lt;sub&gt;e&lt;/sub&gt;</th>
<th>TLX&lt;sub&gt;f&lt;/sub&gt;</th>
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</thead>
<tbody>
<tr>
<td>( N_P )</td>
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<td>(1) 0.019</td>
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<tr>
<td>( (T_M/T)_P )</td>
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<tr>
<td>( (\Sigma</td>
<td>\Delta\gamma</td>
<td>)_P )</td>
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<tr>
<td>( (\alpha_{max})_P )</td>
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<tr>
<td>( N_S )</td>
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<tr>
<td>( (T_M/T)_S )</td>
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<tr>
<td>( (</td>
<td>\Delta V_{C</td>
<td>\max}</td>
<td>)_S )</td>
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<td>V_{C</td>
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<td>( N_{PS} )</td>
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<td>( (T_M/T)_{PS} )</td>
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<td>)_{PS} )</td>
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<td>( (</td>
<td>\Delta V_{C</td>
<td>\max}</td>
<td>)_{PS} )</td>
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<td>( (</td>
<td>V_{C</td>
<td>\max}</td>
<td>)_{PS} )</td>
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<tr>
<td>( (\alpha_{max})_{PS} )</td>
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<tr>
<td>( \hat{E}_{\text{max}} )</td>
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<td></td>
<td></td>
<td>(1) 0.040</td>
<td>(1) 0.032</td>
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<tr>
<td>( N_M )</td>
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<td>( (T_M/T)_{lon} )</td>
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</tbody>
</table>

### Pilot Questionnaire

Most pilots considered the aircraft characteristics realistic to very realistic and found the sensitivity of the control column and wheel appropriate. The speed changes during a descent were generally found to make the task most difficult. For the flight director display, some pilots commented that they missed the annunciation of the flight control modes in order to allow them to understand what the flight director was trying to accomplish. Some pilots also indicated that the tunnel display reduced workload, mainly because of the visualisation of the reference trajectory.
Table 6.16  Metrics used for linear models of the dependent variables.

<table>
<thead>
<tr>
<th>Nr</th>
<th>Metric</th>
<th>Included for dependent variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>((\Sigma</td>
<td>\Delta\gamma</td>
</tr>
<tr>
<td>4</td>
<td>((a_{z_{max}})_P)</td>
<td>(\delta_{T_{cmd}}, N_{trd}, N_{tc&gt;10}, N_{tc=10})</td>
</tr>
<tr>
<td>6</td>
<td>((T_M/T)_S)</td>
<td>(N_{sbr})</td>
</tr>
<tr>
<td>8</td>
<td>(\left(\frac{</td>
<td>V_C</td>
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<tr>
<td>11</td>
<td>((\Sigma</td>
<td>\Delta\gamma</td>
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<tr>
<td>13</td>
<td>(\left(\frac{</td>
<td>V_C</td>
</tr>
<tr>
<td>14</td>
<td>((a_{z_{max}})_{PS})</td>
<td>(\delta_{e_{cmd}})</td>
</tr>
<tr>
<td>19</td>
<td>(\dot{E}_{max})</td>
<td>(e_{IAS}, N_{sbr}, TLX_{ph})</td>
</tr>
<tr>
<td>21</td>
<td>((T_M/T)_{lon})</td>
<td>(e_{IAS})</td>
</tr>
</tbody>
</table>

Figure 6.20  Prediction of STD \(\delta_{T_{cmd}}\) with \((|a_z|_{max})_P\) based on linear regression.

(a) measured values of STD \(\delta_{T_{cmd}}\)  
(b) errors in predicting STD \(\delta_{T_{cmd}}\)
6.3.5 Concluding Remarks

From the 17 metrics that were considered, 9 metrics were found to increase the dependent measures. An increase in the metric $\hat{E}_{\text{max}}$, which describes the commanded energy reductions in the trajectory in relation to the aircraft’s capabilities, was found to increase speed error, the number of times speed brakes were deployed, and TLX physical workload rating. The metric is therefore concluded to be important for describing TDL. From the four metrics relating to numbers of manoeuvres, none of the metrics seemed to influence TDL. The metric $(T_M/T)_{S}$ was included in the regression analysis for predicting $N_{sbr}$. Since the total longitudinal manoeuvre time $(T_M/T)_{lon}$ was also included in the regression analysis, it may not be necessary to make a distinction between manoeuvre times for different manoeuvres. This could potentially be a way of reducing the number of metrics.

Higher values for both metrics relating to the summation of the flight path angle changes $(\Sigma|\Delta\gamma|)_P$ and $(\Sigma|\Delta\gamma|)_PS$ are concluded to increase TDL (indicated by larger vertical position errors and higher workload). It is therefore considered worth studying these metrics further. Higher values for the metrics related to vertical acceleration $(|a_z|_{\text{max}})_P$ and $(|a_z|_{\text{max}})_PS$ and to the longitudinal acceleration $(|\dot{V}_C|_{\text{max}})_S$ and $(|\dot{V}_C|_{\text{max}})_PS$ resulted in more control activity. They are therefore concluded to increase TDL also. On the other hand, none of the metrics relating to the largest change in speed were included in the regression analysis for any of the dependent variables. The size of the change in speed therefore does not seem to be an important factor in describing TDL.

The tunnel-in-the-sky display allows the trajectories to be followed more accurately. It also seemed to reduce the need for additional information in order to understand the shape of the reference trajectory. These may be important characteristics for allowing the flight crew to safely follow flexible arrival trajectories and for reducing task demand load. The tunnel-in-sky-display can, however, result in more control actions.
6.4 Conclusions

The three experiments that were carried out confirmed that the shape of the reference trajectory can influence the TDL of guiding the aircraft manually along a 4-D arrival trajectory. Considering the three experiments separately yields the following more detailed conclusions.

Experiment 1 had a preliminary character and was carried out in a fixed-base simulation laboratory. It was found that especially decelerations in the trajectory can increase TDL.

Experiment 2 considered the influence of the presence of vertical path changes, speed changes, and track changes. The reason for this was that the theory in Chapter 4 was based on it. In Experiment 1 the bank angle exceeded 30 degrees on a number of occasions and large path deviations were seen. Experiment 2 was for that reason carried out in a high-fidelity moving-base simulator with traffic. In Experiment 2 the bank angle only very rarely exceeded 30 degrees and position errors became much smaller. It appeared that TDL was mainly influenced by the longitudinal shape of the trajectory. Changing the lateral shape of the trajectory did not seem to influence TDL. It was shown that more vertical path changes and, therefore, a more diverse shape of the vertical profile can increase the TDL.

Experiment 3 considered the influence of the individual metrics from Chapter 4. The experiment was also carried out on a moving-base simulator. Because it was suspected that the unfamiliar task of 4-D position control made differences due to the trajectory shape harder to detect, Experiment 3 considered speed control instead of along-track position control. Because Experiment 2 indicated the larger influence of the longitudinal shape of the trajectory on TDL as compared to the lateral shape, only the longitudinal metrics were considered. The most important metrics were found to be the commanded energy reductions in the trajectory in relation to the aircraft’s capability of reducing energy, the ratio between time necessary to carry out manoeuvres and the time available, the summation of the sizes of the flight path angle changes that have to be carried out, the maximum vertical acceleration required, and the maximum longitudinal acceleration required. The values of these metrics are calculated in the next chapter for (semi-)optimised arrival trajectories in order to determine if the TDL for pilots is increased.

In all experiments indications were found that the guidance displays discussed in Chapter 5 that give information related to reference position, reference speed, and acceleration can reduce the TDL of following the trajectory. This relates especially to control of along-track position. These displays may, however, result in more control actions. Further display or control augmentation may therefore be required.
ANALYSIS OF FLEXIBLE ARRIVAL TRAJECTORIES

An off-line analysis is carried out with the first objective of quantifying the benefits of allowing flexibility in the shape of the arrival trajectory, in accordance with the objective formulated in Chapter 1. It is recalled that flexibility refers here to planning the optimal trajectory for the current situation. The arrival trajectories are optimised with the multi-objective trajectory optimisation method from Chapter 3. Since increased TDL for pilots may classify certain approaches as undesirable or may require modifications to existing aircraft instruments (Chapter 1), the second objective is to determine if flexible trajectories affect pilot TDL. The metrics identified in Chapter 4 and validated experimentally in Chapter 6 are used to do this. Another concern of allowing flexibility in the arrival trajectory is that airspace complexity and therefore TDL for air traffic controllers may increase (Chapter 1). The third objective, therefore, is to determine if flexibility results in airspace complexity becoming higher. Airspace complexity is estimated with a number of metrics mainly from literature. The analysis is done for Amsterdam Airport Schiphol in The Netherlands.

Section 7.1 starts with describing the setup of the analysis. Subsequently, Section 7.2 presents the results.\footnote{The results are also discussed in (Vormer, Mulder, van Paassen, & Mulder, 2005).}

7.1 Method

7.1.1 Assumptions

In order to be able to quantify any potential benefits of flexible arrival trajectories, the first situation that has to be considered is the way approaches are currently carried out. For this
reason, use is made of recorded radar data from Schiphol Airport made available by Air Traffic Control the Netherlands. The data concern all inbound IFR flights that arrived at Schiphol Airport on one particular day (12 September 1997). The main runways used for landing in the airport configuration at that time were the two runways 18C and 27. The meter fixes Artip (ATP), Sugol (SUG), and River (RIV) were used, see Appendix A. The data concerns the flights from entry into the terminal area until landing and specifies for all flights the aircraft type, the runway (RWY) at which the aircraft landed, the meter fix (MF) that was used, the flight level (FL) at which the meter fix was crossed, the time at which the meter fix was crossed, and the time at which the aircraft landed. From these data a traffic sample is extracted, containing 15 flights with their landing times spanning a time interval of 15-20 minutes. This is a typical time horizon in the final phase of route planning for arrival traffic. The data for the traffic sample that was used is shown in Table 7.1. The sample was selected for a time period when traffic demand was high. It is assumed to be representative of current demand at this airport. The wind direction and speed at the time the sample was taken were 240° and 9.7 m/s, respectively (data obtained from the Royal Netherlands Meteorological Institute). They are used in the analysis and assumed to be representative of the atmospheric conditions near this airport.

In the genetic algorithm, 15 flights are created. For each flight, the genetic algorithm uses the aircraft type that was recorded to determine which data to use from BADA. For each
flight, \((x_{mf}, y_{mf})\) was set to the position of the meter fix that was recorded. The nominal arrival time \(NTA\) for each flight is set to the landing time that was recorded. The other data were incorporated differently in different situations, as will be discussed in Section 7.1.3.

### 7.1.2 Selection of Aspiration Levels

The way of looking for solutions was brought into conformity with the approach of SDM (Section 3.1.3). An aspiration level \(\rho\) needs to be defined that prescribes a minimum performance level that is to be met for each of the objectives as they were defined in Section 3.1.2. Aspiration levels are selected below for each of the objectives individually.

#### Throughput Based on 2007 Target

Schiphol is attempting to increase its capacity to approximately 600,000 movements in the year 2007. This translates into a desired continuous capacity of 125 movements hourly. For inbound peaks (2+1 configuration) this, in effect, results in a desired capacity of 90 arrivals/hr (Werkgroep OGL 2003+, 2001). This value is selected as the aspiration level for this objective and denoted as \(\rho_T\). It is, however, not sure if the system studied even in theory can operate at that level.

#### Maximum Deviation from a Three-Degree Decelerated Approach of 1000 ft

The deviation from a three-degree decelerated approach was taken into account by considering the maximum deviation \(\Delta h\) from a three-degree descent path and the maximum deviation \(\Delta V\) from a speed profile in such a procedure. The aspiration level for \(\Delta h\) was set to 1000 ft and is denoted as \(\rho_h\). The reason for this was that it is the standard separation distance currently applied in radar-controlled airspace. Controllers generally issue speed changes in the order of 20-40 kts. An aspiration level \(\rho_V\) of 20 kts was therefore started with.

#### Noise Load on Community Equal to Current Load

Noise load on community \(L\) was defined as a combination of time spent and altitude flown over populated areas (Section 3.1.2). The value of \(L\) was calculated for current arrival trajectories. The aspiration level for area load \((\rho_L)\) was set to this value, because other reference values are not available. In this way it is required that \(L\) does not increase when flexible arrival trajectories are used.

### 7.1.3 Definition of Cases

The transition from the fixed trajectories used currently towards flexible trajectories is studied in subsequent steps (Table 7.2). This is done through first adding operational constraints to the constraints that were already taken into account, obtaining a model of current operations. Then, the constraints are removed stepwise, allowing optimisation of the trajectories
to some extent. This allows to quantify the effect of each ‘step’ and to determine if it is worthwhile to proceed in this direction. The different steps that are studied are:

- optimising the landing sequences and time schedules (in order to determine if improvements can be made without changing the shape of the arrival trajectories),
- optimising the altitude and speed profiles,
- optimising the final intercept distance,
- optimising the lateral profiles when allowing direct trajectories from the meter fix to the final intercept point, and
- optimising the lateral profiles without imposing any route structure.

These steps have been selected because they are expected to yield ATM benefits (Chapter 1). Allowing direct trajectories is studied as a separate case because it may increase performance in terms of throughput (Vormer et al., 2001).

Case CUR represents the operations as recorded. The standard procedures shown in Figure A.1 were used to define the initial trajectories. The trajectories are coded in segments as was shown in Figure 3.10. Standard speed profiles made available by the National Aerospace Laboratory (also indicated in Figure A.1) were used to define the segment lengths and initial accelerations. A standard speed profile is considered as a guideline by controllers and is normally tuned to the situation. The genetic algorithm was, like the controllers, allowed to make modifications to the speed profile in order to obtain feasible trajectories for the situation. This is done by changing the accelerations (Section 3.2.5). The altitudes at the boundary of the terminal area as they were recorded in the traffic sample were used. A deviation of 500 ft was selected as the maximum allowed difference between scheduled and recorded altitude at the meter fix. In the turns in the traffic pattern the altitude was kept constant to obtain a stepwise descent with level flight segments that is characteristic for current operations. On the other segments the flight path angle is kept constant. This was achieved by selecting the values of $T$, $R$, $L$, $\gamma$, and $a$ accordingly. Using the standard procedures results in the final intercept point not being placed closer to the runway threshold than 6 nmi and not further away than 11 nmi. In addition, the runway assignments from the recorded data are used. The values of $RA$ are thus prescribed. This is indicated in the table also with ‘Conventional’, since these assignments correspond to current operations.

Because current operations are modeled, the recorded landing times are used and not the times that result in minimum wake vortex separation. The genetic algorithm was allowed to choose the landing times with a maximum deviation $d$ of +/- 0.5 minute from the recorded landing times. This was the accuracy with which the times in the recorded data were logged. This corresponds to looking for the best solution possible with the recorded times. The recorded meter fix times were met by decreasing the length of the down wind segment (segment 5) and increasing/decreasing the length of the final leg segments (segments 1 and
2). For the downwind leg a minimum length of 3.0 nmi was used. For the final intercept distance the limits found in the standard procedures of 6 and 11 nmi mentioned above were used. It was found that the same requirement of +/- 0.5 minute for meeting the recorded meter fix time could not be met. The reason for this is most likely that the planning algorithm starts with planning in space and time at the threshold. Differences between the model and the real situation (e.g., different atmospheric conditions or different trajectories used by controllers) may thus be noticed as deviations from the recorded meter fix times. A meter fix time deviation up to +/- 5.0 min was necessary to accommodate these differences. This does mean that the reliability of the results decreases at farther distances from the runway.

