Supporting Trajectory Based Operations in Aerodrome Control

Master of Science Thesis Report

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Front cover image source: Daan Krans

Preface

In front of you lies, or is displayed on your screen when reading this digitally, the report that marks the end of my Master of Science Thesis Project. This is also the final part of the Master Aerospace Engineering at the Delft University of Technology and therefore, this report concludes my time as a student. The project was conducted at the Control and Simulation section of the department of Control and Operations in collaboration with Luchtverkeersleiding Nederland (LVNL) as part of the Centre of Excellence from the Knowledge and Development Centre Mainport Schiphol (KDC).

This document combines the two main deliverables of my Master's Thesis. These are the Master of Science Thesis Paper and its appendices, together with a copy of the Preliminary Report, which also includes the literature study.

When starting the project back in May 2022, I could not have imagined that my Master's Thesis would get this extensive. Nonetheless, I really enjoyed working on it, from exploring the world of tower control at Schiphol and designing a support tool to implementing it into the SectorX simulator together with learning Java and testing it with air traffic controllers.

There are several people I explicitly would like to thank. Starting with the supervisors from the TU Delft. Clark, my daily supervisor, thank you for all the time and effort you have put into guiding me during this project. I am really grateful for the input you have provided to improve my work, from the design of the tool to the contents of this report. Also, Gijs, I would like to thank you for your help. I want to especially highlight your support with SectorX, improving the tool, how to present the results and your feedback on my paper. Furthermore, René, thank you for your help and guidance. I really appreciate your contribution to this project. And Max, I would like to express my gratitude for your supervision and, even with a busy calendar, making time for meetings with students like me. This is truly appreciated. Lastly, to all of the aforementioned, I want to thank you for all the meetings we had during the past (almost) two years. I really enjoyed these and I am truly grateful for all the insights you provided me with.

To my supervisor from the KDC, Ferdinand, first of all, a big thanks for the opportunity you provided to perform this project. I remember that at the end of my internship at iLabs, I came to you looking for a possible thesis at the KDC. You mentioned that you had something in mind that you thought would suit me. When looking back I must admit that you were right. I am also grateful for your support during the project, from brainstorming about the scope to providing me with data. Your knowledge about the ATM system is undeniably valuable for students like me.

Furthermore, I want to express my appreciation to Tim for his operational expertise and for inviting me (two times) to the Schiphol Tower. Also, to all the students I have worked with at iLabs, from interns to my fellow thesis students. Stating all your names here would probably take too much space, nonetheless thank you for our time together, your support and for all the chats we had during our little coffee breaks, which I really enjoyed.

Last but not least, I would like to thank my parents. Thank you for your support during this project and during my studies in general, I could not have done it without you. Also to my brother, Pim, a big thanks for your support and help.

Bob
Elst, April 2024

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4D	Four-Dimensional.
AAA	Amsterdam Advanced ATC.
ACC	Area Control Centre.
ADS-B	Automatic Dependent Surveillance - Broadcast.
ADS-C	Automatic Dependent Surveillance - Contract.
AIBT	Actual In-Block Time.
ANSP	Air Navigation Service Provider.
APP	Approach Control.
ASDE	Airport Surface Detection Equipment.
ATC	Air Traffic Control.
ATCo	Air Traffic Controller.
ATFM	Air Traffic Flow Management.
ATM	Air Traffic Management.
ATS	Air Traffic Services.
BL	Baseline.
CDM	Collaborative Decision Making.
CTOT	Calculated Take-Off Time.
CTR	Controlled Traffic Region.
DPI	Departure Planning Information.
EFSS	Electronic Flight Strip System.
EIBT	Estimated In-Block Time.
EID	Ecological Interface Design.
ELDT	Estimated Landing Time.
EOBT	Estimated Off-Block Time.
EPP	Extended Projected Profile.
ETFMS	Enhanced Tactical Flow Management System.
EXOT	Estimated Taxi-Out Time.
FF-ICE	Flight and Flow Information for a Collaborative Environment.
FIR	Flight Information Region.
FMS	Flight Management System.
GARDS	Go-Around Detectiesysteem.
GC	Ground Controller.
GND	Ground Control.
IA	Intelligent Approach.
IFR	Instrument Flight Rules.
KDC	Knowledge and Development Centre Mainport Schiphol.
LVNL	Luchtverkeersleiding Nederland.
NM	Network Manager.
OPL	Outbound Planner.
RC	Runway Controller.
RECAT	Recategorisation.
RETD	Revised Estimated Time of Departure.
RIASS	Runway Incursion Alert System Schiphol.
SID	Standard Instrument Departure.
SWIM	System Wide Information Management.
TAR	Terminal Area Surveillance Radar.
TBO	Trajectory Based Operations.
TMA	Terminal Manoeuvring Area.
TOBT	Target Off-Block Time.

TSAT	Target Start-up Approval Time.
TTOT	Target Take-Off Time.
TTST	Take-off Timing Support Tool.
TWR	Tower.
UCO	Under Control.
VFR	Visual Flight Rules.
WTC	Wake Turbulence Category.

I

Master of Science Thesis Paper

Trajectory Based Operations in Aerodrome Control: Supporting the Timing of the Take-off Clearance

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Abstract—**The introduction of Trajectory Based Operations (TBO) is set to change the operation on all levels of Air Traffic Control (ATC), including aerodrome control. Here, adherence to a planned four-dimensional trajectory is important to achieve a stable operation. At the same time, this concept provides possibilities for support tools to be used in ATC, by making use of new data and information. This research presents the Take-off Timing Support Tool (TTST) for aerodrome control, and more specifically runway control, at Amsterdam Airport Schiphol. It is incorporated into the already existing Electronic Flight Strip System and features a time axis on which flight strips can be placed. By dragging departures along the time axis a planning and sequence can be constructed, while taking into account the provided solution space to prevent conflicts. An experiment conducted with the TTST showed that professional air traffic controllers used the information from the tool in their decision-making, leading to a decrease in conflict count, and it was demonstrated that a stable planning could be established. Therefore, the TTST is a suitable platform to support TBO in aerodrome control and assists air traffic controllers with time-based control. No significant difference in departure interval was present. The workload did increase moderately.**

Index Terms—**Air Traffic Management, Air Traffic Control, Trajectory Based Operations, Aerodrome Control, Tower Control, Decision Support Tool, Interface Design**

I. Introduction

The current Air Traffic Management (ATM) system is facing major challenges. With a global climate crisis, and therefore the need to reduce aircraft emissions, while at the same time, an expected growth in air traffic [1], modernisation and a more efficient operation are essential. Big changes of the ATM system are proposed to tackle these challenges. One of the key new concepts is Trajectory Based Operations (TBO) [2], in which Four-Dimensional (4D) trajectories (position, altitude and time) play a core role. Collaboration between all stakeholders is essential in TBO, to properly manage and eventually execute the 4D trajectory while sharing information and data extensively [3].

TBO will change the operations of Air Traffic Control (ATC). Due to the gate-to-gate character of the 4D, all levels of ATC, from area to aerodrome control, will be affected. Besides being involved in the planning, ATC should adhere, especially in time, to the trajectories during the execution as much as possible, to achieve a stable operation [4]. This means the operation will shift from distance to more time-based control. Concepts related to this are currently being developed. Examples of these are continuous descent operations [5], [6] and time-based conflict resolution [7]. This shift leads to a more difficult task for Air Traffic Controllers (ATCos). Therefore, technical support tools must be introduced to assist ATCos with time-based control and to maintain safety by resolving conflicts. Also, the availability of new information and data in TBO can be utilised to improve the ATC operation and increase efficiency.

Several studies have proposed support tools for ATC, both for planning and conflict detection & resolution purposes. However, most focus has been on area/en-route [8]–[10] and approach control [11]. This leads to the question of how TBO can be supported in aerodrome control, a unit with a complex operation. Therefore, this study presents a novel support tool for aerodrome control. It supports ATCos in a TBO environment and uses the availability of new data. It is built upon previous work on time-based support tools for area and approach control, by combining elements and transforming these to be applied in aerodrome control. The research focuses on Amsterdam Airport Schiphol, an aerodrome with a complex runway system. More specifically, the support tool will assist Runway Controllers (RCs) at Schiphol by providing the time-based solution space for issuing take-off clearances, while considering separation requirements, such as the Wake Turbulence Categories (WTCs) and air traffic on converging runways. The tool is evaluated by conducting an experiment, including simulations of tower operations at Schiphol.

The relevant background information is presented in Section II. The design of the support tool is introduced in Section III. In Section IV the experiment to evaluate the tool is described, followed by the results and discussion in Sections V and VI, respectively. Finally, the conclusions are presented in Section VII.

II. Background

To be able to provide support in aerodrome control properly, the current aerodrome control operations must be well understood and are therefore presented first. However, in the future, TBO will be introduced, which will impact aerodrome control but could also improve the tower operation. Hence, TBO is discussed secondly. Furthermore, a brief look into some developments (both related and separate from TBO) in aerodrome control is presented.

A. Current Aerodrome Control Operations

To establish a safe and orderly flow of air traffic, ATC is provided. This comes in different levels: area, approach and aerodrome control, where aerodrome or tower control is responsible for traffic at and near the airport, i.e. the Controlled Traffic Region (CTR) [12]. In short, the functions of the tower are providing 1) information and clearances to ensure safety while monitoring this operation, 2) alerting services and 3) the status of aids and equipment in case of failures or irregularities [13].