Case CUR IDEAL considers the same situation as Case CUR, but now in an idealized setting. The runway assignments and landing times are optimised because it may increase ATM performance. This is done by allowing a wider range of solutions than in Case CUR. It is assumed that optimising runway assignments and landing times here results in solutions that can also be executed during real operation. This should result in the best solutions for current operations, given the recorded meter fix times. The results for flexible arrival trajectories discussed below are compared with the results for Case CUR IDEAL and not for Case CUR. This is to assure a more fair assessment of potential benefits. Comparing with Case CUR is not considered fair since Case CUR may include reasons not included in the other cases for disallowing certain solutions. These reasons could be related to weather, traffic outside the terminal area, and the flight crew’s inability to meet the assigned times. Their direct effect on runway assignments and landing times is removed by optimising runway assignments and landing times. The landing times were still required to be within +/- 2.0 min of the recorded times, because larger deviations from the recorded times did produce mostly infeasible solutions.

Case FLX TMS is defined to assess the effects of allowing the meter fix times in Case CUR IDEAL to be changed to a more significant extent. It is still desired to use an upper limit for the deviation from the recorded meter fix time though, because otherwise the traffic demand may become very different. The maximum delay and time advance that can be given at the meter fix were limited to 15 min, because this is a typical time horizon that controllers make plannings for. As opposed to the reference case CUR IDEAL, the originally recorded landing times are not considered. This is indicated in Table 7.2 with the designation ‘not applicable’ (N/A). In Case FLX TMS and all following cases the landing time for each aircraft is therefore chosen as close as possible to the landing time of the leading aircraft without violating wake vortex minima. In this sense optimisation is in these cases more restricted than in Case CUR IDEAL. This was considered acceptable as long as in these cases performance could be shown to be higher. In each of the following cases, a specific operational constraint is removed with respect to Case FLX TMS.

Case FLX ALT/SPD is defined to assess the effects of maintaining the lateral STAR structure but allowing the altitudes and speeds to be optimised. Therefore, the standard altitude and speed profiles are not used for this case. Instead, the genetic algorithm is also
### Table 7.2: Definition of cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Flexile lateral profiles</th>
<th>Flexile altitudes and speeds</th>
<th>Current Idealised CUR IDEAL</th>
<th>Current CUR</th>
<th>Conventional Conventional Conventional Conventional Conventional Optimised</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/A</td>
<td>Direct 6-11</td>
<td>N/A</td>
<td>Conventional</td>
<td>Conventional 6-11</td>
<td>Conventional</td>
</tr>
<tr>
<td>N/A</td>
<td>Direct 6-11</td>
<td>Conventional</td>
<td>Conventional</td>
<td>Conventional 6-11</td>
<td>Conventional</td>
</tr>
<tr>
<td>N/A</td>
<td>Conventional</td>
<td>Flex ALT/SPD</td>
<td>Conventional</td>
<td>Conventional 6-11</td>
<td>Conventional</td>
</tr>
<tr>
<td>N/A</td>
<td>Conventional</td>
<td>Flex TMS</td>
<td>Conventional</td>
<td>Conventional 6-11</td>
<td>Conventional</td>
</tr>
<tr>
<td>N/A</td>
<td>+/− 2.0</td>
<td>Conventional</td>
<td>Conventional</td>
<td>Conventional 6-11</td>
<td>Conventional</td>
</tr>
<tr>
<td>N/A</td>
<td>+/− 0.5</td>
<td>Conventional</td>
<td>Conventional</td>
<td>Conventional 6-11</td>
<td>Conventional</td>
</tr>
</tbody>
</table>

Note: For the purpose of this table, the terms "Direct", "Idealised", and "Optimised" are used to describe the various scenarios of arrival trajectories. The table outlines the conditions under which each case is applicable, focusing on the flexibility of lateral and altitude profiles, as well as the deviation from recorded landing times.
allowed to optimise $\gamma$ and $a$. Changing altitude and speed profiles is addressed simultaneously because they are closely related through energy exchange.

Case SHORT IC is defined to assess the effects of optimising the final intercept distance. As discussed in Chapter 1 a lower final intercept distance may increase ATM performance. The minimum distance allowed here is 3 nmi from the threshold, the minimum distance mentioned earlier (Section 3.1.4). In order to make the differences between a ‘conventional’ final intercept and a ‘short’ final intercept more distinct, the maximum allowed final intercept distance was 6 nmi. This was the smallest distance allowed for a ‘conventional’ intercept. There was one potential problem with these limits. In the standard speed profiles the last 3 nmi of the approach were flown at approach speed. The ILS intercept could for Case SHORT IC take place as close to the threshold as this point. Using the standard speed profile in this case would result in intercepting with approach speed. This is uncommon and not done in the standard procedures. The length of the unaccelerated straight part of the final approach (segment 1) was therefore chosen as 2 nmi, the minimum allowed length (Section 3.1.4). This resulted in at least 1 nmi for decelerating along the ILS path. The final intercept distance is optimised by allowing the genetic algorithm to optimise the value of $L$ for the second segment, within the range that assures the above mentioned limits on the final intercept distance.

Case DIRECT is defined to assess the effects of optimising the lateral profiles when allowing direct trajectories instead of standard trajectories. For all traffic direct trajectories are used from the meter fix to the final approach intercept point. The initial trajectories all consisted of a descent from the meter fix at a constant flight path angle towards the final intercept point. The final approach course was intercepted by conducting a turn in level flight, as is common currently. The altitude profile is not optimised and therefore designated ‘Conventional’. The trajectory was implemented by selecting the values of $T$, $R$, $L$, $\gamma$, and $a$ accordingly. The lateral profile of these direct trajectories may be optimised by choosing the final intercept distance. In order to be able to compare the results with those for Case SHORT IC, the length of segment 1 was here also fixed at 2 nmi, the minimum distance allowed. The lateral shape of the trajectories is thus optimised by changing the length of the accelerated part of the final approach (segment 2). The limits used for the final intercept distance are the limits also used in the cases that did consider the STAR structure. The speed profile for the rest of the trajectory was selected to meet the recorded meter fix time as accurately as possible. In this sense, a conventional speed profile is used and not an optimal one. The speed profile is therefore designated ‘Conventional’.

Case FLX LAT is defined to assess the effects of optimising the trajectories laterally when not limiting the trajectories to conventional or direct trajectories. Since there is no fixed route structure the standard speed and altitude profiles, which are largely based on the horizontal shape of the STARs, cannot be used. In fact, the trajectories can vary for this

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2 Allowing such a reduction results in not applying STARs in their conventional form any more. A different separation constraint is therefore used (Table 3.2).
case significantly in shape. It became very difficult to construct the speed profile to meet the originally recorded meter fix times, as done in Case DIRECT. The speed and altitude profiles are for this reason here optimised. For the same reason as in Case DIRECT, the length of the first segment is fixed at 2 nmi. The final intercept distance is optimised by choosing the length of the second segment. For the final intercept distance the limits are used that were also used in the cases that did consider the STAR structure. The genetic algorithm is allowed to optimise $T$, $R$, $L$, $\gamma$, and $a$.

In the rest of this chapter, only these cases are compared. The interaction between allowing optimisation of the lateral, altitude, and speed profiles is considered to some extent in (Vormer, Mulder, & van Paassen, 2004).

### 7.1.4 Calculating Performance

Performance refers to the scores that are obtained on the different objectives of throughput, altitude deviation, speed deviation, and noise load on community (Section 3.1.2). In order to judge whether or not optimisation can provide the desired increase in performance, aspiration levels have been defined for each objective. If the selected aspiration levels for the objectives can be met, it would be clear that optimisation can provide the desired increase in performance. However, results of off-line analyses (Section 7.2) show that optimisation does not allow to meet the aspiration levels. It is, therefore, necessary to determine how the aspiration levels have to be chosen so that acceptable solutions with respect to the desired performance can be found. These levels are then a measure of the performance that can be achieved on all objectives simultaneously.

For this reason, a so-called constrained aspiration level $\rho^*$ is established for each objective as follows. The scores on the objectives for the solutions found with the optimisation algorithm are assumed to be distributed normally. From all obtained values the mean value and variation can be estimated for each objective. This makes it possible to approximate the cumulative distribution function. A level $\beta$ is then selected and each constrained aspiration level $\rho^*$ is selected so that the fraction of solutions with more than the aspired performance according to the cumulative distribution function equals $\beta$. The initial value selected for $\beta$ is 0.05, but this value is increased if necessary until 5 solutions (the number of solutions that was considered simultaneously) meet the constrained aspiration level $\rho^*$ for each objective. In Figure 7.1 it is illustrated how the aspiration levels are changed until five of the solutions found meet the constrained aspiration levels on all objectives.

### 7.1.5 Calculating TDL Metrics for Pilots

In Table 4.2 a number of metrics were identified to address TDL for pilots. The values of the metrics were calculated in Section 4.2 for a number of manoeuvres using a B747 aircraft model. Since a broad range of different aircraft types are present in the traffic scenario, using the B747 model to calculate the metrics for all trajectories is not expected to give
reliable results. The metrics are therefore calculated by using kinematics. In this way all pilot and aircraft response times are ignored; this gives less detailed but very general results.

Since the trajectory description from Figure 3.8 is used, most of the metrics from Table 4.2 can be calculated by using kinematics. The vertical acceleration, however, cannot be calculated because it is not prescribed in the trajectory. A vertical acceleration of 0.03\(g\) is generally found acceptable by pilots and is therefore used in calculating the other metrics. Fixing the vertical acceleration, however, makes it no longer usable as a metric in this calculation. Some simple calculations have to be made to determine the values of the other metrics.

For vertical flight path changes, the speed is assumed to remain constant during the manoeuvre. The manoeuvre time needed is then determined by calculating how much time is needed to obtain the desired vertical speed using the mentioned vertical acceleration.

Speed changes are described in terms of commanded accelerations over a certain trajectory length. The size of the speed change can thus be calculated. It is therefore also possible to determine the time needed for the speed manoeuvre.

For combined vertical flight path and speed changes the manoeuvre time is determined by comparing the time needed to complete the speed change and the time needed to complete the path change. The maximum of these two values is taken to be the manoeuvre time for combined vertical flight path and speed changes.

For a track change \(\Delta \chi\) can be obtained from,
\[ \Delta \chi = \frac{L \cos \gamma}{R} , \]  

(7.1)

and the turn rate \( \Omega \) from Equation (4.1). The manoeuvre time \( T_M / T \) (where \( T \) is the flight time) can for a track change be calculated using:

\[ T_M = \frac{\Delta \chi}{\Omega} . \]  

(7.2)

In this way the metrics are calculated for the solutions found at the end of the genetic optimisation process.

### 7.1.6 Calculating TDL Metrics for Air Traffic Controllers

Besides the ATM performance and the metrics discussed above, a number of metrics from literature are used to accomplish the objective of assessing the effects of flexible trajectories on airspace complexity. This relates to the task demand load for controllers (Chapter 1). The metrics used are shown in Table 7.3. These metrics assume conventional ATC.

The metrics 1 to 5 were found to be important metrics concerning airspace complexity by Masalonis et al. (2003). The number of crossing points between arrival and departure traffic was added to this list, because a higher number of crossing points creates more interaction between traffic flows, which may increase airspace complexity. Increasing complexity for this reason is not addressed by the other metrics. A point where arrival and departure traffic cross is only counted as a crossing point if the crossing takes place more than 5 nmi from each previously found crossing point. This is to prevent counting a high number of crossing points when in fact they take place at nearly the same point. Counting all these points may bias the results in the sense that solutions with crossing points placed very close together may come out as being worse than solutions with fewer crossing points placed very far apart.

Metrics that describe contraction and extraction levels of the traffic flows have also been proposed as measures of the airspace complexity by addressing the amount of disorder. Metrics called density, divergence, and convergence have been developed by Delahaye and Puechmorel (2000). Higher values of these measures are associated with more disorder and therefore more complexity.

They are defined as follows. Considering two aircraft \( i \) and \( j \) at positions \( r_i \) and \( r_j \), the relative distance is given by \( d_{ij} = r_j - r_i \). The density for aircraft \( i \) is then defined by Delahaye and Puechmorel (2000) as:

\[ D(i) = 1 + \sum_{j=1,j \neq i}^{N} e^{-\alpha \frac{||d_{ij}||}{R}} , \]  

(7.3)

with \( N \) the number of aircraft present, \( \alpha \) a weighted coefficient, and \( R \) a distance. The coefficient \( \alpha \) was chosen as 1 (so that weighting was further not addressed). The distance
7.1 METHOD

Table 7.3  Airspace complexity metrics. The metrics 1 to 5 are based on (Masalonis et al., 2003), metric 6 is a new metric, metrics 7 to 9 are based on (Delahaye & Puechmorel, 2000), and metrics 10 to 13 are also new metrics.

<table>
<thead>
<tr>
<th>Nr</th>
<th>Metric</th>
<th>Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Peak number of aircraft simultaneously in the terminal area</td>
<td>$N_{PK}$</td>
</tr>
<tr>
<td>2</td>
<td>Maximum number of aircraft with an airspeed change greater than 10 knots during a 2-minute interval</td>
<td>$N_{SC}$</td>
</tr>
<tr>
<td>3</td>
<td>Maximum number of aircraft pairs with less than 8 nmi horizontal distance</td>
<td>$N_8$</td>
</tr>
<tr>
<td>4</td>
<td>Maximum number of aircraft pairs with less than 13 nmi horizontal distance</td>
<td>$N_{13}$</td>
</tr>
<tr>
<td>5</td>
<td>Maximum number of aircraft with an altitude change rate over 500 feet per minute</td>
<td>$N_{AC}$</td>
</tr>
<tr>
<td>6</td>
<td>Number of crossings points between arrival and departure flows</td>
<td>$N_C$</td>
</tr>
<tr>
<td>7</td>
<td>Density</td>
<td>$D$</td>
</tr>
<tr>
<td>8</td>
<td>Divergence</td>
<td>$Div$</td>
</tr>
<tr>
<td>9</td>
<td>Convergence</td>
<td>$Conv$</td>
</tr>
<tr>
<td>10</td>
<td>Mean minimum horizontal separation distance</td>
<td>$S_H$</td>
</tr>
<tr>
<td>11</td>
<td>Mean minimum vertical separation distance for traffic at less than 5 nmi horizontal proximity</td>
<td>$S_V$</td>
</tr>
<tr>
<td>12</td>
<td>Mean maximum horizontal closure rate</td>
<td>$CR_H$</td>
</tr>
<tr>
<td>13</td>
<td>Mean maximum vertical closure rate for traffic at less than 5 nmi horizontal proximity</td>
<td>$CR_V$</td>
</tr>
</tbody>
</table>
was chosen as 3 nmi, since this is the standard horizontal separation distance used in the terminal area (see Section 3.1.4). The divergence for aircraft \( i \) is defined as:

\[
\text{Div}(i) = \sum_{j=1,j\neq i}^{N} \left| \frac{d||d_{ij}||}{dt} \right| \left\{ \frac{d||d_{ij}||}{dt} \right\} e^{-\alpha ||d_{ij}||/R}, \tag{7.4}
\]

only taking into account traffic pairs with \( \frac{d||d_{ij}||}{dt} > 0 \). The convergence for aircraft \( i \) is similarly defined as:

\[
\text{Conv}(i) = -\sum_{j=1,j\neq i}^{N} \left| \frac{d||d_{ij}||}{dt} \right| \left\{ \frac{d||d_{ij}||}{dt} \right\} e^{-\alpha ||d_{ij}||/R}, \tag{7.5}
\]

for traffic pairs with \( \frac{d||d_{ij}||}{dt} < 0 \). Because in this application the complexity of the entire airspace is to be determined, the separate contributions from individual flights are here summed to yield cumulative values of \( D, \text{Div}, \) and \( \text{Conv} \) for the entire airspace.