Since this research focuses on Schiphol, the implementation of aerodrome control by Luchtverkeersleiding Nederland (LVNL) (Dutch *Air Navigation Service Provider*) at this airport will be discussed in more depth. Because Schiphol is a large (hub-)airport, the different tasks of the tower are split up amongst different ATCo positions. Generally, in sequence from a departure's perspective [14]:

- **Delivery** provides the en-route clearance based on the filed flight plan.
- **Outbound Planner** creates the initial departure planning based on information and data from the Collaborative Decision Making (CDM) system when pilots call for the start-up clearance. It is checked whether this call is made within the associated time window.
- **Ground Control** is responsible for all traffic on the manoeuvring area at the airport. Foremost, ground control provides taxi clearances from the gate to the runway and vice versa. For departing traffic streams, ground control proposes a departure sequence to runway control.
- **Runway Control** holds the responsibility for the operation at and near the runway. The main task is to issue line-up, take-off and landing clearances. In cooperation with ground control, the departure sequence is determined, where runway control bears the final responsibility.

Since the entire process at the tower comes together at runway control from a departure standpoint, the RC has the most responsibility over this process. Also, runway control is the bridge between the ground and airborne phases of a flight. Therefore most support can be provided here, while also utilising air-ground data-link information. Accordingly, the procedures for runway control will be further elaborated on.

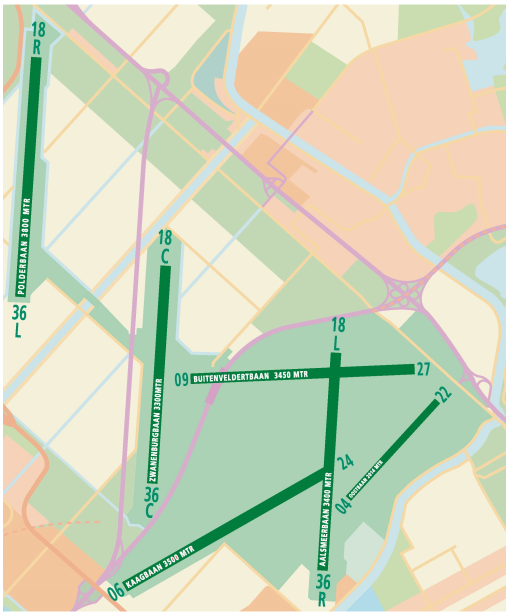

Fig. 1: Schiphol Runway Layout (Source: https://nieuws.schiphol.nl/asset/654801/banenstelselschiphol-202471, Accessed 5-4-2024)

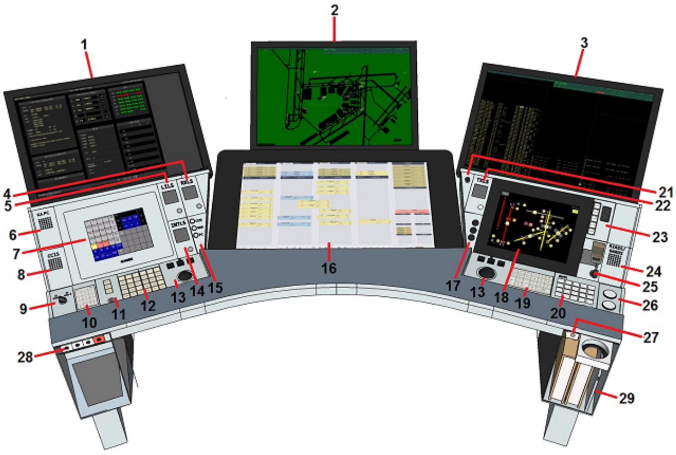

Fig. 2: Schiphol Tower Console [15]

When issuing clearances, the RC must ensure safety at and around the runway. Arriving flights are handed over by approach control when on final approach (approximately 8 nmi from the runway threshold), hence influence on these flights by the RC is very limited. However, the leeway with departures is much greater.

When a departing aircraft approaches the runway holding position, the flight is handed over by ground control and the RC has the option to first issue a line-up clearance or directly issue the take-off clearance. Before take-off clearances can be issued safely, the RC shall take certain factors into account. First, is the WTC, in the form of the European-Recategorisation (RECAT-EU). Second is separation from preceding and succeeding aircraft. This includes certain requirements from International Civil Aviation Organization (ICAO) [13], for example, a one-minute separation between consecutive departures in case

Fig. 3: Screenshot of the EFSS [15]

of diverging tracks. Also, requirements on dependent runways (Figure 1) should be taken into account, especially conflicts that may occur in case of a missed approach on a converging arrival runway (e.g., the combination of 18C and 24 [16], [17]).

To support ATCos with their task, consoles are installed at the Schiphol tower, of which a schematic example is shown in Figure 2. Here, two important parts can be identified.

First, indicated with 2 and 3, are the tower screens. These screens can be configured with different options: 1) the *Electronic Data Display* for accessing flight plan data, 2) the aerial radar, 3) the ground radar or 4) a split screen with the aerial and ground radar combined [15].

Second is the Electronic Flight Strip System (EFSS), indicated with 16. A screenshot of the EFSS screen for RCs is shown in Figure 3. It is used by ATCos in the tower to keep track of all flights under their responsibility and is split up into different sections. Flight strips, containing essential flight information, can be dragged over the EFSS and placed within these sections. For runway control, there are four large sections (vertical columns from top to bottom), each corresponding to a single runway. Within these vertical columns, there is a *pending area* at the top, which contains strips waiting to be handled by the RC, and a *working area* on the bottom, in which strips will be placed of flights currently controlled by the RC. When an arriving flight enters the Schiphol Terminal Manoeuvring Area (TMA), the strip (yellow) will appear in the *pending area* of the corresponding runway, while for departing flights, the strips (blue) will appear when transferred by ground control [15].

B. *Trajectory Based Operations*

TBO differentiates from current operations in terms of three main components: 4D trajectory information, management and information sharing [3].

4D trajectory information (position, altitude and time) will act as the common plan for the execution of the flight. This contrasts with the (paper) flight plan used in current operations, containing only limited information, leading to sub-optimal data sharing and management [13], [18]. The trajectory may be built up out of waypoints with time constraints, including a window, and flight paths with lateral or altitude margins to cope with uncertainties [3]. In current operations, constraints on the departure time are already present in terms of the Target Take-Off Time (TTOT) and Calculated Take-Off Time (CTOT), as part of CDM. Also departure and arrival routes within the TMA and CTR, in the form of the Standard Instrument Departure (SID) and the *Standard Arrival Route*, already exist. However, these elements will be part of the 4D trajectory. Adherence to the constraints is even more favourable in TBO, as deviation leads to rescheduling trajectories and impacting the predictability of the entire system [4].

To achieve the aforementioned, proper management of the trajectories is vital. The generation and revision process consists of looping over: proposing, predicting and evaluating trajectories. During this process, all relevant stakeholders are involved, and will eventually agree on the planning. Before and during execution the trajectories will be updated with the latest data and information and, when needed, will be revised [3].

Information and data will be shared amongst the stakeholders to facilitate the management of trajectories and is subdivided into categories: environmental factors, information supporting CDM, information for trajectory prediction and the agreed trajectories [3]. A variety of, already existing and future, technical enablers must accomplish this, such as *System Wide Information Management* (information sharing platform [19]), *Flight and Flow Information for a Collaborative Environment* (replacing the current flight plan [20]) and Automatic Dependent Surveillance - Contract (ADS-C) (aircraft data link [21]) [18].

The introduction of TBO, and therefore the use of 4D trajectories, will change the operations on all levels, due to its gate-to-gate character. As adherence to the trajectory is important to have a successful execution, supporting ATCos is essential, also in aerodrome control. Furthermore, the availability of more data and information, especially trajectory information and predictions, can be utilised in decision support for ATC. The introduction of this new concept of operations, together with the opportunities that come with it, provides the possibility to develop new tools to support decision-making in aerodrome control, hence this research.

C. Developments in Air Traffic Management

To increase safety and efficiency, innovations and improvements are proposed and introduced to the ATM system. Many of them are also related to and/or affect aerodrome control, making them relevant to this research.

At Schiphol, *Deep Turnaround* is introduced. Here, cameras monitor the turnaround process and an artificial intelligence algorithm detects the different sub-processes. Based on this data, a more reliable prediction can be made in terms of accurate Target Off-Block Time (TOBT) updates [22]. The TOBT thereafter forms the basis for the departure planning within the CDM process and therefore also affects the TTOT [23].

Subsequently, efforts are made to improve the operation after start-up, i.e. the taxi phase. Okuniek *et al.* [24] developed a concept of operations for aerodrome surface operations within TBO, by including 4D taxi trajectories. This leads to improved efficiency and capacity, environmental benefits, and increasing predictability of the taxi operation. When also considering the flight deck perspective, predictions of taxi times, both before and during taxiing, can be improved [25].

Recently, optimisations of the departure and approach separation to prevent wake turbulence have been proposed, in terms of the introduction of RECAT-EU [26], which is implemented at Schiphol (Section II-A). Here, aircraft are categorised based on mass and wing span in six different categories instead of the traditional three as described by ICAO [13] (or sometimes four, when including the super category [14]). In the future, the WTC separation may be further refined with the introduction of *Pair-Wise Separation*, where the separation is based on the specifics of individual aircraft types [27].

One of the important factors of, and prerequisite for, TBO is more accurate trajectory predictions, by sharing more data and information between parties [3]. To reduce prediction uncertainty, ADS-C Extended Projected Profile (EPP) is introduced, which is a down-link from the aircraft's *Flight Management System* [28]. Several studies have shown that the data included in ADS-C EPP reports can be used to improve, especially ground-based, trajectory predictions [29]–[31]. In practice, these messages contain information on the arrival path in great detail[1], which is relevant for aerodrome control. For the departure trajectory, however, the level of detail is lacking[1].

III. Interface Design

As presented in Section II-B, with the introduction of TBO, aviation operations will be changed and new opportunities arise when utilising the availability of information and data. This forms the basis for the newly developed decision support tool.

The design of this tool will be discussed in this section, starting with the design rationale. This is followed by the description of different elements of the tool: the time axis, visualisation of conflicts and the radar screen elements. How to work with the tool is presented subsequently. Last, the relation between the tool, and TBO and future concepts will be discussed.

A. Design Rationale

The introduction of new tools and technologies in aerodrome control is deemed more complicated compared to approach and area control, due to the difference in working environment. In tower control, air traffic is primarily controlled based on the outside view instead of a radar screen, and displays and interfaces are only for support [13]. To prevent adding additional displays and interfaces in the current console (Figure 2), and therefore having to pay attention to more sources of information, the tool is integrated into the already existing EFSS (Figure 3). Additionally, efforts have been made to reduce information access costs, such that the heads-down time is limited.

Previous studies on decision support tools for ATC were used as the starting point of the design. Previously, inbound planning tools for both area [9], [10] and approach [11] control were developed. These presented the expected arrival time at certain points in a *Time-Space Diagram* and the ATCos were able to adjust these times to establish separation. Furthermore, the solution space diagram has been proposed in several studies [8], [32], which shows the range of possibilities in terms of heading and/or speed commands to resolve the conflicts between aircraft.

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[1] Source: Specialist on Flight Management Systems and Data Link from Airbus

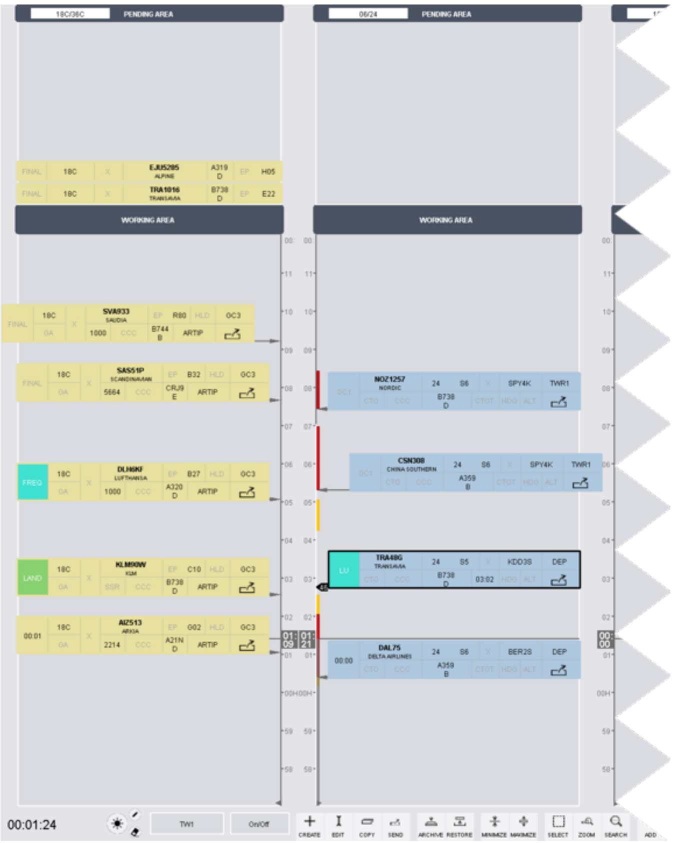


Fig. 4: Screenshot of the TTST implemented in the EFSS

The novel design incorporates a time axis into the EFSS, on which the flight strips can be placed. As follows from Section II-A, most support can be provided for departing traffic, while taking into account arriving traffic streams. Also, because of fixed taxi paths and SIDs, the timing of the departure is the most important aspect of the work domain of the RC. Therefore, the tool shows the solution space in time for issuing take-off clearances and was named the Take-off Timing Support Tool (TTST). This turns the EFSS from a tool to only keep track of flights into a means for timing and sequencing control. A screenshot of the TTST incorporated in the EFSS is shown in Figure 4.

B. Time Axis

The time axis forms the foundation of the TTST (Figure 4). It is placed next to the *working area* and can be put on both sides of this section by the operator. The labels on the time axis indicate the clock time, similar to the *Advanced Schiphol Arrival Planner* interface used by Schiphol approach control [33]. Since at LVNL, tower and approach control is in most cases a combined profession, the RCs are already familiar with this time representation. The horizontal line indicates the current time. To look further into the future or past, the time axis can be dragged up or down.

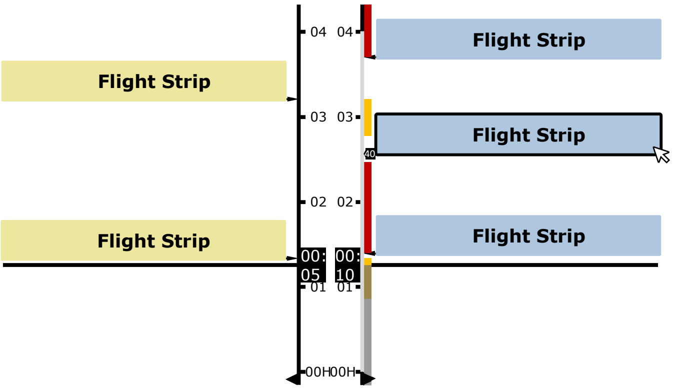


Fig. 5: TTST Time Axis and Solution Space

When flight strips of arriving aircraft are dragged to the *working area* and released, they will snap to the expected arrival time. Flight strips of departing aircraft will already appear in the *pending area* when taxiing has started. When dragged to the *working area* for the first time, the strip will snap to the TTOT on release. The strips will automatically move down with time when put on the time axis. For a selected strip, the number of seconds of the clock time is shown within the arrow (Figure 5).

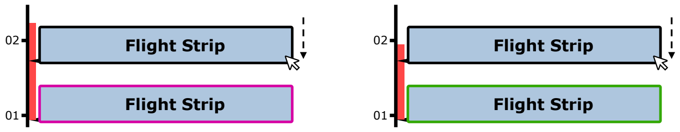
Because of the lack of influence on arriving traffic streams by the RC (Section II-A), arrivals are locked on the expected arrival time. Departures, however, can be dragged along the time axis and by doing so, alter the planned departure time. This time can also be set by first selecting the strip and then tapping on the desired time. When the flight departs, the strip is locked at the departure time. To still accommodate flagging flights by offsetting the strip, a leader line connects the strip to the arrow pointing to the time axis, as is demonstrated in Figure 4.

In the original EFSS, a timer, mainly used for WTC separation purposes, is included in the header of the working areas. Within the TTST, the timer has been moved down, next to the horizontal line indicating the current time. It displays the countdown till the next flight strip on the time axis, i.e. the next arrival or departure. Since the strips are moving down towards the horizontal line and timer, access cost is reduced, by not having to move attention between header and flight strip. This is in line with the *minimizing information access cost* principle, formulated by Wickens *et al.* [34].

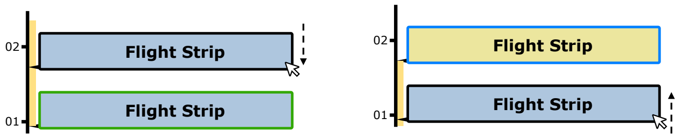
C. Solution Space

The solution space in time is built up by displaying the departure window and conflicts on the time axis when a departure is selected (Figure 5). By doing so, at one glance it is visible at what time a flight can depart safely.

The departure (or TTOT) window is indicated in white on the time axis (from 00:00 until 00:04 in Figure 5). The conflicts appear as small rectangles next to the time axis. When desired, more information on the conflicts can be obtained by hovering the arrow of the strip over the rectangles, which will highlight the current conflicts and corresponding strips. By releasing a strip within a conflict, it will jump to the nearest solution, however, this may not



(a) WTC (b) ICAO



(c) SID (d) Missed Approach

Fig. 6: TTST Conflicts

be the earliest time. For example, when released within a WTC conflicts, the required RECAT-EU separation will be set. Two types of conflicts can be distinguished:

- **Comply**: These conflicts must be adhered to, and are shown in red.
- **Advice**: These conflicts may be taken into account, but can be deactivated by hovering more than two seconds over this conflict. These are shown in yellow.

Furthermore, there are different sources of conflict. By hovering over the conflicts, and therefore accessing additional information, the border of the conflicting strip will get a different colour. This provides information about the source of the conflict. The colours are based on the ones used for the Intelligent Approach (IA) [33], which is a system to support approach controllers to establish separation for arriving aircraft. However, the definitions are slightly transformed to be used for departures. As mentioned before, most RCs are also Schiphol approach controllers, and therefore consistency is provided in the use of colours as is favourable according to the *principle of consistency* [34]. The different sources are (Figure 6):

(a) **WTC**: RECAT-EU wake turbulence separation requirements. The conflict type is *comply* and it is highlighted in magenta. (IA colour: WTC [33])
(b) **ICAO**: One-minute separation, which is required in case of diverging tracks between two consecutive departures. The conflict type is *comply* and it is highlighted in green. (IA colour: runway occupancy time [33])
(c) **SID**: When following the same (initial) departure route, one-and-a-half-minute separation is included[2]. The conflict type is *advice* and it is highlighted in green. (IA colour: runway occupancy time [33])
(d) **Missed Approach**: Arriving flights on converging runways may cause a conflict in case of a go-around. This conflict starts when the arriving aircraft is projected to be one nautical mile from the runway threshold and ends when the aircraft is projected to land[2]. The conflict type is *advice* and it is highlighted in blue. (IA colour: minimum arrival separation [33])

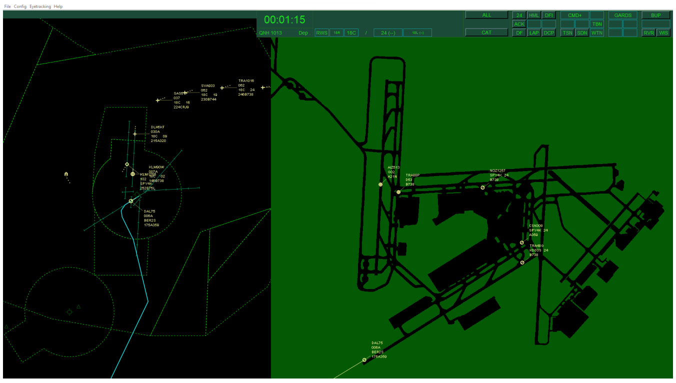


Fig. 7: Screenshot of the tower screen with the SID trajectory provided by the TTST

Additionally, flights cannot depart in the past and therefore the area below the horizontal line is light grey and partly transparent (to still be able to see the conflicts below).