A number of simple metrics were also used that described the distances between and closure rates of aircraft pairs. They are used because maintaining separation is one of the main tasks of ATC. Larger separation distances may therefore reduce the airspace complexity that a controller faces. For horizontal separation, at each point in time and for each aircraft the lowest separation with other traffic is first determined. The value of \( S_H \) is then taken as the mean value of this minimum separation over all traffic and over all time. The same is done for \( S_V \) except that only traffic in horizontal proximity is taken into account. A distance of less than 5 nmi was selected to define horizontal ‘proximity’ because it is a standard minimum separation distance often used, see for example (Hoekstra, 2001). In a similar way the mean maximum closure rates \( CR_H \) and \( CR_V \) are determined. Thus, all metrics used to describe airspace complexity refer to all traffic in the airspace considered. These metrics are also calculated for the final solutions found by the genetic algorithm.

### 7.2 Results

The genetic optimisation process is a stochastic process and the outcome may therefore be different each time. The genetic algorithm was run thirty times for each case and the results are analysed with a statistical analysis. For all runs, Figure 7.2 shows how the fitness \( f \) changes from generation to generation for each case. Since \( f < 0.5 \) for all runs, it follows that \( F > 2 \), which means that for all runs at least one of the desired aspiration levels is not met by a factor larger than 2. Thus, either the throughput \( T \) is more than two times lower than desired, or the altitude deviation \( \Delta h \), or the speed deviation \( \Delta V \), or the noise load on community \( L \) is more than two times higher than desired.

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3The minimum separation distance of 3 nmi used in the terminal area (see Section 3.1.4) was not used, because it is unlikely that vertical separation will only be considered by controllers after a separation violation has occurred.
It can be seen that for the first couple of cases the genetic algorithm can only provide a limited improvement in the value of $f$, whereas for the higher case numbers significant improvements can be made. It can also be seen that the level of convergence is different depending on the case. Although it cannot be proven that better solutions cannot be found, the genetic search process was continued for 500 generations so that for most runs reasonable convergence was achieved.

The typical shape of obtained solutions is illustrated in Figures G.1 to G.21 in Appendix G by showing examples of obtained solutions. For each case three figures are shown. The first figure shows for all trajectories the shape of the trajectory in the horizontal plane projected on a map of the environment, where the solid trajectories represent the arrival trajectories and the dashed the standard departure routes used for this runway configuration. The first figure also shows for all flights the difference $d$ between the scheduled time of arrival $STA$ and the nominal time of arrival $NTA$ from Table 7.1. This is done for the times at the touch down point (the runway) and at the meter fix. The second figure shows for all trajectories the altitude $h$, calibrated airspeed $V_C$, bank angle $\Phi$, energy rate demand $\dot{E}$, and energy rate demand with speed brakes deployed $\dot{E}_{sbr}$ against the reference time $t$. The reference time was for all cases the same. The third figure shows the properties of the different segments of the trajectory, with $T$ segment type, $L$ segment length, $\gamma$ flight path angle, and $a$ acceleration.

The cases are compared to each other with respect to ATM performance by compar-
ing the scores on the objectives throughput $T$, altitude deviation $\Delta_h$, speed deviation $\Delta_V$, and noise load on community $L$. The cases are compared with respect to TDL for pilots by comparing the scores on the metrics from Table 4.2, except for the vertical acceleration: $N_P$, $(T_M/T)_P$, $(\Sigma|\Delta\gamma|)_P$, $N_S$, $(T_M/T)_S$, $(\Delta V_C|_{\text{max}})_S$, $(|V_C|_{\text{max}})_S$, $N_{PS}$, $(T_M/T)_{PS}$, $(\Sigma|\Delta\gamma|)_{PS}$, $(|\Delta V_C|_{\text{max}})_{PS}$, $(|V_C|_{\text{max}})_{PS}$, $N_T$, $(T_M/T)_{lat}$, $\Sigma|\Delta\chi|$, $|\Omega|_{\text{max}}$, $\hat{E}_{\text{max}}$, $N_M$, $(T_M/T)_{lon}$, and $(T_M/T)_{tot}$. The cases are compared with respect to airspace complexity by comparing the scores on the metrics $N_{PK}$, $N_{SC}$, $N_S$, $N_{13}$, $N_{AC}$, $N_C$, $D$, $Div$, $Conv$, $S_H$, $S_V$, $CR_H$, and $CR_V$.

7.2.1 Performance

The constrained aspiration levels found are shown for the different objectives in Figure 7.3, where also the aspiration levels that were originally selected are indicated. It can be concluded that the selected aspiration levels of 90 arrivals/hr for $T$, 1000 ft for $\Delta_h$, and 20 kts for $\Delta_V$ are not met. This shows the difficulty of meeting all aspirations at the same time and the competitiveness of the objectives. Statistically significant differences between the cases were observed for all objectives ($T$: $F_{6.203} = 729.015$, $p \leq 0.01$; $\Delta_h$: $F_{6.203} = 2350.636$, $p \leq 0.01$; $\Delta_V$: $F_{6.203} = 1434.244$, $p \leq 0.01$; $L$: $F_{6.203} = 244.615$, $p \leq 0.01$).

For the throughput $T$, a Student-Newman-Keuls (SNK) test with $\alpha=0.05$ showed that Cases FLX TMS, FLX ALT/SPD, SHORT IC, DIRECT, and FLX LAT resulted in higher values than Case CUR IDEAL. The mean throughput was for Case CUR IDEAL equal to 43.73 arrivals/hr, whereas it increased for Cases DIRECT and FLX LAT to 56.16 and 56.35 arrivals/hr, respectively. This corresponds to an increase up to about 28 % arrivals/hr more. Optimising the arrival times and the shape of the trajectories is therefore concluded to enable increased throughput.

For the altitude deviation $\Delta_h$, an SNK test showed that Cases FLX ALT/SPD and FLX LAT (the two cases where altitude and speed profiles were optimised) are the cases with the lowest altitude deviation. The mean value of $\Delta_h$ was equal to 2560 and 3106 ft, respectively. For Case CUR IDEAL it was equal to 4729 ft, which confirms that optimisation of the profiles resulted in altitude profiles closer to those belonging to a continuous descent approach. The reduction of the mean value for Case FLX ALT/SPD as compared with Case CUR IDEAL is equal to 2169 ft, which is significant because it is more than the standard vertical separation distance of 1000 ft applied by ATC.

For the speed deviation $\Delta_V$, an SNK test showed that Case SHORT IC resulted in the best score: the mean value of $\Delta_V$ was 49.08 kts, whereas for Case CUR IDEAL it was 81.43 kts. The lower deviation for Case SHORT IC is explained by the later deceleration to final approach speed (Section 7.1.3). The cases where the genetic algorithm optimises the altitude and speed profiles do not result in lower values of $\Delta_V$ than Case CUR IDEAL. This is explained by the fact that to resolve energy-related constraint violations the genetic algorithm favoured changing the speed profile over changing the altitude profile.
Figure 7.3  Means and 95% confidence intervals of the scores on the objectives. The dashed lines show the initially selected aspiration levels.
Figure 7.4  Means and 95% confidence intervals of the metrics related to vertical path changes.
7.2 RESULTS

Figure 7.5  Means and 95% confidence intervals of the metrics related to speed changes.
Figure 7.6 Metrics related to combined vertical path and speed changes (1).
7.2 RESULTS

For the noise load on community $L$, an SNK test ($\alpha=0.05$) showed that Cases CUR and CUR IDEAL resulted in the worst scores. The mean value of $L$ was 0.00829 s/m$^2$ for Case CUR IDEAL. The other cases all resulted in statistically significant better values for $L$: the lowest value was found for Case FLX ALT/SPD and was equal to 0.00621 s/m$^2$, corresponding to a decrease of about 25%. This indicates that optimising the altitude and speed profiles, optimising the final intercept distance, and optimising the lateral profiles all significantly reduce the time flown over residential areas at low altitude.

7.2.2 Task Demand Load Metrics for Pilots

Vertical Path Changes

It is clear that changing the shape of the trajectories affects the values of the metrics related to vertical path changes (Figure 7.4). The differences between the cases were statistically significant for all metrics relating to vertical path changes ($N_P$: $F_{6,3143} = 383.691$, $p \leq 0.01$; $(T_M/T)_P$: $F_{6,3143} = 486.404$, $p \leq 0.01$; $(\Sigma|\Delta\gamma|)_P$: $F_{6,3143} = 561.853$, $p \leq 0.01$). An SNK test at $\alpha=0.05$ showed that for the Cases FLX ALT/SPD, DIRECT, and FLX LAT the mean values of $N_P$ (2.35, 3.06, and 3.47, respectively), $(T_M/T)_P$ (0.08, 0.12, and 0.07, respectively), and $(\Sigma|\Delta\gamma|)_P$ (8.30, 12.64, and 7.50, respectively) were higher than for Case CUR IDEAL (1.96 for $N_P$, 0.04 for $(T_M/T)_P$, and 5.12 for $(\Sigma|\Delta\gamma|)_P$).
Figure 7.8 Means and 95% confidence intervals of the metrics related to track changes.
7.2 RESULTS

(a) maximum energy rate demand

(b) total number of manoeuvres

(c) longitudinal manoeuvre time

(d) total manoeuvre time

Figure 7.9  Means and 95% confidence intervals of remaining metrics.
Speed Changes
The metrics related to speed changes (Figure 7.5) also all showed statistically significant differences between the cases ($N_S$: $F_{6.3143} = 414.793, p \leq 0.01$; $(T_{M/T})_S$: $F_{6.3143} = 313.268, p \leq 0.01$; $(|\Delta V|_{max})_S$: $F_{6.3143} = 884.868, p \leq 0.01$; $(|\dot{V}|_{max})_S$: $F_{6.3143} = 845.316, p \leq 0.01$). However, according to an SNK test with $\alpha=0.05$ only few metrics increased in size when compared to Case CUR IDEAL. Cases SHORT IC and DIRECT did result in the highest number of speed changes (the mean values were equal to 1.75 and 1.76, respectively, versus 1.17 for Case CUR IDEAL). Case DIRECT also resulted in the highest decelerations (the mean value was equal to 0.81 versus 0.46 m/s$^2$ for Case CUR IDEAL).

Combined Vertical Path and Speed Changes
For the combined vertical path and speed manoeuvres (Figures 7.6 and 7.7) statistically significant differences were also found between the cases for all metrics ($N_{PS}$: $F_{6.3143} = 2144.420, p \leq 0.01$; $(T_{M/T})_{PS}$: $F_{6.3143} = 1346.294, p \leq 0.01$; $(\Sigma|\Delta\gamma|)_{PS}$: $F_{6.3143} = 897.861, p \leq 0.01$; $(|\Delta V|_{max})_{PS}$: $F_{6.3143} = 1002.125, p \leq 0.01$; $(|\dot{V}|_{max})_{PS}$: $F_{6.3143} = 706.206, p \leq 0.01$). For all metrics higher mean values were found (SNK, $\alpha=0.05$) for Case FLX ALT/SPD (1.77 for $N_{PS}$, 0.24 for $(T_{M/T})_{PS}$, 5.47 deg for $(\Sigma|\Delta\gamma|)_{PS}$, 44.03 m/s for $(|\Delta V|_{max})_{PS}$, and 0.31 m/s$^2$ for $(|\dot{V}|_{max})_{PS}$), Case SHORT IC (0.22 for $N_{PS}$, 0.03 for $(T_{M/T})_{PS}$, 0.65 deg for $(\Sigma|\Delta\gamma|)_{PS}$, 5.95 m/s for $(|\Delta V|_{max})_{PS}$, and 0.09 m/s$^2$ for $(|\dot{V}|_{max})_{PS}$), Case DIRECT (1.27 for $N_{PS}$, 0.25 for $(T_{M/T})_{PS}$, 4.95 deg for $(\Sigma|\Delta\gamma|)_{PS}$, 34.75 m/s for $(|\Delta V|_{max})_{PS}$, and 0.26 m/s$^2$ for $(|\dot{V}|_{max})_{PS}$), and Case FLX LAT (2.98 for $N_{PS}$, 0.27 for $(T_{M/T})_{PS}$, 7.24 deg for $(\Sigma|\Delta\gamma|)_{PS}$, 40.33 m/s for $(|\Delta V|_{max})_{PS}$, and 0.34 m/s$^2$ for $(|\dot{V}|_{max})_{PS}$) than for Case CUR IDEAL (0.04 for $N_{PS}$, 0.01 for $(T_{M/T})_{PS}$, 0.12 deg for $(\Sigma|\Delta\gamma|)_{PS}$, 1.74 m/s for $(|\Delta V|_{max})_{PS}$, and 0.02 m/s$^2$ for $(|\dot{V}|_{max})_{PS}$). The values of the metrics relating to path-speed manoeuvres thus generally became higher for flexible arrival trajectories. According to these results, introducing more combined vertical path and speed manoeuvres is an important component of increasing efficiency.

Track Changes
For the lateral factors shown in Figure 7.8 an ANOVA showed statistically significant differences between the cases for all considered metrics ($N_{T}$: $F_{6.3143} = 1149.358, p \leq 0.01$; $(\Sigma|\Delta\chi|)$: $F_{6.3143} = 448.121, p \leq 0.01$; $(|\Omega|_{max})$: $F_{6.3143} = 118.733, p \leq 0.01$; $(T_{M/T})_{lat}$: $F_{6.3143} = 632.435, p \leq 0.01$). An SNK test with $\alpha=0.05$ showed that the values for all metrics were lower for Cases DIRECT (2.0 for $N_{T}$, 89.04 deg for $(\Sigma|\Delta\chi|)$, 1.49 deg/s for $(|\Omega|_{max})$, and 0.10 for $(T_{M/T})_{lat}$) and FLX LAT (2.67 for $N_{T}$, 161.89 deg for $(\Sigma|\Delta\chi|)$, 1.57 deg/s for $(|\Omega|_{max})$, and 0.16 for $(T_{M/T})_{lat}$) than for Case CUR IDEAL (3.0 for $N_{T}$, 237.42 deg for $(\Sigma|\Delta\chi|)$, 1.64 deg/s for $(|\Omega|_{max})$, and 0.23 for $(T_{M/T})_{lat}$). For Case DIRECT this
Figure 7.10  Means and 95% confidence intervals of airspace complexity metrics 1-4.
is explained by the fact that using direct trajectories results in less turning. For Case FLX LAT, however, optimisation of the lateral profiles did result in much more diverse trajectories in lateral sense than for the current situation. This could be accomplished without increasing the TDL metrics in lateral sense. In fact, the values of all metrics relating to lateral motion were significantly lower than for current operations (but higher than for the direct trajectories).