D. Radar Screen

Changes to the current interface by the TTST are not only limited to the EFSS. Also, the tower screen has been improved. When a strip is selected at the EFSS, the route of this flight is shown on the radar screen, as can be seen in Figure 7. For departures, the SID is displayed. For arrivals, the displayed route consists of the *Final Approach Fix* and the runway threshold, since vectoring patterns are applied by approach control before this part.

E. Working with the Take-off Timing Support Tool

With the TTST, the flight strips are chronologically ordered from bottom to top. Also in the current situation, ATCos sort the strips in the same way. However, the vertical spacing is with the tool a measure of the separation in time between flights.

Strips of arriving flights still appear at the same time, when the flight enters the Schiphol TMA. With the current EFSS, the ATCos have to sort these strips themselves, since the order of appearance can be different from the order of arrival, due to differences in track miles and control by Schiphol approach. This process is improved by the TTST, where the strip will move to the expected arrival time at the time axis and therefore will be automatically sorted.

To accommodate planning departures further ahead, as is favourable in TBO, strips of departures already appear upon taxiing. This could also help RCs with determining the departure sequence together with ground control. In general, the workflow for departures, which is also demonstrated in Figure 8, is as follows:

(1) Drag from the *pending* to the *working area*, which sets the departure time at the TTOT.
(2) When desirable, change the planned departure time by dragging or tapping on the time axis while using the solution space to prevent conflicts.

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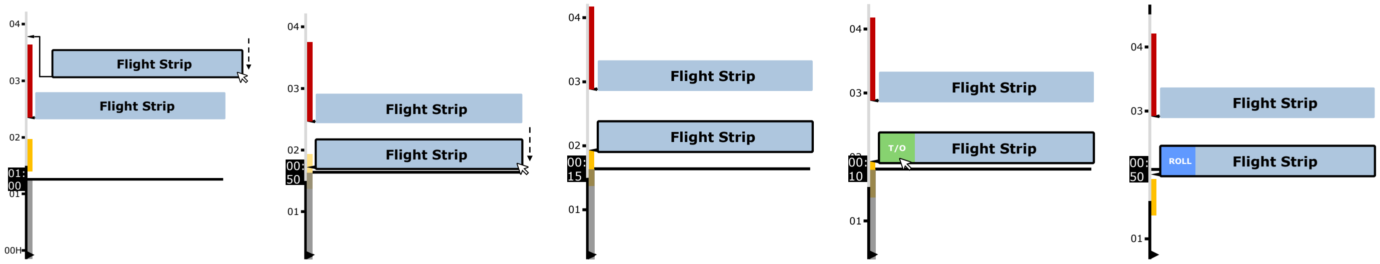
[2] Based on operational experience. Source: Schiphol Runway Controller



(1) Drag from *pending* to *working area*

(2) Change the planned departure time

(3) Release the flight strip to find the nearest solution and update the consecutive departures to stay out of conflict

(4) Issue the take-off clearance

(5) Detection of the take-off roll

Fig. 8: TTST Workflow

(3) Release to set the planned departure time. Release within an active conflict to set the departure time to the nearest solution. The planned times of consecutive departures are updated to resolve conflicts.
(4) When approaching the planned departure time, issue the take-off clearance.
(5) At the start of the take-off roll, the flight strip is moved and locked to the corresponding time.

By initially snapping the strip at the TTOT, focus can be given to the next few departures. When the aircraft is approaching the runway, and the flight strip therefore the line indicating the current time, or when there is a low demand, the operator can start planning a conflict-free departure time by using the information provided by the TTST.

To prevent demanding too much attention, and therefore heads-down time, some automation has been introduced. As mentioned before, releasing a strip within an active conflict will update the time to the nearest solution. Additionally, when the aircraft has not started the take-off roll yet, the corresponding flight strip will not move further than the current time. Eventually, when the roll has started, the strip is automatically locked to the actual departure time, such that correct separation from the succeeding flight is assured within the solution space. To prevent succeeding strips from moving into an active conflict when a strip is pending departure or when the sequence is changed by the operator, the departure times are automatically updated. This happens on a bottom-to-top basis, i.e. starting with the next planned departure, and updating the departure time to the next available solution (Algorithm 1). In this way, the sequence can easily be changed by simply dragging and releasing a flight strip below a different strip, which will automatically set the separation as required by the different conflict sources.

F. Relation with Trajectory Based Operations and Future Concepts

As described in Section II-B, within TBO, 4D trajectories form the basis of future operations together with improved planning and adherence. One of the key aspects of the TTST is to improve the planning of departures in aerodrome control by actively managing the planned departure time while taking conflicts. By providing the flight strips of departures at an earlier stage, the RC can plan further ahead in a time-based manner. Also displaying the departure window can increase the awareness of the departure window, which is part of the 4D trajectory.

Alg. 1: Automated ‘Solution-Finding’ for Departures

```
$D \ni d$                    ▷ Set of Departures, Sorted Bottom-Top
$t_{pd}\ of\ d$              ▷ Planned Departure Time
$t_{start} \leftarrow t_{pd_0}$   ▷ First Planned Departure Time
$C \ni c$                    ▷ Set of Conflicts
$t_{cmax}\ of\ c$            ▷ End Time of Conflict

for $d \in D$ do
    $t_{pd} \leftarrow \max(t_{pd}, t_{start})$
    $C \leftarrow \{c \text{ at } t_{pd}\}$
    while $C \neq \emptyset$ do
        for $c \in C$ do
            $t_{pd} \leftarrow \max(t_{pd}, t_{cmax})$
        end for
        $C \leftarrow \{c \text{ at } t_{pd}\}$
    end while
end for
```

Additionally, aerodrome control can benefit from the availability of data and information within TBO, and use this to support the ATCo’s decision-making process. Improved trajectory predictions can be used to determine conflicts and as mentioned in Section II-C, the ADS-C EPP data link plays an important role. For arrivals, this data can be used to determine the missed approach conflicts (time at one nautical mile from the runway threshold and the landing time). However, a departure inside this window does not necessarily result in a conflict and therefore this source in the TTST solution space is turned into an advice. EPP is currently lacking detail on the departure trajectory and (for now) less suitable for determining the required separation. Hence, the default one-and-a-half-minute separation advice is chosen for departures on the same (initial) SID.

The TTST is designed to easily incorporate future developments, described in Section II-C. Better turnaround predictions, such as *Deep Turnaround*, result in more accurate TTOTs (part of the 4D trajectory) and eventually better adherence to this departure window (shown in the TTST). Subsequently, taxi time predictions could be incorporated by extending the light grey area in Figure 5 to the expected arrival time at the runway. Furthermore, conflicts can easily be changed, from changing the window to adding new sources. This includes implementing *Pair-Wise Separation* in the WTC source, but also refining the missed approach conflict window. Better departure path predictions, for example through an increase in detail in ADS-C EPP messages, can be used to determine the required separation between consecutive departures. When accurate enough, this source can eventually be turned into a *comply* type. Together, these developments will make the TTST more powerful.

Furthermore, implementation of the TTST is not only limited to Schiphol, as the use of sources for conflicts is flexible. For example, it could also be implemented at a regional airport, such as Rotterdam The Hague or Eindhoven Airport. These airports only have a single runway and, as a result, use a mixed-mode configuration. To accommodate this within the TTST, a runway occupancy time conflict could be introduced. Additionally, conflicts with traffic streams to Schiphol can be included and use gaps within these streams to let traffic from the smaller airports cross and therefore remove restrictions on altitude, which is beneficial for residents of the surrounding areas.

IV. Experiment

To be able to test if the TTST works as intended and to get valuable feedback from the end users, the RCs, an experiment has been conducted with professional ATCos.

First, the goal of the experiment will be set out, followed by the hypotheses and assumptions. Thereafter, the independent, control and dependent variables will be presented. Next, the setup, participants, scenarios and lastly the task and procedure will be discussed.

A. Goal

The main goal of the experiment was to evaluate the new TTST and therefore how well the new TTST supports TBO in aerodrome control. A comparison was made between the current operations, with the corresponding toolset (Baseline (BL)), and working with the new tool (TTST). To get as close to reality as possible, the scenarios were based on real air traffic schedules at Schiphol and data from the operation. The focus lay on improving safety, improving the planning of the departure time, and decreasing the take-off interval.

Additionally, the experiment was set up to gather feedback on the tool using a survey. By utilising the operational expertise, the TTST can be improved and potentially increase the acceptance by the ATCos.

B. Hypotheses

For the experiment, several hypotheses were drafted and tested. These are related to the safety, planning of the take-off and the departure capacity, respectively. The TTST is hypothesised to:

H.1 prevent missed approach conflicts because the conflict is visualised and therefore can be easily taken into account since the participants do not have to determine the separation by themselves.

H.2 reduce the flight strip interactions after transfer by ground control because the departure time can already be planned before and only the clearances have to be issued afterwards.

H.3 decrease the departure time interval because the departure time is visualised and the interval is therefore actively managed.

C. Assumptions

To be able to conduct the experiment, some assumptions for the scenarios had to be made. First, it was assumed that all aircraft were equipped with ADS-C EPP, or a similar system. Consequently, the arrival path, and therefore the missed approach conflict window, could be accurately predicted. Second, the sequence in which the departing aircraft arrived at the runway holding positions was fixed and transfer from ground control happened when the aircraft was within 150 m from the runway centreline. There were however intersection starts and hence, the participants could apply minor changes to the sequence. Third, the pilot response time was based on a dataset with the take-off clearance time and the start of the roll at Schiphol provided by the LVNL. All departures had the same delay (normal distribution), irrespective of, for example, the airline. Last, arrivals would also land when the participants had not issued a clearance.

D. Independent Variables

The experiment contained one independent variable: the configuration (baseline and TTST). This allowed for an evaluation of the new tool compared to the current operation, which was simulated in the baseline.

E. Control Variables

Several control variables were present in the experiment. First, the experiment environment and the simulator setup, as will be presented in Section IV-G. Second the scenarios including the duration, presented air traffic and the pilot delay.

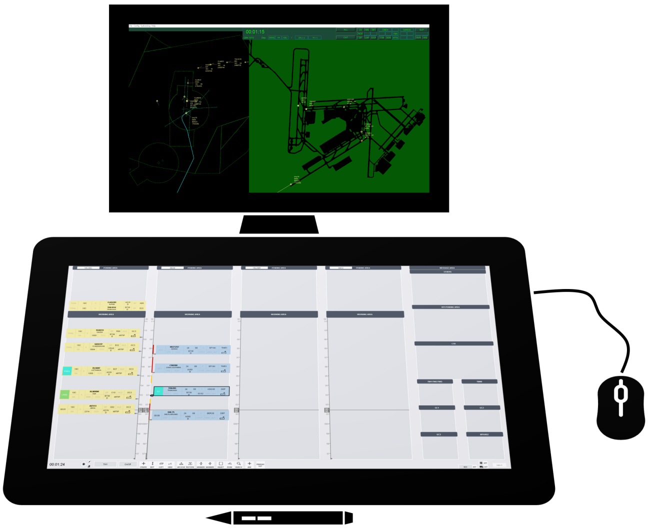


Fig. 9: Experiment Setup

F. Dependent Variables

As follows from the experiment goal and hypotheses, the dependent variables are related to the safety, planning and departure interval.

For the safety aspect, it was determined if an aircraft departed within a conflict window. To be able to measure this, based on the aircraft states, the time of the start of the take-off roll was recorded. This data was also used to evaluate the departure interval. Second, the conflict windows, as presented in the TTST, were recorded. Based on these two variables, the aircraft which departed in conflict, as well as the number of conflicts could be determined.

To assess the planning, actions performed by the participants were recorded. This includes interaction with the flight strip and actions related to the TTST (planning a departure, finding the nearest solution and highlighting conflicts). Additionally, the time of transfer of control by ground control is recorded, to also evaluate the planning during the taxi phase.

Furthermore, the workload ratings, using the *Rating Scale Mental Effort* [35], provided by the participants after both parts were used to determine the effects of the TTST on this aspect. Finally, the responses to the questionnaire were also part of the dependent variables.

G. Setup

For the experiment, the *SectorX* ATC human-in-the-loop simulator was used. First, the Schiphol tower interface, i.e. the tower screen with aerial and ground radar, and the EFSS was implemented in the software. Next, the TTST was included. Both Figures 4 and 7 are screenshots of *SectorX*. The simulation could be controlled by issuing clearances via the flight strips in the EFSS and therefore no voice radio-telephony was needed.

The setup of the experiment consisted of a regular computer monitor, acting as a tower screen, and a large touchscreen, acting as EFSS (Figure 9). This meant that no (artificial) outside view was available during the experiment and traffic had to be controlled using only radar information. This is, however, a familiar situation for RCs, since during periods of bad visibility from the tower, traffic has to be controlled similarly [14]. Furthermore, a pen to be used on the touchscreen and a mouse to adjust settings on the monitor were available.

H. Participants

Six professional RCs from LVNL voluntarily participated in the experiment, resembling 8.5% of the total population of 71 licensed Schiphol RCs[3]. They were split into two groups with a different start configuration. The age and years of experience are presented in Table I.

TABLE I: Diversity of the Participants

Start Configuration	**Age**	**Years of Experience**
Baseline	$\mu = 31.7$, $\sigma = 4.8$	$\mu = 5.8$, $\sigma = 3.2$
TTST	$\mu = 31.0$, $\sigma = 2.9$	$\mu = 6.3$, $\sigma = 2.1$
Overall	$\mu = 31.3$, $\sigma = 4.0$	$\mu = 6.1$, $\sigma = 2.7$

The experiment was approved by the TU Delft Human Research Ethics Committee under application number 3613 and all participants provided written informed consent.

I. Scenarios

The experiment consisted of four distinct scenarios, based on real air traffic data to match practice as closely as possible. The focus lay on departing aircraft, and therefore no control over arrivals was possible during the experiment. For departing aircraft only line-up and take-off clearances had to be issued, i.e. only stop and go instruction. To achieve realistic flight performance, recorded radar data provided by LVNL was replayed, while including pause moments at the holding positions, after lining up and to prevent collisions on the ground. Furthermore, at the control points (holding positions and after lining up), data points with no significant aircraft movement were taken out in the replay, since these were redefined by the participants during the simulation. When a line-up clearance was issued, a two-second delay was included to simulate the engine spool-up.

Each scenario consisted of both arriving and departing traffic. Here, one runway pair was active, one runway for arrivals and one for departures. All scenarios contained a converging runway combination, meaning missed approach conflicts had to be taken into account (Figure 1). The specifics of the different scenarios can be found in Table II. The scenario used for the measurement featured the 18C/24 runway combination since this is a frequently used combination at Schiphol.

[3] Source: Luchtverkeersleiding Nederland

TABLE II: Specifics of the Scenarios (S)

	S1	**S2**	**S3**	**S4**
Date (2023)	26-02	08-05	08-04	05-05
Time	09:20:10 - 09:30:10	13:20:00 - 13:30:00	13:00:00 - 13:10:00	11:47:58 - 12:02:58
Simulation Speed	1.5	1.5	1.5	1.5
Duration [min]	6.7	6.7	6.7	10
Runways (Arr/Dep)	06 / 09	18C / 24	06 / 09	18C / 24
Aircraft Count (Arr/Dep)	5 / 7	6 / 5	3 / 5	8 / 8
Aircraft Mix (RECAT)	B,D,E	B,D,E	B,D,E	B,D,E
Surface Wind [° ; kts]	060 ; 15	260 ; 05	050 ; 09	240 ; 04
Pilot Delay [s]	$\mu = 22.3$, $\sigma = 5.2$	$\mu = 22.3$, $\sigma = 5.2$	$\mu = 22.3$, $\sigma = 5.2$	22.3
Type	Training	Training	Training	Measurement

TABLE III: Experiment design matrix, where runs 4 and 8 were used for the measurements, while the others were used for the training

	R1	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**
	Baseline				TTST			
P1	S1	S2	S3	S4	S2	S3	S1	S4
P2	S3	S1	S2	S4	S1	S2	S3	S4
P3	S2	S3	S1	S4	S3	S1	S2	S4
	TTST				Baseline			
P4	S2	S3	S1	S4	S1	S2	S3	S4
P5	S1	S2	S3	S4	S3	S1	S2	S4
P6	S3	S1	S2	S4	S2	S3	S1	S4

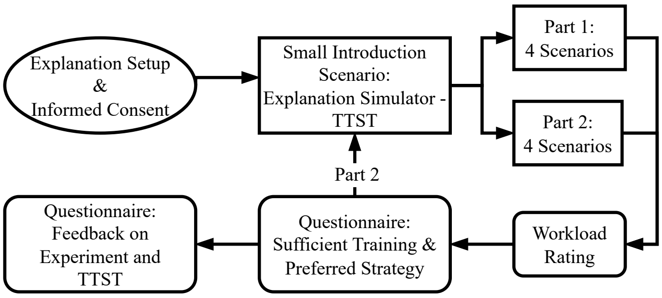


Fig. 10: Workflow followed during the experiments

J. Task and Procedure

During the experiment, the participants were asked to control the traffic in eight runs, divided into two parts, where the TTST was either disabled (baseline) or enabled. To have a fair comparison, the scenarios for both parts were the same. Each part featured three training scenarios and ended with a measurement scenario that was identical in both parts. A Latin-square matrix was used for the order in which the training scenarios and the two configurations were presented, to achieve a balanced design. Here, the configuration followed a within-participants design, while the order in which these configurations were presented followed a between-participants design. Therefore, in total, a mixed experiment design was followed. The experiment design matrix is shown in Table III. As can be concluded from this table and Table II, the training took twice as long as the measurement and the pilot delays during the measurement were not variable.

To prevent recognition, flight identifications were replaced and three training scenarios separated the measurements, which also included a different runway combination (06 / 09 instead of 18C / 24).

During all experiments, the same steps were followed, which are schematically shown in Figure 10.

V. RESULTS

To compare the TTST to the baseline, the experiment featured a within-participants design for the configuration. Only a low number of data points are present in the results due to the limited number of participants. Therefore the Wilcoxon Signed-Ranks Test [36] was applied to the results to quantify any significant difference between the two configurations.

To achieve a balanced experiment, the start configuration (baseline or TTST) followed a between-participants design. However, ideally, no difference is present between these two groups. The results of the questionnaires show no noticeable dissimilarities. For the other results within this section, an indication is present to distinguish the different groups, either by a marker or by participant number (P1 to P3 started with the baseline and P4 to P6 with the TTST).

The results are presented in five parts. The first three are related to the three hypotheses: safety, departure planning and capacity, respectively. This is followed by the workload and lastly, the results related to the realism are shown.

A. Safety

The safety was assessed by determining whether a flight departed in conflict. Figure 11 presents the departure sequence for every single participant, split into the baseline and the TTST, while also indicating the conflict windows. Since for both configurations, the arriving traffic stream was the same, the missed approach conflicts are shown in the background in light grey. For conflicts between consecutive departures, the conflict with the largest window is displayed. When a flight departed within a conflict, the colour of the marker indicates the type and the boxes next to the marker the sources.