For Case SHORT IC statistically significant higher mean values were found for $(T_M/T)_{\text{lat}}$ (0.28) and $\Sigma|\Delta \chi|$ (253.47 deg) than for Case CUR IDEAL (0.23 and 237.42 deg, respectively). A shorter intercept distance resulted in a small increase in lateral manoeuvre time, which is explained by the fact that turning onto final approach course is done at a lower speed, thus increasing the manoeuvre time. Also, Case FLX ALT/SPD resulted in a (small) increase of maximum turn rate.

**Other Metrics**

In Figure 7.9 the results for the remaining metrics are shown, for all of which statistically significant differences between the cases were found ($\hat{E}_{\text{max}}$: $F_{6,3143} = 403.039$, $p \leq 0.01$; $N_M$: $F_{6,3143} = 941.188$, $p \leq 0.01$; $(T_M/T)_{\text{lon}}$: $F_{6,3143} = 674.990$, $p \leq 0.01$; $(T_M/T)_{\text{tot}}$: $F_{6,3143} = 205.325$, $p \leq 0.01$). For all metrics, statistically significantly higher mean values were found (SNK, $\alpha=0.05$) for Cases FLX ALT/SPD ($0.95$ for $\hat{E}_{\text{max}}$, $7.77$ for $N_M$, $0.38$ for $(T_M/T)_{\text{lon}}$, and $0.60$ for $(T_M/T)_{\text{tot}}$), DIRECT ($0.98$ for $\hat{E}_{\text{max}}$, $8.09$ for $N_M$, $0.44$ for $(T_M/T)_{\text{lon}}$, and $0.54$ for $(T_M/T)_{\text{tot}}$) and FLX LAT ($0.93$ for $\hat{E}_{\text{max}}$, $7.77$ for $N_M$, $0.38$ for $(T_M/T)_{\text{lon}}$, and $0.60$ for $(T_M/T)_{\text{tot}}$).
9.28 for $N_M$, 0.36 for $(T_M/T)_{lon}$, and 0.52 for $(T_M/T)_{tot}$ than for Case CUR IDEAL (0.70 for $E_{max}$, 6.17 for $N_M$, 0.20 for $(T_M/T)_{lon}$, and 0.43 for $(T_M/T)_{tot}$). Except for $(T_M/T)_{lon}$, Case SHORT IC resulted in statistically significant higher mean scores (0.85 for $E_{max}$, 6.75 for $N_M$, and 0.48 for $(T_M/T)_{tot}$) than Case CUR IDEAL. For the Cases FLX ALT/SPD, SHORT IC, DIRECT, and FLX LAT the energy rate demand becomes closer to 1 than for Case CUR IDEAL. This means aircraft are required to be operated closer to their performance limits. The higher number of manoeuvres for the Cases FLX ALT/SPD, SHORT IC, DIRECT, and FLX LAT is necessary to obtain profiles closer to those of a continuous descent approach.

### 7.2.3 Task Demand Load Metrics for Air Traffic Controllers

The values of the considered airspace complexity metrics are shown in Figures 7.10 to 7.13. Statistically significant differences were found between the cases for all metrics ($N_{PK}$: $F_{6,203} = 15.968$, $p \leq 0.01$; $N_{SC}$: $F_{6,203} = 32.193$, $p \leq 0.01$; $N_8$: $F_{6,203} = 21.527$, $p \leq 0.01$; $N_{13}$: $F_{6,203} = 23.267$, $p \leq 0.01$; $N_{AC}$: $F_{6,203} = 42.171$, $p \leq 0.01$; $N_C$: $F_{6,203} = 186.460$, $p \leq 0.01$; $D$: $F_{6,203} = 12.257$, $p \leq 0.01$; $Div$: $F_{6,203} = 11.044$, $p \leq 0.01$; Conv: $F_{6,203} = 16.537$, $p \leq 0.01$; $S_H$: $F_{6,203} = 108.487$, $p \leq 0.01$; $S_V$: $F_{6,203} = 6.918$, $p \leq 0.01$; $CR_H$: $F_{6,203} = 22.574$, $p \leq 0.01$; $CR_V$: $F_{6,203} = 98.508$, $p \leq 0.01$).

For the peak number of aircraft in the terminal area ($N_{PK}$), Case CUR IDEAL resulted in a mean value of 11.2. The flexible arrival trajectories generally resulted in lower values according to an SNK ($\alpha=0.05$) test. The lowest value was found for Case SHORT IC and was equal to 9.5. For $N_8$, the maximum number of aircraft pairs with less than 8 nmi separation, Case FLX TMS was the only case which resulted in a higher mean score (26.1) than Case CUR IDEAL (24.5); Cases FLX ALT/SPD, DIRECT, and FLX LAT resulted in lower scores (23.1, 22.0, and 20.6, respectively) than Case CUR IDEAL (SNK, $\alpha=0.05$). An SNK test also showed that for the mean value of $N_{13}$, the maximum number of aircraft pairs with less than 13 nmi separation, flexible arrival trajectories generally resulted in lower values. For Case CUR IDEAL it was 37.9, whereas the lowest value was 28.7, which was found for Case FLX LAT. Based on the results for $N_{PK}$, $N_8$, and $N_{13}$ it can be concluded that more freedom in the trajectories helps to decrease the traffic densities and the number of aircraft at low separation distances.

A similar trend was found for the maximum number of aircraft changing altitude significantly ($N_{AC}$): the flexible trajectories generally resulted in lower values. The mean value was for Case CUR IDEAL equal to 9.1. The lowest mean value was found for Case FLX ALT/SPD and was equal to 6.6.

For the maximum number of aircraft changing speed significantly ($N_{SC}$), Case CUR IDEAL resulted in the highest mean value (7.1), followed by Case CUR (6.9). An increasing number of aircraft simultaneously changing speed therefore does not seem to be a concern for the studied flexible arrival trajectories. Cases FLX ALT/SPD, SHORT IC, and FLX LAT
Figure 7.12  Means and 95% confidence intervals of airspace complexity metrics 7-10.
Figure 7.13  Means and 95% confidence intervals of airspace complexity metrics 10-13.
in fact decreased the mean value of $N_{SC}$ to 5.3, 5.2, and 6.1, respectively (SNK, $\alpha=0.05$).

The mean number of crossing points ($N_C$) was for Case CUR IDEAL equal to 5.8. It increased, however, considerably, for the optimised lateral profiles in Case FLX LAT (SNK, $\alpha=0.05$), where it was equal to 9.8. Since this value is almost two times higher than for Case CUR IDEAL, an increasing number of crossing points may be an important concern for the flexible arrival trajectories.

For the density ($D$), Case CUR IDEAL resulted in the highest mean value (25.18). Cases FLX ALT/SPD, SHORT IC, DIRECT, and FLX LAT resulted in statistically significant lower mean values (22.94, 22.37, 22.55, and 23.20, respectively), as found with an SNK test at $\alpha=0.05$. This supports the earlier conclusion that more freedom in the trajectories helps to decrease the traffic densities.

For the divergence ($Div$), an SNK test at $\alpha=0.05$ showed that only Case FLX LAT resulted in a statistically significant higher mean value ($12950.91 \text{ m}^2/\text{s}^2$) than Case CUR IDEAL ($6629.64 \text{ m}^2/\text{s}^2$). It is therefore concluded that flexibility in the lateral profiles may increase airspace complexity due to more divergence in the traffic flows.

For the convergence ($Conv$), an SNK test at $\alpha=0.05$ showed that Cases FLX ALT/SPD, SHORT IC, and FLX LAT resulted in statistically significant higher mean values (18621.99, 19215.78, and 19797.82 $\text{ m}^2/\text{s}^2$, respectively) than Case CUR IDEAL (14286.45 $\text{ m}^2/\text{s}^2$). This indicates that flexible trajectories may also result in higher airspace complexity due to more convergence in the traffic flows.

For the mean minimum horizontal separation distance ($S_H$), the values found for Case FLX LAT were comparable to those for CUR IDEAL (SNK, $\alpha=0.05$): the mean value was equal to 11.15 nmi for Case FLX LAT and to 11.05 nmi for Case CUR IDEAL. All the other cases resulted in a lower value than Case CUR IDEAL. The lowest value was found for Case FLX TMS, in which case it was equal to 7.66 nmi. Thus, almost all the studied flexible arrival trajectories decreased the minimum horizontal separation as compared to the original situation. The only exception was Case FLX LAT, which is due to the added horizontal flexibility that allows for more spreading of trajectories.

For the mean minimum vertical separation distance ($S_V$), the only statistically significant difference with an SNK test at $\alpha=0.05$ from Case CUR IDEAL was found for Case FLX TMS. The mean value was 992.4 ft for Case CUR IDEAL versus 945.6 ft for Case FLX TMS, which is only a small difference.

For the mean maximum horizontal closure rate $CR_H$, the highest mean value was found for Case CUR IDEAL (135.1 m/s). An SNK test ($\alpha=0.05$) showed that all other cases resulted in statistically significant lower values. This indicates that higher horizontal closure rates are not a concern for flexible arrival trajectories.

For the mean maximum vertical closure rate $CR_V$, Case CUR IDEAL resulted in a mean value of 1.45 m/s. With an SNK test at $\alpha=0.05$ statistically significant higher values were found for Cases FLX ALT/SPD (2.73 m/s), SHORT IC (1.74 m/s), DIRECT (2.46 m/s), and FLX LAT (2.61 m/s). It is therefore concluded that optimising the altitude and
speed profiles, optimising the final intercept distance, and optimising the lateral profiles all may increase vertical closure rates.

7.3 Conclusions

The multi-objective scheduling algorithm from Chapter 3 was used to schedule arrival trajectories in the terminal area of Schiphol Airport. It was observed that for the currently used arrival procedures the ATM performance related to throughput, deviation from three-degree decelerated approaches, and noise impact on community could not be increased significantly by only optimising runway assignments and landing times as compared to data recorded from practice. This confirms the high degree of efficiency with which the current procedures are applied.

However, it was found that changing the times at which traffic entered the terminal area resulted in more throughput. Changing the trajectories also did improve the performance. Allowing flexible arrival trajectories in the sense that the altitude and speed profiles were optimised and that the final intercept distance was optimised resulted in higher throughput. Two different cases of optimising the lateral profiles were considered. The first case prescribed that all trajectories should be direct trajectories from the meter fix to the final intercept point. The second case did not prescribe any lateral route structure. In both cases throughput was higher than for conventional trajectories. Throughput was up to about 28% higher than for current operations. In addition, applying the flexible trajectories was shown to enable the application of altitude profiles closer to those belonging to a continuous descent approach and to allow routing flights less often over residential areas. The maximum deviation from an altitude profile belonging to a continuous descent approach was for flexible arrival trajectories up to 2000 ft lower than for standard arrival trajectories. The noise impact on community, modeled as a combination of time spent and altitude flown over residential areas, was reduced with up to about 25%.

These maximum benefits could not be obtained simultaneously. The lowest deviation from an altitude profile belonging to a continuous descent approach and the lowest noise impact on community were obtained when only optimising the altitude and speed profiles of the standard trajectories. On the other hand, the highest throughput was obtained for optimised altitude, speed, and lateral profiles.

The task demand load of the pilot’s task of controlling the aircraft was assessed with the metrics from Chapter 4. It is concluded that the TDL of controlling the aircraft with respect to longitudinal motion increases for the flexible arrival trajectories. This could be a source of concern that may put limits on the shapes of the generated trajectories. The increase in TDL is mainly caused by the necessity of more manoeuvres to achieve flight profiles closer to those of a continuous descent approach while still meeting all the constraints. The flexible arrival trajectories typically resulted in one additional vertical path manoeuvre (which refers to changing the flight path angle). Also, they resulted in up to
about 3 combined vertical path and speed manoeuvres in the arrival trajectory, requiring about 25% of the time needed to complete the arrival. These manoeuvres are at present normally not applied during the arrival procedure. In addition, the energy rate demand became for flexible trajectories much closer to 1. This means that aircraft had to be operated closer to performance limits. There were no indications found that the task demand load relating to lateral motion was increased due to the use of flexible arrival trajectories.

A number of metrics were used to address airspace complexity. The traffic density generally became lower for flexible arrival trajectories than for conventional trajectories because more airspace could be used. The flexible trajectories could, however, result in almost doubling the number of crossing points between arrival and departure traffic, more disorder (more divergence and more convergence) in the traffic flows, almost doubling the average value of the maximum vertical closure rates between aircraft pairs, and reducing the average value of the minimum horizontal separation distances between aircraft pairs with more than 3 nmi. When the lateral profiles were optimised a decrease in minimum horizontal separation distance could be prevented. It is concluded though that flexible arrival trajectories may increase airspace complexity. It is therefore also concluded that flexible arrival trajectories may increase TDL for air traffic controllers.
8.1 Conclusions

8.1.1 Benefits of Flexible Arrival Trajectories

A multi-objective genetic algorithm was developed that provides a way to optimise arrival trajectories. The scheduling algorithm considers four objectives: throughput, deviation from altitude and speed profiles of a three-degree decelerated approach, and noise impact on community. Based on the theory of satisficing decision making, it tries to find solutions that meet prescribed scores on all objectives. This allows to approximate the part of the Pareto front that is useful for a decision maker and that represents desirable solutions.

An off-line analysis was conducted for traffic arriving at Amsterdam Airport Schiphol. It was shown that allowing flexible arrival trajectories improves ATM performance when compared to conventional arrival trajectories. Allowing flexible arrival trajectories in the sense that the altitude and speed profiles were optimised and that the final intercept distance was optimised resulted in higher throughput. Two cases of optimising the lateral profiles were considered. The first case prescribed that all trajectories should be direct trajectories from the meter fix to the final intercept point. The second case did not prescribe any lateral route structure. In both cases throughput was higher than for conventional trajectories. The throughput was increased with a maximum of about 28 % arrivals per hour more. Higher throughput may help to reduce the number of delays currently experienced.

In addition, applying these trajectories was shown to enable the application of altitude profiles closer to those belonging to a continuous descent approach. The maximum deviation from an altitude profile belonging to a continuous descent approach was for flexi-
ble arrival trajectories up to 2000 ft lower than for current arrival trajectories. Profiles closer to those belonging to a continuous descent approach allow a thrust level closer to idle for a greater portion of the flight, reducing noise and emissions. The maximum deviation from a speed profile belonging to a continuous descent approach, however, could not be decreased. This is because the genetic algorithm prefers changing the speed profile over changing the altitude profile when trying to meet the constraints. The profiles belonging to a continuous descent approach were based on a fixed flight path angle and a fixed deceleration. They were equal for all traffic. Although for flexible trajectories a more continuous altitude profile is followed, it remains to be shown that this also results in lower noise and emissions. This may be difficult with the BADA models that were used. Although the BADA models do include some configuration changes, they do not include all flap configurations. Since flap configurations can influence the required thrust significantly, it may be necessary to use more detailed aircraft models to calculate thrust, noise, and emissions accurately.