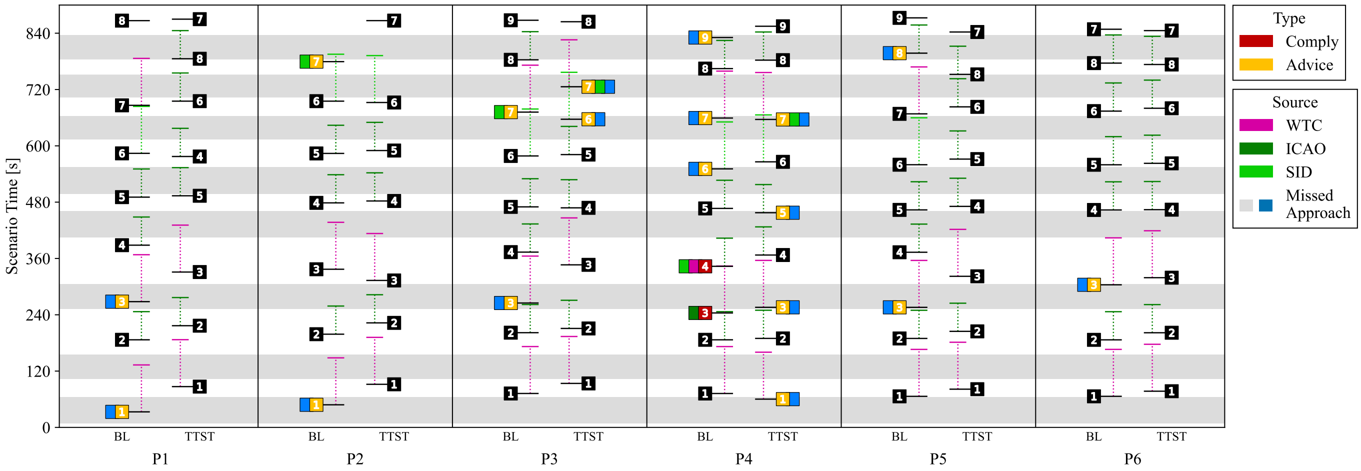


Fig. 11: Departure sequence, while indicating conflicts and the conflict window with arrivals (Missed Approach) and the largest window with the previous departure

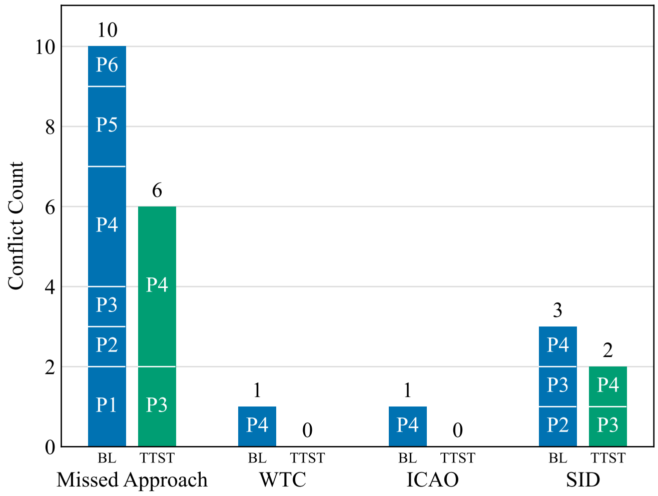


Fig. 12: Conflict Source Occurrence

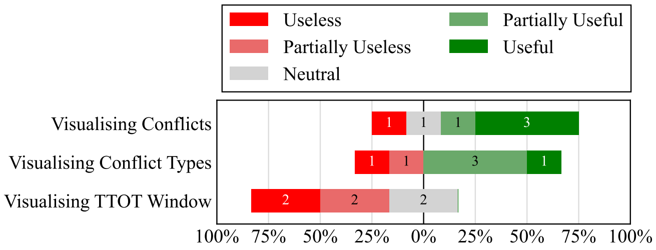


Fig. 13: ATCos' Feedback on the Conflict Visualisation

It can be seen that several conflicts occurred with both configurations. The *comply* type of conflicts only occurred with P4 and all during the baseline. Flight 3 had an ICAO and flight 4 a WTC conflict with 2.8 s and only 0.6 s margin, respectively. The *advice* type, however, occurred with all participants. Especially for flight 3, a difference can be noted between the baseline and TTST. With P1, P3, P5 and P6 this flight departed within a missed approach conflict during the baseline, while with the tool this flight departed when the arrival had landed. With P4, the missed approach conflict happened with the tool enabled. Three times, a flight departed in a combined conflict: two times flight 7 with P3 and P4 (both with the TTST) and a single time flight 4 with P4 (during the baseline).

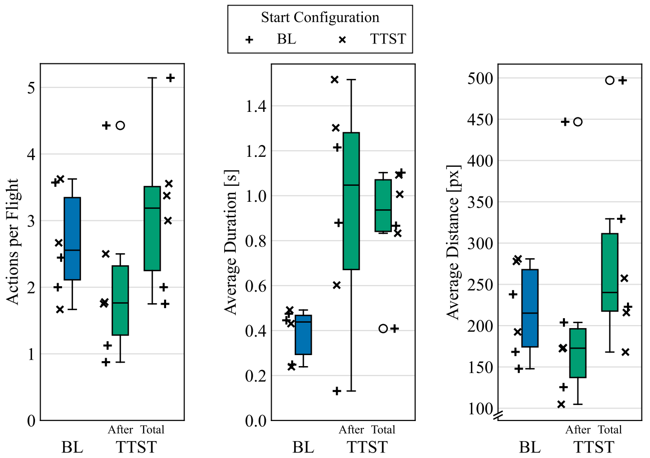
To get a better view of the conflict count, these are split up based on source (Figure 12). In general, a decrease in the number of conflicts can be seen when using the TTST: from 15 to 8 (-46.7%). For the missed approach as source, which had the most occurrences, not only the count was reduced but also the number of participants who had this conflict decreased: from every participant to only two. However, for the participants that did have these conflicts with the TTST (P3 and P4), the count increased (both with one).

Figure 13 shows the feedback from the participants on the visualisation of the conflicts. In general, it was mostly deemed useful and to a lesser extent also the types. The TTOT window, however, was perceived as not useful at all. It should be noted that P1 did not find these aspects useful and therefore indicated all of these as ‘useless’.

B. Departure Planning

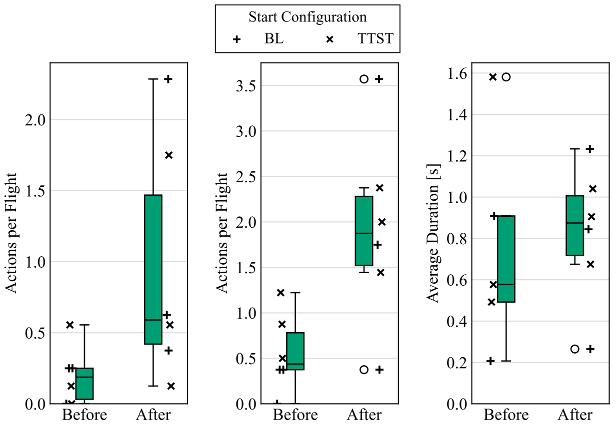
In terms of departure planning, Figure 11 also shows some differences between the baseline and TTST. With P1, P5 (TTST) and P6 (both baseline and TTST), flight 8 has been put in front of 7. With P1, also flights 4 and 5 have been swapped with the TTST.

The actions with departures performed on the EFSS with the TTST could be split up between after transfer by ground control and the total. During the baseline, actions



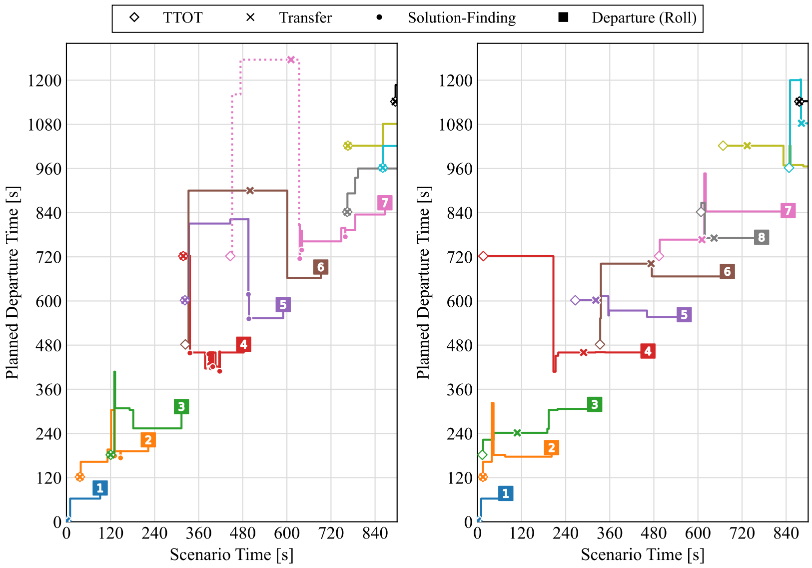
(a) Actions (b) Duration (c) Distance

Fig. 14: Average departures strip drag actions. For the TTST it is split up into after transfer by ground control and the total.



(a) Solution-Finding by Releasing within Conflict (b) Conflict Highlight (≥ 0.1 s) (c) Conflict Highlight Time (≥ 0.1 s)

Fig. 15: Average TTST actions before and after transfer by ground control



(a) P2 (b) P6

Fig. 16: Departure planning history, starting when dragged to the *working area* (TTOT) and indications of transfer by ground control, 'solution-finding' (releasing within a conflict) and the start of the take-off roll. A dotted line means dragged back to the *pending area*.

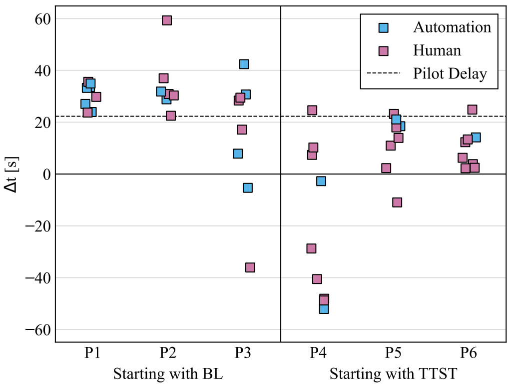


Fig. 17: Difference between the last planned and actual departure time, including an indication of who made the last time change. A positive value means planned too early and vice versa.

could only be performed after transfer since this was the moment at which the departure strips would become available. Figure 14 shows the average drag actions per flight, duration and distance (both average per action). These only include the flights that started their take-off roll before the scenario ended. The average action count per flight (14a) tends to decrease with TTST after transfer ($Med = 2.6$ vs. 1.8), except for one outlier corresponding to P2. This is, however, not significant, $Z = 1.572$, $p = 0.078$. In total, again with a large number for P2 with the tool, no significant difference is present ($Med = 2.6$ vs. 3.2), $Z = -0.943$, $p = 0.438$. The average duration per action (14b) seems to differ more between participants after transfer with the tool compared to the baseline and also significantly increases ($Med = 0.4$ s vs. 1.0 s), $Z = -1.992$, $p = 0.031$. This significant increase is also present when considering the totals ($Med = 0.4$ s vs. 0.9 s), $Z = -2.201$, $p = 0.016$. Last, for the average drag distance per action (14c), a (not significant, $Z = 0.943$, $p = 0.219$) decrease can be seen (except for the outlier) between the baseline ($Med = 215$ px) and tool ($Med = 173$ px). On the other hand, a minor (also not significant, $Z = -0.734$, $p = 0.281$) increase can be seen when taking both after and before transfer into account with the TTST ($Med = 240$ px). The two outliers with the tool correspond to P1.

The specific TTST actions could be split up into before and after transfer by ground control (Figure 15). Requesting an automated solution by releasing a strip inside a conflict (15a), happened significantly more after transfer ($Med = 0.2$ vs. 0.6), $Z = -2.023$, $p = 0.029$. Here, P2 and P6 did not perform this action before transfer. The other TTST action analysed is highlighting conflicts, and therefore accessing additional information. To be counted as a highlight, it should have lasted more than 0.1 s. Also here, the number of highlights per flight (15b) significantly increases after transfer ($Med = 0.4$ vs. 1.9), $Z = -2.023$, $p = 0.029$. The largest value after transfer in both figures corresponds to P2. It can be seen that the participants who started with the TTST had more highlights before transfer compared to the ones starting with the baseline (where P2 had no highlights before transfer). However, the numbers are quite low, mostly less than one highlight per flight. The average duration per highlight (15c) did not significantly differ ($Med = 0.58$ s vs. 0.88 s), $Z = 0.405$, $p = 0.813$. What should be noted is that before transfer one data point is missing, since P2 did not highlight any conflict before transfer.

Another way of looking at planning the departures is visualising the planning history. Figure 16 shows the planned departure time as set by P2 and P6 during the scenario and the changes made. Every line corresponds to a single flight and starts when first dragged to the *working area*, which sets the time to the TTOT. Included is also the transfer time by ground control. When the transfer happened before the start of the departure planning, the indication will coincide with the first appearance in the *working area*. A vertical line means a change in planned departure time, while a horizontal means that the strip is not dragged along the time axis. When comparing P2 and P6, it can be noted that P2, in general, started working with the strips at a later stage (e.g., with flights 3, 4 and 8). Flight 7 was even dragged back to the *pending area*. After dragging to the *working area* P2 applied more and larger changes, also when only considering after transfer. Furthermore, several times, P2 applied the ‘solution-finding’ by releasing strips within a conflict, while P6, mainly planned the departure without using this ‘trick’. These two participants were considered to be the two extremes and are therefore shown here, while the others were somewhere in between.

Following the departure planning history, the difference between the planning (last planned departure time) and the actual departure could be determined (Figure 17). A negative value means a pessimistic planning (too late) and vice versa. A minor difference can be seen between the first and last three participants, i.e. between the group starting with the baseline and with the TTST, respectively. These tend to be slightly lower for the latter one, on average 26.0 s vs. −0.1 s. Also, whether the automation or the participant made the last change, in general, seems to be mixed. P2, P4, P5 and P6 had fewer interventions by automation compared to P1 and P3. Here with P6 only once the automation made the last change.

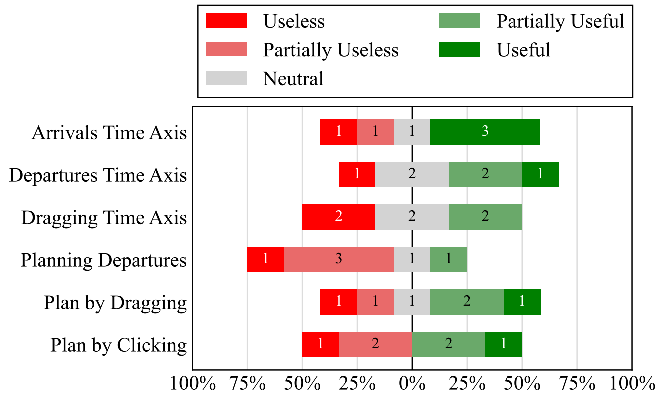
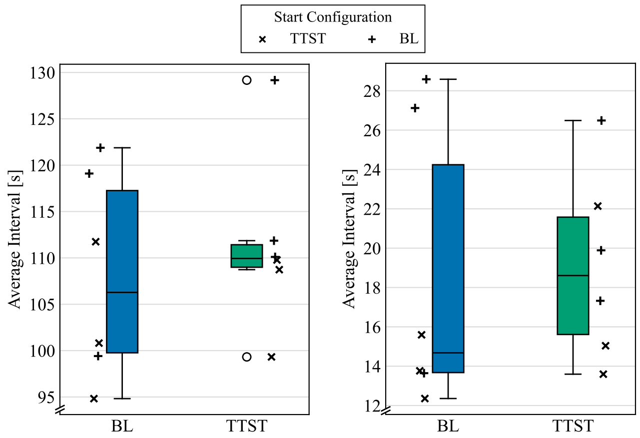


Fig. 18: ATCos’ Feedback on the Departure Planning



(a) Between Departures (b) With Closest Conflict

Fig. 19: Average Departure Interval

When looking at the participant’s feedback regarding planning the departures (Figure 18), it can be seen that it was not deemed very useful. Within this planning, dragging strips was perceived as a bit more useful compared to clicking, but only by one participant. However, the time axis was deemed more useful, despite the strong connection with planning the departure. As for the conflict visualisation, P1 marked all these aspects as useless.

C. Departure Capacity

For P1, P2, P4 and P6, no change in departure capacity can be noted (Figure 11). Here P2 had the lowest number of departures (seven). On the other hand, P3 and P5 were able to let nine flights depart during the baseline and 8 with the TTST. Overall, three participants (P3, P4 and P5) had nine departures with the baseline, while with the TTST only P4 succeeded in this.

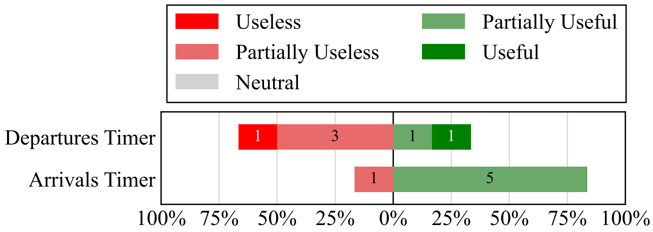


Fig. 20: ATCos' Feedback on the TTST Timers

From the departure times, the departure interval could be determined. Figure 19 presents the average interval between consecutive departures (19a) and the average interval between the departure and the closest conflict (19b). For both cases, no significant difference can be observed ($Med_{BL} = 106.3$ s and 14.7 s vs. $Med_{TTST} = 110.0$ s and 18.6 s, respectively), $Z = -1.363,\ p = 0.219$ and $Z = -0.105,\ p = 1.000$, respectively. However, for the average interval between departures, except for two outliers, less spread is present with the TTST.

TABLE IV: Number of Arrivals between First and Last Departure

	P1	**P2**	**P3**	**P4**	**P5**	**P6**
BL	8	7	7	6	7	7
TTST	7	7	7	8	7	7

Table IV presents the arrivals count during the realized departure flow (i.e., the number of arrivals between the first and last departures). It can be seen that in general, these do not differ much between the baseline and TTST. P4 had the lowest number during the baseline, while with the tool this participant had the highest number.

Related to the departure capacity are the timers counting down to the next strip included in the TTST. The feedback (Figure 20) shows that the timer for arrivals was deemed quite useful, while for departures the responses were a bit mixed.

D. Workload

Figure 21 shows the workload rating by the participants after both runs. For this, the *Rating Scale Mental Effort* was used and the corresponding labels are shown on the right. When using the TTST, the perceived workload was significantly higher ($Med = 14$ vs. 33), $Z = -2.201,\ p = 0.018$.