In order to determine to what degree traffic was routes over residential areas, the noise impact on community was additionally studied. Because it was not the main topic of the thesis, noise impact on community was calculated by only considering the time spent and altitude flown over residential areas. It was reduced with up to about 25% for flexible arrival trajectories. In order to make a more reliable calculation of noise impact on community, the noise produced by the airplanes in generating the required thrust needs to be included. This may also require more accurate airplane models.

The maximum benefits indicated could not be obtained simultaneously. The lowest deviation from an altitude profile belonging to a continuous descent approach and the lowest noise impact on community were obtained by optimising altitude and speed profiles of current trajectories. On the other hand, the highest throughput was obtained for optimised altitude, speed, and lateral profiles. Before it can be judged which of these results is most desirable, it is required to first establish clear acceptable limits for the different objectives.

The results obtained for flexible arrival trajectories were compared with the results for an 'idealised' representation of current operations. The idealised situation meant that in an operationally recorded traffic sample the runway assignments and landing times were optimised. This was done because the recorded data may have been influenced by reasons for disallowing certain solutions that were not included in the analysis. Allowing the genetic algorithm to optimise the schedules for both conventional and flexible trajectories allows a more fair comparison than comparing the results for the flexible trajectories directly with the data from the operational scenario. However, the flexible trajectories scheduled by the genetic algorithm are not necessarily acceptable. The use of flexible arrival trajectories in the situation considered may be complicated by aspects which no data was available about or which were not modeled. Examples of such aspects are local weather, turbulence, VFR flights, traffic outside the terminal area, and departing traffic.

To some extent, the tools for communication, navigation, and surveillance (CNS) that are needed to fly these flexible arrival trajectories are already available. Navigation accuracy
during the entire arrival procedure has increased significantly due to the introduction of satellite navigation. This is important to allow standard routes not being followed any more. Most aircraft are equipped with an FMS that supports RNAV operation, which removes the necessity to follow ground-based navigation fixes.

This work, however, presupposes the availability of certain new tools for CNS. Flying curved approaches may require the microwave landing system (MLS), which is currently not installed at most airports. It was assumed here that curved approaches can be flown. Data link, currently used only for a few applications, is expected to provide the functionality of communicating the planned trajectory between ATC and the aircraft. It was assumed in the analysis also that this type of data link was available.

### 8.1.2 Task Demand Load for Pilots

Flexible arrival trajectories may become more complex than those used today. In addition, 4-D constraints may become more stringent. This may result in the task demand load of flying the aircraft along the assigned trajectory becoming higher. In order to address this concern, a number of metrics for describing the task demand load of guiding the aircraft along a 4-D trajectory were identified. Only the task of manually controlling the aircraft was considered. The metrics were validated experimentally in a flight simulator. In the experiments arrival trajectories had to be flown into Amsterdam Airport Schiphol.

The experiments confirmed that the shape of the reference trajectory influenced the task demand load, where the largest influence was due to the vertical shape of the trajectory and the speed profile. It could not be shown that changing the lateral shape of the trajectory influences task demand load. This result is particularly interesting when considering that many of the trajectories that were evaluated experimentally included bank angles close to the maximum value used in practice. It is possible that only changing the lateral shape of the trajectories can increase ATM performance without increasing task demand load. It has not been studied if this is the case though or how much performance can be gained. Changing the lateral shape of the trajectory can, however, be expected to increase task demand load for air traffic controllers (Section 8.1.3).

In the experiments the only task considered was guiding the aircraft along the reference trajectory. Other pilot tasks, such as responding to changing winds and communicating with ATC were not considered. Monitoring separation from other traffic was only taken into account to a very limited extent. All traffic, if present, was also well-separated and behaved accordingly. It is likely that changing the lateral shape of the trajectory affects the complexity of predicting future positions of the own aircraft and the surrounding traffic. This may increase the task demand load of pilot tasks not considered here, particularly monitoring separation from traffic.

The most important characteristics of the trajectory that affected task demand load were the commanded energy reductions in the trajectory in relation to the energy reductions that the aircraft can realise, the ratio between time necessary to carry out manoeuvres and
the time available, the summation of the sizes of the flight path angle changes that have to be carried out, the maximum vertical acceleration, and the maximum longitudinal acceleration.

The off-line analysis indicated that the values of the metrics for the pilot task demand load relating to longitudinal motion generally increased for the flexible arrival trajectories. This is mainly caused by the necessity of more manoeuvres. These manoeuvres are necessary to achieve an altitude profile closer to a profile where altitude decreases continuously while still meeting all the constraints. The flexible arrival trajectories typically resulted in one additional manoeuvre of changing the flight path angle and up to about 3 manoeuvres where the flight path angle and speed have to be changed simultaneously. At present, these manoeuvres are normally not applied during the arrival procedure. The energy rate demand became for flexible trajectories much closer to 1, meaning that aircraft had to be operated closer to performance limits. There were no indications found that the task demand load relating to lateral motion was increased due to the use of flexible arrival trajectories.

In the experiments indications were found that a primary flight display based on a tunnel-in-the-sky display that gives information related to reference position, reference speed, and acceleration can reduce the task demand load, especially in relation to control of along-track position. Such a display generally increased path-following performance in the vertical, lateral, and longitudinal direction. More accurate control of along-track position allows meeting time constraints better. This has been identified as an important way of increasing ATM efficiency. It is therefore concluded that the 4-D guidance displays studied may help to increase ATM efficiency and to keep task demand load acceptable for increasingly complex arrival trajectories.

### 8.1.3 Task Demand Load for Air Traffic Controllers

Task demand load for air traffic controllers was assessed by estimating airspace complexity. This was done by calculating the values of a number of metrics from literature that describe geometric properties of the traffic flows. These metrics assume conventional ATC. The number of points where arrival and departure traffic cross was introduced as a new metric. The reason for this was that a higher number of crossing points creates more interaction between traffic flows, which is an effect not addressed by the other metrics used. In addition, metrics were taken into account that describe the distances between and closure rates of aircraft pairs.

The traffic density generally became lower for flexible arrival trajectories than for conventional trajectories because more airspace could be used. The flexible trajectories could, however, result in almost doubling the number of crossing points between arrival and departure traffic, more disorder in the traffic flows (through more convergence and more divergence), almost doubling the average value of the maximum vertical closure rates between aircraft pairs, and reducing the average value of the minimum horizontal separation distances between aircraft pairs with more than 3 nmi. For the case that lateral profiles were optimised, a decrease in minimum horizontal separation distance could be prevented. It
is concluded though that flexible arrival trajectories may increase airspace complexity. It is therefore also concluded they may increase task demand load for air traffic controllers. Similar to the pilot’s task, improvements in human-machine interfaces in air traffic control may help to reduce task demand load.

8.2 Recommendations

8.2.1 Off-line Analyses

Although the results are encouraging, it is important to note that the analysis discussed in the thesis considered only Amsterdam Airport Schiphol in a particular traffic and weather situation. To justify the introduction of flexible arrival trajectories, the benefits of these trajectories need to be demonstrated for more sites. It is also necessary to determine how traffic demand, weather, and runway configuration influence ATM performance.

The approach of satisficing decision making prevented the specification of weight factors, which is often very difficult. Instead, desired levels of performance, referred to as aspiration levels, need to be established for each objective. The selected aspiration levels drive the search in a certain direction. It is therefore likely that different aspiration levels also result in different performance scores. The effects of selecting different aspiration levels at the beginning of the search process need to be considered in future work since this may result in finding different solutions. In addition, the aspiration levels that air traffic controllers use may well depend on the circumstances. It may therefore be necessary to conduct experiments with controllers in order to determine which aspiration levels they use and which performance scores can then be obtained.

It is recommended to carry out the analysis with more accurate airplane models for comparing thrust, noise, and emissions for the different trajectories. It is also to be noted that the scheduling algorithm used attempts to schedule a continuously decreasing altitude and speed profile that is equal for all aircraft. Aircraft, however, descent and decelerate at specific rates, which are influenced by aircraft configuration. It is recommended to carry out a similar analysis for trajectories based on descent and deceleration rates dependent on aircraft type and configuration. These trajectories may be calculated with FMS optimisation algorithms.

8.2.2 Robustness

Because genetic optimisation is based on continuously evolving solutions, it is particularly suitable for adapting solutions to changing circumstances. In this case, these changing circumstances can be related to, for example, weather, runway configuration, aircraft not conforming to agreed flight paths, and miscommunication.

At the beginning of the project, this was one of the reasons for choosing a genetic algorithm as the solution methodology. In the thesis, however, this aspect is not studied.
Being able to respond effectively to changing circumstances is key to both safety and efficiency. Research is therefore warranted that considers the effects of changing circumstances in the process of looking for solutions.

### 8.2.3 Implementation in ATC Operational Practice

The thesis did not consider how the scheduling method discussed here may be implemented in ATC operational practice. It is clear that implementing a process of scheduling flexible arrival trajectories based on for instance genetic optimisation requires extensive additional research and evaluations. In particular, there are several potential problems that need to be studied.

One problem is related to wake vortex separation. Wake vortex separation is currently applied on the straight ILS approach path. Once new arrival trajectories are introduced, however, the vortices may be located at varying locations instead of only on the standard ILS path. This poses a potential problem, because it may make the separation problem for the air traffic controller more complex. This may be a reason for limiting the allowed shapes of arrival trajectories. For example, aircraft that generate large vortices may only be allowed on specific trajectories. It is first necessary though to determine what the criteria are for trajectories to be acceptable with respect to this aspect of wake vortex separation.

Another problem is related to the ATC human-machine interface. The solution search process based on sequential improvements is in essence more compatible with an operator’s approach to selecting and improving solutions than calculating the scores of many potential solutions and selecting the one with the highest score. It needs to be studied though which information from the scheduling algorithm should be communicated with air traffic controllers and in what form.

A disadvantage of using genetic algorithms is that because of its random nature, different solutions may result every time the same problem is solved. This is an important issue to be taken into account when developing a system to be used in operational practice. It may be necessary to let such a system consider only those solutions that result in substantial improvements over the actual schedule. Schedules that are radically different but yield only limited improvements may need to be discarded.

### 8.2.4 Planning Volumes of Airspace in 4-D

Support tools for air traffic controllers currently being developed focus on assistance for trajectory scheduling. However, it has been argued that available resources such as airspace may be exploited better by using centralised scheduling only for generating constraints in space and time. The aircraft operators should then be allowed to optimise their trajectories within these constraints (Wilson, 1996). This may be done with the FMS, although new functions will have to be added to current FMS systems.
The scheduling method designed in Chapter 3 may be extended to schedule 4-D volumes of airspace instead of trajectories. The issue of scheduling constraints in 4-D, however, needs to be addressed in more detail before such a method can be developed. Some of the requirements that have to be satisfied for describing 4-D space effectively and a preliminary approach as to how this may be done are outlined in (Vormer, Melissen, Mulder, & van Paassen, 2004).

### 8.2.5 Metrics for Pilot Task Demand Load

Theory about the effects of the flight path on task demand load exist only in a limited form. Hypotheses about possible metrics that may be important for task demand load were formed in this work inspired by the categories of workload as they are considered in the task load index (TLX) method. Although the importance of some of these metrics for task demand load was shown, predicting the task demand load proved to be very difficult.

On the one hand, this may be caused by the fact that only a linear regression analysis was carried out. It needs to be studied if second-order or higher-order regression analyses are more successful in predicting task demand load. In addition, it is recommended by statisticians to keep the number of independent variables small. This can help to improve the quality of the regression analysis. In this work, the metrics related to number of manoeuvres, manoeuvre time, cumulative size of vertical path changes, vertical acceleration, speed change, and longitudinal acceleration were considered separately for vertical path changes, speed changes, and combined vertical path and speed changes. Combining the contributions from different manoeuvres for these metrics may be a suitable way of reducing the number of metrics. It needs to be studied if this gives better results for the regression analysis.

On the other hand, the values of the metrics may be calculated more accurately using a non-linear aircraft model. In addition, handling qualities criteria may be used to formulate hypotheses about other factors that are important for task demand load.

### 8.2.6 Experiments

In the experiments carried out to study the task demand load for the pilot, the only task considered was guiding the aircraft along the reference trajectory. Although in one of the experiments surrounding traffic was included, it is recommended to conduct more experiments with traffic present. This is because the complexity of predicting the future separation from other traffic may be influenced by the shape of the trajectory. In particular factors that were found to be of less importance for the task of guiding the aircraft along the trajectory, such as the lateral shape of the trajectory and the sizes of the speed changes, may influence the ability of comprehending current and future traffic situations. It is also recommended to increase the fidelity of the experiments by including more realistic winds and communication with ATC based on data link. Responding to winds and communicating with ATC are important tasks of flight crews during the approach. The use of data link will provide an
additional challenge because it is currently used only in a very limited form.

8.2.7 Airspace Complexity
Airspace complexity remains an important topic of current research. It is viewed from many different perspectives and there is no formula that can readily be applied to calculate it. In this work metrics were used that appear to be considered important for airspace complexity by different people. It is, however, not known if an increase in one metric can be compensated by a decrease in another metric. It was concluded here that an increase in the value of a metric may result in an increase in complexity. The relative importance and the relationship between the different metrics is not clear though and needs to be studied before an accurate prediction of TDL for air traffic controllers can be made.

8.2.8 Establishing Constraints for TDL Metrics
Although a number of metrics have been shown to be important for the task demand load for pilots and controllers, it is not known if these metrics may be integrated into a single measure. It is also not known if it is possible to specify the largest allowed value of such a measure of task demand load. It is, however, more likely that constraints need to be met on a number of metrics for trajectories to be acceptable (see the discussion in Section 3.1.3). It is therefore recommended to establish constraints for the metrics studied here.
The runway system at Schiphol Airport in Amsterdam currently consists of the 5 main runways 18L-36R, 09-27, 06-24, 18R-36L, and 18C-36C. The sixth short runway 04-22 is normally only used for general aviation but can also be employed for the rest of the traffic if required.

For most large airports, use is normally made of standard terminal arrival routes (STARs) from the entry point into the terminal area to the runway. For Schiphol, traffic starts the approach normally from the initial approach fix (IAF) at one of the terminal area entry points Artip, Sugol, or River at about 7,000 ft. The navigation between IAF and interception of final approach course is currently based on radar vectoring by ATC with the STARs as standard reference trajectories. The STARs provide lateral profiles only.

The runways are used in different configurations. Since for the available traffic data (Section 7.1.1) the main runways used for landing were 18C and 27, the standard approach routes for these runways are shown in Figure A.1. At present, Northwest arrivals are generally not scheduled any more for runway 18C but for the recently added runway 18R instead. However, since the traffic sample used was taken before runway 18R was added, the Northwest route from Sugol to runway 18C is still considered in this work. Except for the different final approach, the route currently in use is the same.

Controllers commonly use unpublished but standard ‘trombone’ approaches to vector traffic flows onto final approach (Histon et al., 2001). In a trombone approach the length of the final leg is varied to adapt the final approach to the situation. Interception of the ILS glide path, which prescribes a descent angle of 3 degrees, takes generally place between about 6 and 11 nmi from the runway threshold. Depending on the length of the final approach segment the final approach starts at an altitude between about 2,000 and 3,000 ft.

During night hours part of the arrival route may be flown as a continuous descent. However, high traffic loads during day times normally result in level flight segments in the
arrival trajectory and in interception of the final approach course in level flight. Leveling off is always conducted above 2,000 ft and in general takes place outside residential areas to minimise noise disturbance for the environment.

The speeds shown in Figure A.1 represent general speed instructions given by controllers. Below 10,000 ft the maximum speed is always restricted to 250 kts IAS.

To accommodate departure traffic, standard outbound trajectories called standard instrument departures (SIDs) have been defined (Figure A.2). Since in the traffic data available almost all traffic departed from runways 24 and 18L, the SIDs for these two runways are shown.
Figure A.1  Standard approach procedures for runways 18C and 27 at Schiphol Airport. Traffic enters the terminal area through the meter fixes Artip, River, and Sugol from where standard approach trajectories are normally used to guide the aircraft towards the runways. The standard approach routes for runway 18C and runway 27 are shown. It should be noted that the indicated Northwest route that is shown to connect to runway 18C (previously designated 19R) represents the situation at Schiphol before February 2003. This route is currently used to guide traffic to the newly added runway 18R instead, which is not considered in this study.
Figure A.2  Schematic overview of the SIDs from runways 24 and 18L at Schiphol Airport.
The aircraft symmetric equations of motion as derived in for instance (Mulder, van Staveren, & van der Vaart, 2000) are given by:

\[
\begin{bmatrix}
C_{X_{u}} - 2\mu_c D_c \\
C_{Z_{u}} \\
0 \\
C_{m_u}
\end{bmatrix}
\begin{bmatrix}
C_{X_{u}} \\
C_{Z_{u}} + (C_{Z_{a}} - 2\mu_c) D_c \\
0 \\
C_{m_{a}} + C_{m_{u}} D_c
\end{bmatrix}
\begin{bmatrix}
C_{X_{0}} \\
- C_{X_{0}} \\
- D_c \\
C_{m_{q}} - 2\mu_c K_{Y}^2 D_c
\end{bmatrix}
\begin{bmatrix}
\dot{u} \\
\dot{\alpha} \\
\dot{\theta} \\
\dot{q}
\end{bmatrix}
= \begin{bmatrix}
-C_{X_{\delta_e}} \\
-C_{Z_{\delta_e}} \\
0 \\
-C_{m_{\delta_e}}
\end{bmatrix}
\cdot \delta_{e}
+ \begin{bmatrix}
-C_{X_{\delta_T}} \\
-C_{Z_{\delta_T}} \\
0 \\
-C_{m_{\delta_T}}
\end{bmatrix}
\cdot \delta_{T}, \quad (B.1)
\]

where \( D_c = \frac{\dot{c}}{V} \frac{d}{dt} \) and \( \dot{u} = \frac{u}{V} \). The contribution from \( \delta_T \) was added to the original equations here in a similar way as the contribution from \( \delta_e \) since this work also considers the throttle input. However, none of the aircraft models that were used specified the values of the derivatives related to \( \delta_T \). In (How, 2003) the maximum value used for the acceleration in the direction of aircraft velocity for a B747 was 0.3g. For this reason, \( C_{X_{\delta_T}} \) was estimated as:

\[
C_{X_{\delta_T}} = \frac{1}{2\rho V^2 S} \cdot 0.3 \cdot mg, \quad (B.2)
\]

using the procedure for making forces dimensionless as described in (Mulder et al., 2000) and for \( 0 \leq \delta_T \leq 1 \). Similar to the mentioned literature, \( C_{Z_{\delta_T}} \) and \( C_{m_{\delta_T}} \) were assumed to be equal to 0.
These equations are the linearised equations of motion that describe for all variables used the deviations from a nominal condition. This system can also be represented in the state-space form,

\[ \dot{x} = A \, x + B \, u, \]  

(B.3)

\[ y = C \, x + D \, u, \]  

(B.4)

with,

\[ x = [ \, \dot{u} \, \alpha \, \theta \, q \, ]^T, \]  

(B.5)

and,

\[ u = [ \, \delta_e \, \delta_T \, ]^T. \]  

(B.6)

This is done by re-writing Equation (B.1) according to the procedure described in (van der Vaart, 1994), obtaining the linear time-independent matrices \( A \) and \( B \).

The state-space model is augmented with \( h \) as extra state by augmenting the \( A \) matrix using the equation:

\[ \dot{h} = V (\theta - \alpha). \]  

(B.7)

The matrices \( C \) and \( D \) are selected finally so that:

\[ y = [ \, \dot{u} \, \alpha \, \theta \, q \, h \, \gamma \, ]^T, \]  

(B.8)

by additionally using:

\[ \gamma = \theta - \alpha. \]  

(B.9)
STABILITY AND CONTROL DERIVATIVES

Table C.1 Symmetric stability and control derivatives for the Cessna Citation 500 in cruise configuration at 128.2 m/s (van der Vaart, 1994).

<p>| | | | | |</p>
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<tr>
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<tbody>
<tr>
<td>$V$</td>
<td>128.2 m s$^{-1}$</td>
<td>$c$</td>
<td>2.022 m</td>
<td>$K_Y^2$</td>
</tr>
<tr>
<td>$m$</td>
<td>5207 kg</td>
<td>$S$</td>
<td>24.2 m$^2$</td>
<td>$\mu_c$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>0.7361 kg m$^{-3}$</td>
<td>$C_{X_0}$</td>
<td>$-0.0197$</td>
<td>$C_{Z_0}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$C_{X_u}$</td>
<td>$-0.0545$</td>
<td>$C_{Z_u}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$C_{X_\alpha}$</td>
<td>$0.3127$</td>
<td>$C_{Z_\alpha}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$C_{X_q}$</td>
<td>$0.0833$</td>
<td>$C_{Z_q}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$C_{X_{\delta_p}}$</td>
<td>$-0.2817$</td>
<td>$C_{Z_{\delta_p}}$</td>
</tr>
</tbody>
</table>
Table C.2  Symmetric stability and control derivatives for the Cessna Citation 500 in cruise configuration at 160.3 m/s (van der Vaart, 1994).

\[
\begin{array}{cccc}
V & = & 160.3 \text{ m s}^{-1} & \bar{c} = 2.022 \text{ m} & K_Y^2 = 1.114 \\
m & = & 5207 \text{ kg} & S = 24.2 \text{ m}^2 & \mu_c = 142 \\
\rho & = & 0.7361 \text{ kg m}^{-3} \\
C_{X_0} & = & -0.0277 & C_{Z_0} = -0.2160 \\
C_{X_u} & = & -0.0698 & C_{Z_u} = -0.4702 & C_{m_u} = 0.0561 \\
C_{X_\alpha} & = & 0.0744 & C_{Z_\alpha} = -5.6149 & C_{m_\alpha} = -0.4982 \\
C_{X_q} & = & 0.0259 & C_{Z_q} = -0.2039 & C_{m_q} = 0.1689 \\
C_{X_\delta e} & = & -0.0131 & C_{Z_{\delta e}} = -0.5814 & C_{m_{\delta e}} = -1.2269 \\
\end{array}
\]

Table C.3  Symmetric stability and control derivatives for the Boeing B747-100 in approach configuration with flaps at 30 degrees (Mulder et al., 2000).

\[
\begin{array}{cccc}
V & = & 73.0 \text{ m s}^{-1} & \bar{c} = 8.321 \text{ m} & K_Y^2 = 2.488 \\
m & = & 254240 \text{ kg} & S = 510.97 \text{ m}^2 & \mu_c = 48.81 \\
\rho & = & 1.125 \text{ kg m}^{-3} \\
C_{X_0} & = & 0 & C_{Z_0} = -1.49 \\
C_{X_u} & = & -0.42 & C_{Z_u} = -2.98 & C_{m_u} = -0.185 \\
C_{X_\alpha} & = & 1.59 & C_{Z_\alpha} = -5.293 & C_{m_\alpha} = -1.05 \\
C_{X_q} & = & 0 & C_{Z_q} = 6.70 & C_{m_q} = -3.45 \\
C_{X_{\delta e}} & = & 0 & C_{Z_{\delta e}} = -6.66 & C_{m_{\delta e}} = -21.98 \\
C_{X_{\delta e}} & = & 0 & C_{Z_{\delta e}} = -0.353 & C_{m_{\delta e}} = -1.42 \\
\end{array}
\]
D.1 Flight Director

Pitch
The pitch bar of the FD indicates the commanded pitch attitude angle $\theta_{cmd}$. The flight director logic was based on the control laws used in a B747 flight simulator. The value of $\theta_{cmd}$ is calculated based on altitude deviation and altitude deviation rate, where the gains used were the gains used for following the ILS approach path. The controller did also include a pitch damper. The sensitivity of the pitch bar was set to 13 mm per 10 deg, which was the scale of the pitch ladder.

Typical altitude time histories are shown in Figure D.1. In Experiment 3 flight path anticipation was added (Section 6.3.2). This was done by predicting the future altitude deviation and deviation rate for 10 seconds ahead assuming $\gamma$ and speed remained constant. This altitude deviation and deviation rate were fed to the FD.

Roll
The roll bar of the FD indicates the commanded roll angle $\phi_{cmd}$. In Experiment 1 a controller used in previous applications for LNAV with this aircraft model was used. It made use of feedback of lateral deviation and track angle error. This controller, however, was replaced in Experiment 2 with a controller used for MLS guidance in a B747 simulator. This controller was more suitable for the approach phase. The controller was based on feedback of lateral deviation and lateral deviation rate. A roll damper was included for all experiments.
Figure D.1  Time histories of altitude for one pilot following the flight director.

Figure D.2  Time histories of track angle for one pilot following the flight director.
The sensitivity of the roll bar was initially set to 7.8 mm per 10 deg, after consultation of a general aviation pilot. However, in Experiment 2 the sensitivity was reduced to 2.0 mm per 10 deg as the roll bar was found too sensitive. In Experiment 2 turn anticipation was also added by feeding a prediction of lateral deviation and deviation rate for 7 seconds ahead to the FD (Section 6.2.3). The prediction was made assuming speed and track angle remained constant. Examples of typical track angle time histories are shown in Figure D.2.

### D.2 Longitudinal Position Controller

The longitudinal position controller calculates a commanded change in $V_{IAS}$. It aims to reduce the difference in along-track position between aircraft ($x_{a/c}$) and bubble ($x_{bubble}$) and difference in along-track speed between aircraft ($V_{a/c}$) and bubble ($V_{bubble}$) to zero, see Figure D.3. The gain on along-track position was tuned to $K_P = 0.0085$ and the gain on along-track speed to $K_D = 0.4$. Typical time histories are shown in Figure D.4.

![Block diagram of the longitudinal position controller.](image)

**Figure D.3** Block diagram of the longitudinal position controller.

![Time histories of longitudinal position error $e_{lon} = x_{bubble} - x_{a/c}$ for one pilot following the longitudinal position controller in Experiment 2 for four different trajectories (corresponding to the four trajectory types used).](image)

**Figure D.4** Time histories of longitudinal position error $e_{lon} = x_{bubble} - x_{a/c}$ for one pilot following the longitudinal position controller in Experiment 2 for four different trajectories (corresponding to the four trajectory types used).
This appendix lists the runs carried out in the experiments (Chapter 6).
Table E.1  Runs in Experiment 1 (all pilots). The trajectory types are specified in Section 6.1.2. With respect to the PFD, 1 refers to the flight director display, 2 to the basic bubble display, 3 to the speed marks display and 4 to the modified Grunwald display.

<table>
<thead>
<tr>
<th>Run</th>
<th>Type</th>
<th>PFD</th>
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<tbody>
<tr>
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<td>4</td>
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<tr>
<td>2</td>
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Table E.2  Runs in Experiment 2 (pilots 1 to 4). The trajectory types are specified in Section 6.2.2. With respect to the PFD, 1 refers to the flight director display, 2 to the basic bubble display and 3 to the modified Grunwald display.

<table>
<thead>
<tr>
<th>Run</th>
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Table E.3  Runs in Experiment 2 (pilots 5 to 7). The trajectory types are specified in Section 6.2.2. With respect to the PFD, 1 refers to the flight director display, 2 to the basic bubble display and 3 to the modified Grunwald display.

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Table E.4 Runs in Experiment 3 (pilots 1 to 3). The trajectory types are specified in Section 6.3.2. With respect to Alt, 1 refers to an interception altitude of 2,000 ft, 2 to 2,300 ft, 3 to 2,600 ft, and 4 to 3,000 ft. With respect to the PFD, 1 refers to the flight director display and 2 to the tunnel display.

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Table E.5  Runs in Experiment 3 (pilots 4 to 6). The trajectory types are specified in Section 6.3.2. With respect to Alt, 1 refers to an interception altitude of 2,000 ft, 2 to 2,300 ft, 3 to 2,600 ft, and 4 to 3,000 ft. With respect to the PFD, 1 refers to the flight director display and 2 to the tunnel display.

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Table E.6  Runs in Experiment 3 (pilot 7). The trajectory types are specified in Section 6.3.2. With respect to Alt, 1 refers to an interception altitude of 2,000 ft, 2 to 2,300 ft, 3 to 2,600 ft, and 4 to 3,000 ft. With respect to the PFD, 1 refers to the flight director display and 2 to the tunnel display.

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This appendix contains the reference trajectories used in Experiment 2 (Section 6.2).
Figure F.1  Reference trajectory for trajectory type 1 and display 1 (first run).

Figure F.2  Reference trajectory for trajectory type 1 and display 1 (second run).
Figure E.3 Reference trajectory for trajectory type 1 and display 2 (first run).

Figure E.4 Reference trajectory for trajectory type 1 and display 2 (second run).
Figure F.5  Reference trajectory for trajectory type 1 and display 3 (first run).

Figure F.6  Reference trajectory for trajectory type 1 and display 3 (second run).
Figure E.7 Reference trajectory for trajectory type 2 and display 1 (first run).

Figure E.8 Reference trajectory for trajectory type 2 and display 1 (second run).
Figure E.9 Reference trajectory for trajectory type 2 and display 2 (first run).

Figure E.10 Reference trajectory for trajectory type 2 and display 2 (second run).
Figure F.11 Reference trajectory for trajectory type 2 and display 3 (first run).

Figure F.12 Reference trajectory for trajectory type 2 and display 3 (second run).
Figure F.13  Reference trajectory for trajectory type 3 and display 1 (first run).

Figure F.14  Reference trajectory for trajectory type 3 and display 1 (second run).
Figure F.15  Reference trajectory for trajectory type 3 and display 2 (first run).

Figure F.16  Reference trajectory for trajectory type 3 and display 2 (second run).
Figure F.17  Reference trajectory for trajectory type 3 and display 3 (first run).

Figure F.18  Reference trajectory for trajectory type 3 and display 3 (second run).
Figure E.19 Reference trajectory for trajectory type 4 and display 1 (first run).

Figure E.20 Reference trajectory for trajectory type 4 and display 1 (second run).
Figure F.21 Reference trajectory for trajectory type 4 and display 2 (first run).

Figure F.22 Reference trajectory for trajectory type 4 and display 2 (second run).
Figure E.23 Reference trajectory for trajectory type 4 and display 3 (first run).

Figure E.24 Reference trajectory for trajectory type 4 and display 3 (second run).
EXAMPLES OF ARRIVAL TRAJECTORIES

This appendix contains examples of arrival trajectories generated in Chapter 7.
EXAMPLES OF ARRIVAL TRAJECTORIES

(a) arrival and departure trajectories

(b) differences between scheduled and measured times at the runway

(c) differences between scheduled and measured times at the meter fix

Figure G.1 Trajectories and time schedules for Case CUR.
Figure G.2  Profiles for all trajectories for Case CUR.
### Figure G.3  Segment properties for all trajectories for Case CUR.
(a) arrival and departure trajectories

(b) differences between scheduled and measured times at the runway

(c) differences between scheduled and measured times at the meter fix

Figure G.4 Trajectories and time schedules for Case CUR IDEAL.
Figure G.5 Profiles for all trajectories for Case CUR IDEAL.
Figure G.6  Segment properties for all trajectories for Case CUR IDEAL.
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(a) arrival and departure trajectories

(b) differences between scheduled and measured times at the runway

(c) differences between scheduled and measured times at the meter fix

Figure G.7 Trajectories and time schedules for Case FLX TMS.
Figure G.8  Profiles for all trajectories for Case FLX TMS.
Figure G.9  Segment properties for all trajectories for Case FLX TMS.
Figure G.10  Trajectories and time schedules for Case FLX ALT/SPD.
Figure G.11 Profiles for all trajectories for Case FLX ALT/SPD.
Figure G.12  Segment properties for all trajectories for Case FLX ALT/SPD.
(a) arrival and departure trajectories

(b) differences between scheduled and measured times at the runway

(c) differences between scheduled and measured times at the meter fix

Figure G.13 Trajectories and time schedules for Case SHORT IC.
Figure G.14 Profiles for all trajectories for Case SHORT IC.
Figure G.15  Segment properties for all trajectories for Case SHORT IC.
Figure G.16 Trajectories and time schedules for Case DIRECT.
Figure G.17  Profiles for all trajectories for Case DIRECT.
Figure G.18  Segment properties for all trajectories for Case DIRECT.
214 EXAMPLES OF ARRIVAL TRAJECTORIES

Figure G.19 Trajectories and time schedules for Case FLX LAT.
Figure G.20 Profiles for all trajectories for Case FLX LAT.
Figure G.21  Segment properties for all trajectories for Case FLX LAT.
H.

NOTATIONS AND ABBREVIATIONS

H.1 Notations

Symbols

\( a \)     longitudinal acceleration \( (=dV_C/dt) \), m/s\(^2\)
\( a_z \)   vertical acceleration, m/s\(^2\)
\( A \)     area
\( A \)     system matrix
\( B \)     input matrix
\( c \)     integer
\( \bar{c} \) mean aerodynamic chord, m
\( C \)     output matrix
\( C \)     stability/control derivative
\( Conv \) convergence
\( CR_H \) mean maximum horizontal closure rate, m/s
\( CR_V \) mean maximum vertical closure rate, m/s
\( d \)     time deviation, s
\( d \)     3-D distance vector
\( D \)     density
\( D \)     distance, m
\( D \)     drag, N
\( D \)     feed forward matrix
\( D_c \)   = \( \frac{c}{V^2} \frac{d}{dt} \)
Div \quad \text{divergence}

\begin{align*}
e_{2D} & \quad \text{2-D position error, m} \\
e_{IAS} & \quad \text{speed error, m/s} \\
e_{lat} & \quad \text{cross-track error, m} \\
e_{lon} & \quad \text{longitudinal position error, m} \\
e_{N_{sbr}} & \quad \text{error in predicting } N_{sbr}, \text{ min}^{-1} \\
e_v & \quad \text{vertical position error, m} \\
e_{\delta T_{cmd}} & \quad \text{error in predicting STD } \delta T_{cmd}, \% \\
E & \quad \text{total energy, J} \\
\dot{E} & \quad \text{energy rate demand } (= \frac{\dot{E}_{cmd}}{\dot{E}_{min}}) \\
\text{ETA} & \quad \text{estimated time of arrival} \\
f & \quad \text{fitness} \\
f' & \quad \text{scaled fitness} \\
f & \quad \text{mean fitness} \\
F & \quad \text{objective function value} \\
F_{i,j} & \quad \text{F distribution with } i \text{ and } j \text{ degrees of freedom} \\
g & \quad \text{gravitational acceleration, m/s}^2 \\
h & \quad \text{altitude, m} \\
H & \quad \text{transfer function} \\
i & \quad = \sqrt{-1} \\
ID & \quad \text{flight identification code} \\
\text{Im}\{\} & \quad \text{imaginary part of a complex variable} \\
K & \quad \text{gain} \\
K_Y & \quad \text{non-dimensional radius of gravitation about the } Y-\text{axis of the stability axis reference frame} \\
L & \quad \text{noise load on community, s/m}^2 \\
L & \quad \text{length, m} \\
m & \quad \text{aerodynamic moment about the } Y-\text{axis of the stability axis reference frame, Nm} \\
m & \quad \text{mass, kg} \\
M & \quad \text{number of segments} \\
N & \quad \text{number of aircraft} \\
N & \quad \text{number of manoeuvres} \\
N_8 & \quad \text{maximum number of aircraft pairs with less than 8 nmi horizontal distance} \\
N_{13} & \quad \text{maximum number of aircraft pairs with less than 13 nmi horizontal distance} \\
N_{AC} & \quad \text{maximum number of aircraft with an altitude change rate over 500 feet per minute} \\
N_{bv} & \quad \text{number of times per minute that the bubble boundaries are violated, min}^{-1} \\
N_C & \quad \text{number of crossings points between arrival and departure flows} \\
N_M & \quad \text{total number of manoeuvres}
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<td>maximum number of aircraft with an airspeed change greater than 10 knots during a 2-minute interval</td>
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<td>mean minimum vertical separation distance, m</td>
</tr>
<tr>
<td>$STA$</td>
<td>scheduled time of arrival</td>
</tr>
<tr>
<td>$t$</td>
<td>time, s</td>
</tr>
<tr>
<td>$T$</td>
<td>flight time, s</td>
</tr>
<tr>
<td>$T$</td>
<td>segment type</td>
</tr>
<tr>
<td>$T$</td>
<td>time frame, s</td>
</tr>
<tr>
<td>$T$</td>
<td>throughput, hr$^{-1}$</td>
</tr>
<tr>
<td>$T$</td>
<td>thrust, N</td>
</tr>
<tr>
<td>$T_p$</td>
<td>commanded thrust</td>
</tr>
<tr>
<td>$T_M$</td>
<td>time needed to carry out a manoeuvre, s</td>
</tr>
<tr>
<td>$T_{ri}$</td>
<td>roll-in time, s</td>
</tr>
<tr>
<td>$u$</td>
<td>speed along the $X$-axis of the stability axis reference frame, m/s</td>
</tr>
<tr>
<td>$\dot{u}$</td>
<td>$= u/V$</td>
</tr>
<tr>
<td>$u$</td>
<td>input vector</td>
</tr>
<tr>
<td>$V$</td>
<td>true airspeed, m/s</td>
</tr>
<tr>
<td>$V_{a/c}$</td>
<td>aircraft along-track speed, m/s</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
</tr>
<tr>
<td>$V_{app}$</td>
<td>approach speed, m/s</td>
</tr>
<tr>
<td>$V_{at}$</td>
<td>along-track speed, m/s</td>
</tr>
<tr>
<td>$V_{BCS}$</td>
<td>bubble capture speed, m/s</td>
</tr>
<tr>
<td>$V_{bubble}$</td>
<td>bubble along-track speed, m/s</td>
</tr>
<tr>
<td>$V_C$</td>
<td>calibrated airspeed, m/s</td>
</tr>
<tr>
<td>$V_{des}$</td>
<td>reference descent speed, m/s</td>
</tr>
<tr>
<td>$V_e$</td>
<td>speed error, m/s</td>
</tr>
<tr>
<td>$V_g$</td>
<td>ground speed, m/s</td>
</tr>
<tr>
<td>$V_{IAS}$</td>
<td>indicated airspeed, m/s</td>
</tr>
<tr>
<td>$W$</td>
<td>weight, N</td>
</tr>
<tr>
<td>$x, y, z$</td>
<td>position coordinates in Earth-fixed reference frame</td>
</tr>
<tr>
<td>$\mathbf{x}$</td>
<td>state vector</td>
</tr>
<tr>
<td>$x_{a/c}$</td>
<td>aircraft along-track position, m</td>
</tr>
<tr>
<td>$x_{bubble}$</td>
<td>bubble along-track position, m</td>
</tr>
<tr>
<td>$x_e$</td>
<td>position error, m</td>
</tr>
<tr>
<td>$X$</td>
<td>aerodynamic force along the $X$-axis of the stability axis reference frame, N</td>
</tr>
<tr>
<td>$\mathbf{y}$</td>
<td>output vector</td>
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<tr>
<td>$Z$</td>
<td>aerodynamic force along the $Z$-axis of the stability axis reference frame, N</td>
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>$\alpha$</td>
<td>angle of attack, rad</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>significance level</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>weighted coefficient</td>
</tr>
<tr>
<td>$\beta$</td>
<td>fraction of solutions above aspiration level</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>flight path angle, rad</td>
</tr>
<tr>
<td>$\delta_a$</td>
<td>aileron deflection, rad</td>
</tr>
<tr>
<td>$\delta_e$</td>
<td>elevator deflection, rad</td>
</tr>
<tr>
<td>$\delta_T$</td>
<td>thrust ($=T/T_{max}$)</td>
</tr>
<tr>
<td>$\Delta h$</td>
<td>maximum deviation from altitude profile, m</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>time interval, s</td>
</tr>
<tr>
<td>$\Delta t_e$</td>
<td>effective time delay, s</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>time interval, s</td>
</tr>
<tr>
<td>$\Delta T_{sep}$</td>
<td>required time separation, s</td>
</tr>
<tr>
<td>$\Delta V$</td>
<td>maximum deviation from speed profile, m/s</td>
</tr>
<tr>
<td>$\Delta V_{act}$</td>
<td>difference between bubble and a/c along-track speed, m/s</td>
</tr>
<tr>
<td>$\Delta V_C$</td>
<td>speed change, m/s</td>
</tr>
<tr>
<td>$\Delta V_{pc}$</td>
<td>speed change for position control, m/s</td>
</tr>
<tr>
<td>$\Delta V_{vc}$</td>
<td>speed change for velocity control, m/s</td>
</tr>
<tr>
<td>$\Delta \gamma$</td>
<td>flight path angle change, rad</td>
</tr>
<tr>
<td>$\Delta \chi$</td>
<td>track angle change, rad</td>
</tr>
<tr>
<td>$\theta$</td>
<td>pitch attitude angle, rad</td>
</tr>
</tbody>
</table>
\[ \mu_c = \frac{m_{\text{PS}}}{\rho_{\text{S}}} \]

- \( \rho \) : air density, \( \text{m/s}^3 \)
- \( \rho \) : aspiration level
- \( \rho^* \) : constrained aspiration level
- \( \sigma \) : standard deviation
- \( \Sigma |\Delta \gamma| \) : summation of all flight path angle changes in a trajectory, rad
- \( \Sigma |\Delta \chi| \) : summation of all track angle changes in a trajectory, rad
- \( \tau \) : time constant, s
- \( \phi \) : roll angle, rad
- \( \Phi \) : bank angle, rad
- \( \chi \) : track angle, rad
- \( \omega \) : frequency, rad/s
- \( \Omega \) : turn rate, rad/s

**Subscripts**

- \( 0 \) : initial
- \( \text{cmd} \) : commanded
- \( d \) : descent
- \( D \) : differential
- \( \text{entry} \) : entry point into the terminal area
- \( \text{final} \) : point of touch down
- \( h \) : altitude deviation
- \( i \) : aircraft
- \( i \) : flight
- \( j \) : aircraft
- \( j \) : segment
- \( L \) : noise load on community
- \( \text{lon} \) : longitudinal
- \( \text{lat} \) : lateral
- \( \text{max} \) : maximum
- \( mf \) : meter fix
- \( \text{min} \) : minimum
- \( n \) : neuromotor
- \( p \) : propulsion
- \( P \) : vertical path change
- \( P \) : proportional
- \( PS \) : combined vertical path and speed change
- \( r, \text{ref} \) : reference
<table>
<thead>
<tr>
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<th>Description</th>
</tr>
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<tr>
<td>$S$</td>
<td>speed change</td>
</tr>
<tr>
<td>$sbr$</td>
<td>speed brakes</td>
</tr>
<tr>
<td>$td$</td>
<td>prescribed point of touch down</td>
</tr>
<tr>
<td>$T$</td>
<td>track change</td>
</tr>
<tr>
<td>$T$</td>
<td>throughput</td>
</tr>
<tr>
<td>$tot$</td>
<td>total</td>
</tr>
<tr>
<td>$V$</td>
<td>speed deviation</td>
</tr>
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</table>

### H.2 Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>2/-3/-4-D</td>
<td>two-/three-/four-dimensional</td>
</tr>
<tr>
<td>a/c</td>
<td>aircraft</td>
</tr>
<tr>
<td>AAA</td>
<td>Amsterdam Advanced ATC System</td>
</tr>
<tr>
<td>AFCS</td>
<td>automatic flight control system</td>
</tr>
<tr>
<td>ANOVA</td>
<td>analysis of variance</td>
</tr>
<tr>
<td>ARTCC</td>
<td>air route traffic control center</td>
</tr>
<tr>
<td>ATC</td>
<td>air traffic control</td>
</tr>
<tr>
<td>ATFM</td>
<td>air traffic flow management</td>
</tr>
<tr>
<td>ATM</td>
<td>air traffic management</td>
</tr>
<tr>
<td>ATP</td>
<td>Artip</td>
</tr>
<tr>
<td>BADA</td>
<td>Eurocontrol Base of Aircraft Data</td>
</tr>
<tr>
<td>BCS</td>
<td>bubble capture speed</td>
</tr>
<tr>
<td>CAA</td>
<td>Civil Aviation Authority</td>
</tr>
<tr>
<td>CAS</td>
<td>calibrated airspeed</td>
</tr>
<tr>
<td>CDM</td>
<td>collaborative decision making</td>
</tr>
<tr>
<td>CNS</td>
<td>communication, navigation, and surveillance</td>
</tr>
<tr>
<td>COMPAS</td>
<td>Computer Oriented Metering Planning and Advisory System</td>
</tr>
<tr>
<td>CTAS</td>
<td>Center TRACON Automation System</td>
</tr>
<tr>
<td>CUR</td>
<td>current</td>
</tr>
<tr>
<td>CUR IDEAL</td>
<td>current ‘idealised’</td>
</tr>
<tr>
<td>DLR</td>
<td>Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)</td>
</tr>
<tr>
<td>EDA</td>
<td>En Route Descent Advisor</td>
</tr>
<tr>
<td>EEC</td>
<td>Eurocontrol Experimental Centre</td>
</tr>
<tr>
<td>EFIS</td>
<td>electronic flight instrumentation system</td>
</tr>
<tr>
<td>EFMS</td>
<td>experimental flight management system</td>
</tr>
<tr>
<td>Eurocontrol</td>
<td>European Organisation for the Safety of Air Navigation</td>
</tr>
<tr>
<td>FAA</td>
<td>Federal Aviation Administration</td>
</tr>
<tr>
<td>FAST</td>
<td>Final Approach Spacing Tool</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>FCFS</td>
<td>first come first serve</td>
</tr>
<tr>
<td>FD</td>
<td>flight director</td>
</tr>
<tr>
<td>FL</td>
<td>flight level</td>
</tr>
<tr>
<td>FLX ALT/SPD</td>
<td>flexible altitude and speed profiles</td>
</tr>
<tr>
<td>FLX LAT</td>
<td>flexible lateral profiles</td>
</tr>
<tr>
<td>FLX TMS</td>
<td>flexible times</td>
</tr>
<tr>
<td>FMS</td>
<td>flight management system</td>
</tr>
<tr>
<td>GA</td>
<td>genetic algorithm</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>IAF</td>
<td>initial approach fix</td>
</tr>
<tr>
<td>IAS</td>
<td>indicated airspeed</td>
</tr>
<tr>
<td>ICAO</td>
<td>International Civil Aviation Organization</td>
</tr>
<tr>
<td>IFR</td>
<td>instrument flight rules</td>
</tr>
<tr>
<td>ILS</td>
<td>instrument landing system</td>
</tr>
<tr>
<td>LCD</td>
<td>liquid crystal display</td>
</tr>
<tr>
<td>LNAV</td>
<td>lateral navigation</td>
</tr>
<tr>
<td>MAESTRO</td>
<td>Means to Aid Expedition and Sequencing of Traffic with Research of Optimisation</td>
</tr>
<tr>
<td>MF</td>
<td>meter fix</td>
</tr>
<tr>
<td>MLS</td>
<td>microwave landing system</td>
</tr>
<tr>
<td>N/A</td>
<td>not applicable</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>ND</td>
<td>navigation display</td>
</tr>
<tr>
<td>NLR</td>
<td>Nationaal Lucht- en Ruimtevaartlaboratorium (National Aerospace Laboratory)</td>
</tr>
<tr>
<td>PD/1/2/3</td>
<td>First/Second/Third PHARE Demonstration</td>
</tr>
<tr>
<td>PFD</td>
<td>primary flight display</td>
</tr>
<tr>
<td>PHARE</td>
<td>Programme for Harmonised Air Traffic Management Research in Eurocontrol</td>
</tr>
<tr>
<td>PID</td>
<td>proportional integral differential</td>
</tr>
<tr>
<td>RIV</td>
<td>River</td>
</tr>
<tr>
<td>RMS</td>
<td>root mean square</td>
</tr>
<tr>
<td>RNAV</td>
<td>area navigation</td>
</tr>
<tr>
<td>RTCA</td>
<td>Radio Technical Committee for Aeronautics</td>
</tr>
<tr>
<td>RVSM</td>
<td>Reduced Vertical Separation Minimum</td>
</tr>
<tr>
<td>RWY</td>
<td>runway</td>
</tr>
<tr>
<td>SDM</td>
<td>satisfying decision making</td>
</tr>
<tr>
<td>SHORT IC</td>
<td>short intercept</td>
</tr>
<tr>
<td>SID</td>
<td>standard instrument departure</td>
</tr>
<tr>
<td>SIMONA</td>
<td>The International Research Institute for Simulation, Motion and</td>
</tr>
<tr>
<td>Notation</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
</tr>
<tr>
<td>SNK</td>
<td>Student-Newman-Keuls</td>
</tr>
<tr>
<td>SRS</td>
<td>SIMONA Research Simulator</td>
</tr>
<tr>
<td>STAR</td>
<td>standard terminal arrival route</td>
</tr>
<tr>
<td>STD</td>
<td>standard deviation</td>
</tr>
<tr>
<td>SUG</td>
<td>Sugol</td>
</tr>
<tr>
<td>TDL</td>
<td>task demand load</td>
</tr>
<tr>
<td>TLX</td>
<td>task load index</td>
</tr>
<tr>
<td>TMA</td>
<td>Traffic Management Advisor</td>
</tr>
<tr>
<td>TRACON</td>
<td>terminal radar approach control</td>
</tr>
<tr>
<td>VFR</td>
<td>visual flight rules</td>
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De huidige vliegbanen rondom luchthavens zijn gebaseerd op gepubliceerde standaardroutes. In de praktijk voorzien luchtverkeersleiders normaal gesproken vluchtbemanningen van instructies op een tactische basis, wat resulteert in aanpassingen op de standaardroutes. Dit is noodzakelijk om efficiëntie te verhogen en milieubelasting te verminderen omdat de standaardroutes hetzelfde zijn voor verschillende situaties in termen van verkeer en weer. Dit kan echter niet verhinderen dat de luchthavens een knelpunt zijn gaan vormen in het huidige luchtvervoerssysteem. Dit uit zich in de vorm van groeiende vertragingen, emissies en geluidsoverlast.

Het is aangetoond dat het mogelijk is om de vorm van vliegbanen zodanig te kiezen dat vertragingen of milieubelasting minimaal zijn. Het kiezen van de baan om een bepaald criterium te minimaliseren of te maximaliseren wordt aangeduid als het optimaliseren van de vliegbaan. Een voorbeeld van een baan die met betrekking tot geluidsproductie is geoptimaliseerd is de baan die in een ‘continuous descent approach’ of ‘three-degree decelerated approach’ wordt gevlogen. Het is aangetoond dat een dergelijke baan milieubelasting kan verminderen omdat een groot deel van de nadering met laag motorvermogen wordt gevlogen. Nochtans is het implementeren van optimale banen zoals in een continuous descent approach echter vaak moeilijk. Operationele snelheids- en hoogtebeperkingen en ad hoc instructies van verkeersleiders om conflicten op te lossen belemmeren het gebruik van optimale vliegbanen. Het wordt verwacht dat het verminderen van de noodzaak van tactische interventies het gemakkelijker maakt om optimale banen te implementeren. Om de
noodzaak van tactische acties te verminderen, is een meer strategische manier van omgaan met aankomende vluchten voorgesteld.

Naast het meer strategisch plannen van vliegbanen, is ook voorgesteld om deze strategisch geplande banen *flexibel* te maken. Met flexibiliteit wordt in dit werk bedoeld het plannen van de optimale baan voor de huidige situatie. Een dergelijke optimale baan is niet altijd hetzelfde, omdat de vorm van de baan afhankt van het criterium gebruikt voor optimalisatie, vliegtuigeigenschappen en weersomstandigheden. Dit is de reden dat de term flexibiliteit in deze context wordt gebruikt. Het plannen van flexibele banen is tot nu toe hoofdzakelijk beperkt tot en-route verkeer. Voor het aankomende verkeer zijn de standaardbanen gewoonlijk gehandhaafd. Deze standaardbanen zouden kunnen worden vervangen door bijvoorbeeld vaste banen behorende bij een continuous descent approach. Dit is echter moeilijk aangezien deze banen van de situatie afhangen. Het toestaan van flexibele aankomstbanen zou anderzijds verhoogd gebruik van continuous descent approaches mogelijk kunnen maken omdat de baan aan een bepaalde situatie kan worden aangepast. Flexibele aankomstbanen zouden daarom kunnen resulteren in lagere geluidsproductie. Het plannen van flexibele aankomstbanen zou ook kunnen resulteren in verhoogde verkeersdoorvoer omdat aankomstvolgorde en -tijden op een meer strategisch manier kunnen worden geoptimaliseerd. Het optimaliseren in een vroeger stadium resulteert over het algemeen in een breder scala aan mogelijkheden die kunnen worden overwogen en daarom ook in een betere uiteindelijke oplossing. Bovendien zou het toestaan van flexibele banen milieubelasting kunnen verminderen door de laterale profielen van de baan op een meer strategische manier aan de huidige condities aan te passen zodanig dat minimale milieubelasting wordt bereikt.

Eerder onderzoek heeft aangetoond dat optimale banen meer complex kunnen worden dan momenteel gebruikte banen. De gebruikelijke interpretatie van een meer complexe baan is dat de vorm van de baan minder gestructureerd is. De reden dat de flexibele banen voor aankomend verkeer minder gestructureerd zijn dan voor en-route verkeer is gerelateerd aan de invloed van de vorm van de baan op de taken van vliegers en verkeersleiders. In het algemeen wordt de inspanning die voor het uitvoeren van een taak vereist is aangeduid als *task demand load*. In het algemeen wordt gedacht dat het meer complex, of minder gestructureerd, maken van de baan de *task demand load* voor de vlieger en de verkeersleider verhoogt. De taken van vliegers en verkeersleiders zijn gewoonlijk ingewikkelder en uitgebreider in de aankomstfase dan in de en-route fase. De *task demand load* is daardoor over het algemeen hoger in de aankomstfase. Het wordt daarom ook gedacht dat vooral het introduceren van flexibele banen in de aankomstfase kan resulteren in hogere, wellicht onaanvaardbare, *task demand load*. Er bestaat echter slechts zeer beperkt theorie over de invloed van de vorm van de baan op de *task demand load* voor zowel vliegers als verkeersleiders.

Omdat nauwkeurigere, op tijd gebaseerde navigatie in de toekomst wordt voorzien, worden displays ontwikkeld die de vlieger kunnen helpen bij het minimaliseren van afwijkingen van geplande vliegbanen, zowel in ruimte als in tijd. Deze displays zouden het ook
mogelijk kunnen maken om meer complexe banen te vliegen met nog steeds acceptabele task demand load. Deze displays zouden daarom een belangrijke enabler kunnen zijn voor flexibele aankomstbanen.

Deze studie heeft drie doelstellingen. Ten eerste, om aan te tonen dat flexibele aankomstbanen kunnen leiden tot verhoogde vliegtuigdoorvoer, een verhoogd gebruik van continuous descent approaches en lagere milieubelasting in vergelijking tot de huidige banen. Ten tweede, om te bepalen welke factoren in de definitie van de baan tot de task demand load voor vliegers bijdragen, om te bepalen of de task demand load hoger is voor flexibele aankomstbanen dan voor de huidige banen en om te bepalen of de displays in ontwikkeling de task demand load kunnen verlagen. Ten derde, om te bepalen hoe en in welke mate het introduceren van flexibele aankomstbanen de task demand load voor luchtverkeersleiders verhoogt.

De mogelijke voor- en nadelen van flexibele aankomstbanen worden onderzocht in een off-line analyse. Hierin worden de momenteel gebruikte aankomstbanen vergeleken met banen die geoptimaleerd zijn voor een specifieke situatie in termen van het hoogteprofiel, het snelheidsprofiel en het laterale profiel. De criteria die voor optimalisering worden gebruikt zijn doorvoer, de mate waarin continuous descent approaches worden toegepast en milieubelasting. De algoritmen die in het verleden voor baanoptimalisering gebruikt zijn, lossen in het algemeen een single-objective probleem op, zelfs als meerdere optimalisatiecriteria beschouwd worden. Het is echter gesuggereerd dat dit kan resulteren in ongewenste oplossingen. Multi-objective optimalisering zou kunnen resulteren in betere oplossingen in termen van aanvaardbare prestaties op meerdere criteria. Dit is belangrijk voor het beschouwde probleem. Recentelijk zijn algoritmen ontwikkeld die aangeduid worden als genetische algoritmen. Genetische algoritmen zijn stochastische zoekmethodes die op het proces van natuurlijke evolutie volgens Darwin zijn gebaseerd. Zij worden beschouwd als geschikter voor multi-objective optimalisatie dan klassieke optimalisatiemethodes. Bovendien zijn genetische algoritmen over het algemeen geschikt om de oplossingen snel aan veranderende omstandigheden aan te passen. Om deze redenen gebeurt het optimaliseren van banen hier met behulp van een multi-objective genetisch algoritme. De analyse wordt gedaan voor de luchthaven Schiphol van Amsterdam in Nederland. De analyse toont aan dat het gebruiken van flexibele aankomstbanen kan resulteren in hogere doorvoer, vliegprofielen meer in overeenstemming met die van continuous descent approaches en vluchten die minder vaak woongebieden kruisen.

Een aantal metrieken voor het beschrijven van de task demand load van de taak van de vlieger om het vliegtuig langs de geplande baan te leiden worden geïdentificeerd in een off-line analyse. Deze metrieken worden experimenteel getoetst in een vluchtsimulator. De experimenten bevestigen dat de vorm van de baan de task demand load beïnvloedt. Deze invloed betrof voornamelijk de longitudinale vorm van de baan. Het kon niet worden aangetoond dat de laterale vorm van de baan de task demand load beïnvloedt. Het wordt aangeraden om te bestuderen of deze metrieken geïntegreerd kunnen worden tot één enkele
voorspelling van task demand load en of aanvaardbare grenzen hiervoor opgesteld kunnen worden. De experimenten gaven ook aan dat displays in ontwikkeling die informatie met betrekking tot referentiepositie, referentiesnelheid en versnelling geven de task demand load kunnen verminderen. Dit is vooral met betrekking tot besturing van de positie langs de baan. De off-line analyse gaf aan dat de task demand load met betrekking tot longitudinale bewegingen hoger werd als de flexibele aankomstbanen werden gebruikt. Dit wordt hoofdzakelijk veroorzaakt door de noodzakelijkheid van meer manoeuvres om vluchtprofielen meer in overeenstemming met die van een continuous descent approach te bereiken zonder dat er randvoorwaarden worden overschreden. Er zijn geen indicaties gevonden dat de task demand load met betrekking tot laterale bewegingen hoger wordt.

De task demand load voor luchtverkeersleiders is ook onderzocht met behulp van metrieken. Deze metrieken beschrijven of de verkeerssituatie in het geheel minder gestructureerd wordt en of deze gevoeliger wordt voor afwijkingen van de geplande banen in de praktijk. Dit wordt in het algemeen aangeduid als een verhoging van de ‘complexiteit’ van het luchtruim. Een verhoging van de complexiteit van het luchtruim wordt in het algemeen verondersteld te resulteren in verhoogde task demand load voor verkeersleiders. Hoofdzakelijk zijn metrieken gebruikt uit eerder onderzoek die geometrische eigenschappen van de verkeersstroom beschrijven. De verkeersdichtheid werd over het algemeen lager voor flexibele aankomstbanen in vergelijking met conventionele banen omdat meer luchtruim kan worden gebruikt. De flexibele banen resulteerden echter in meer punten waar aankomend en vertrekkend verkeer elkaar kruisen, hogere verticale snelheden waarmee verkeer elkaar nadert en lagere horizontale afstanden tussen verkeer. Hoewel voor flexibele aankomstbanen die in termen van de laterale profielen werden geoptimaliseerd een daling van horizontale afstanden tussen verkeer kon worden verkomen, wordt er geconcludeerd dat flexibele aankomstbanen de complexiteit van het luchtruim kunnen verhogen. Het wordt daarom ook geconcludeerd dat de task demand load voor luchtverkeersleiders hoger zou kunnen worden. Net als bij de taak van de vlieger, zouden verbeteringen in mens-machine interfaces voor luchtverkeersleiders mogelijk kunnen helpen de task demand load te verminderen.
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