Also, how much demand the interface (EFSS) took from the participants eventually contributed to the workload. Figure 22, together with Figure 14a, shows the average drag actions (22a and 14a) and durations (22b) per flight for arrivals, departures and these two combined. When only considering arrivals, both the count ($Med = 2.8$ vs. 0.9) and the duration ($Med = 0.9$ s vs. 0.2 s) significantly decreased when using the TTST, $Z = 2.201,\ p = 0.018$ and $Z = 2.201,\ p = 0.016$, respectively. For departures only, no significant difference is present for the average number of drag actions per flight (aSection V-B). However, the average duration per flight increased significantly ($Med = 0.9$ s vs 3.0 s), $Z = -2.201,\ p = 0.016$. When combining arrivals and departures, a significant decrease can be noted in average drag actions per flight ($Med = 2.6$ vs. 2.0), $Z = 1.992,\ p = 0.031$. At the same time, the average duration per flight slightly increases when using the TTST ($Med = 0.9$ s vs. 1.7 s), but not significantly, $Z = -1.572,\ p = 0.078$.

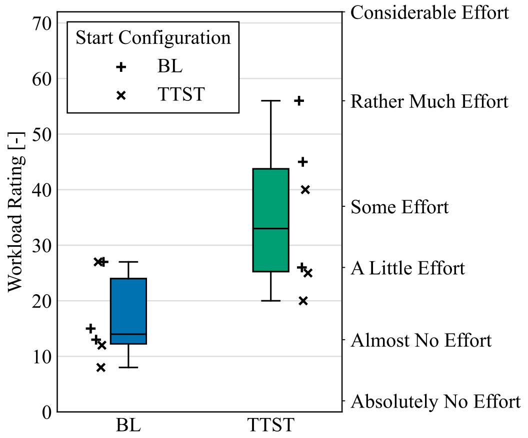
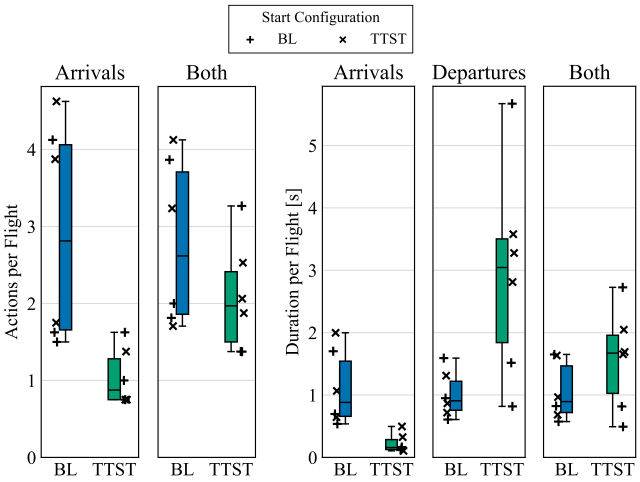


Fig. 21: Workload rating, including the *Rating Scale Mental Effort* labels



(a) Count

(b) Duration

Fig. 22: Average Drag Action Parameters per Flight

E. Realism

The participants were asked about the realism of the simulation. Figure 23 shows the rating for the different elements. All elements of the simulation were deemed realistic.

VI. DISCUSSION

The results of the experiment are discussed in three main parts. First the TTST principles. Subsequently,

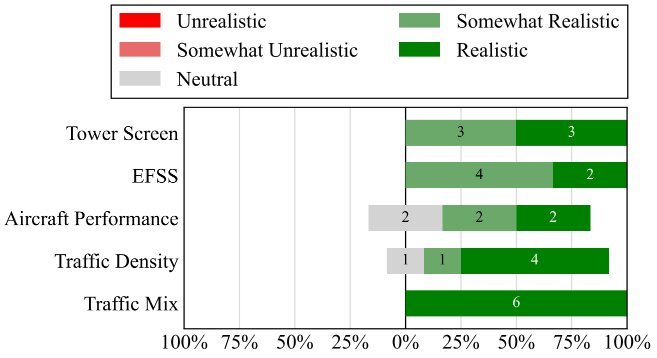


Fig. 23: ATCos' Feedback on the Realism

the workload is discussed. Finally, recommendations for further research are drafted.

A. *Take-off Timing Support Tool Principles*

The TTST was designed to support RCs with detecting conflicts for departing flights and resolving them by timing the take-off clearance, while at the same time improving the planning of departures. These principles are also encapsulated in the hypotheses drafted in Section IV-B. It should be noted that the tool includes a lot of changes to the way the EFSS is used, while the participants only had limited time (30 minutes) to familiarise themselves with the TTST.

First, the safety was envisioned to be improved, by visualising conflicts and being able to resolve these within the tool. As can be concluded from Figures 11 and 12, the number of conflicts decreases when using the TTST. Most conflicts occurred, including the two *comply* types, with P4. However, this can be explained by the fact that this was the only participant able to let nine flights depart in both runs and therefore applying an 'optimistic' separation.

Special attention shall be given to the two *advice* conflict types (missed approach and SID) since these two were defined based on a 'rule of thumb'. This means that not every RC may adhere to this and differences in definitions of the rules may exist. Therefore, a departure within these conflicts in the baseline does not mean that this was a conflict according to the participant since a different 'rule of thumb' could be applied. However, with the TTST, the presented conflict window was the same for all participants. It is interesting to note that also for these types a decrease can be seen, especially for the missed approach which also occurred with fewer participants with the tool enabled. This suggests that the participants do take the information presented in the TTST into account in their decision-making, even when a different strategy was applied during the baseline. As an example, P1, P3, P5 and P6 waited with the departure of flight 3 until the missed approach conflict was over (Figure 11). The same can be seen for flight 1 with P1 and P2. Regarding hypothesis 1, not all missed approach conflicts were prevented, hence rejecting this hypothesis. However, a decline is visible.

During the experiments and discussions with the participants, it became clear that the conflicts currently incorporated in the TTST solution space were a bit too basic. In other words, most participants could already apply the correct separation without the use of tooling. However, as pointed out by one of the participants, the TTST did resemble the mental picture of the RCs. This means that the tool succeeded in visualising the control strategy in terms of safety. And since the information presented was used by the participants, more complex conflicts can be implemented, for example along track departure conflicts with a vertically changing wind field (different wind direction/magnitude when climbing), which are difficult for humans alone to incorporate.

For the second principle, regarding planning departures, P1 and P5 swapped flights 7 and 8 when using the TTST (Figure 11). This indicates that these participants used the visualisation of the WTC conflict to apply a smaller separation by letting the aircraft with a lower category depart first.

The average number of drag actions per departing flight after transfer by ground control tends to decrease with the TTST (Figure 14a), despite adding a function to the strip placement (planning the departure time) and dragging strips (gathering information on conflicts). The decrease may not be significant, but also no increase is visible. The additional functions are also reflected in the increase in average drag duration per action, both after transfer and in total (Figure 14b). The same holds for the upward trend in total average distance per action (Figure 14c). The lower distance after transfer by ground control can be explained since the departure is imminent and therefore the time changes are smaller, which is connected to the distance. Strictly, hypothesis 2, stating that there would be fewer strip actions after transfer with the tool, cannot be accepted, but a downward trend is visible.

The longer average duration per action after transfer with the TTST indicates that the participants were still planning the departure when the aircraft was already close to the runway. This is also supported by the results of the specific TTST actions (Figure 15). An interesting case here is P2. From the planning history (Figure 16a) it becomes clear that the planned time is altered quite a lot, especially after transfer by ground control. This is also reflected by the outliers for the average drag actions per flight (Figure 14a). Also, this participant only highlighted conflicts after transfer. The large number of 'solution-finding' can be explained with flight 4. Around 400 s into the simulation a lot of these actions can be seen. Analyses showed that the participant was trying to deactivate the missed approach conflict while establishing the required WTC separation with flight 3 (Figure 11). Also for P2, especially with flights 5, 6 and 7, strips were moved up first, and when the departure was imminent, these were moved down again. More or less, the workflow of the original EFSS was applied (which is something the tool allows to do). This follows also from the fact that flight 7 was even put back in the *pending area* and later dragged back to the *working area*. Altogether, this demonstrates that this participant was planning mostly last minute. Also, P1 more or less applied the same original workflow, which follows from an analysis of the large average drag distance per action (Figure 14c). This participant waited several times with dragging strips to the *working area* until transfer already happened and therefore had to drag it all the way down to the horizontal line indicating the current time.

However, not all participants applied the same strategy to this. As an example, P6 (Figure 16b) was able to establish a more stable planning. This follows from the relatively long horizontal lines preceding the actual departure. A good example is flight 4, where all departure time changes happened before transfer and thereafter only the line-up and take-off clearance had to be issued.

What can be seen when comparing P2 and P6 is that the latter, in general, started working with the departures at an earlier stage. This is probably one of the reasons for the more stable planning and also why only one 'solution-finding' action was needed. More training with the TTST could lead to participants, and operators in general, applying the P6's strategy.

Most participants pointed out that, in reality, the planning of departures can be very difficult, due to the uncertainty in many factors of the ground process, such as taxi time and the different turnaround processes (when planning even further ahead). This is also reflected in the feedback on planning departures in Figure 18. However, P6 demonstrates that it is possible to get a stable planning after taxiing has started. This stable planning is also reflected in the difference between the planning and the actual departure (Figure 17). It can be seen that for this participant all flights departed within 25 s from the planned time, while for P2, it ranged from 23 s to 60 s. Also, P6 made the last change to the planning, except for a single flight. This means that last-minute intervention by automation was (almost) not needed, which is also a sign of a stable planning. Furthermore, this figure shows that the group starting with the baseline planned mostly too early, while the other group planned closer to the actual departure time. The difference in average is 26.1 s, which is close to the pilot delay of 22.3 s. This means that especially with the first group a take-off clearance was issued when the strip reached the horizontal line. The difference has possibly to do with the group starting with the TTST had the briefing about the pilot delay 'fresh in memory', while for the other group, the baseline part was in between. From a safety standpoint, planning too early is not really problematic, since in this case the RC should make sure that there is enough spacing with the next conflict, which can also easily be noticed in the TTST. The separation with the consecutive departures is automatically updated, without the need for any intervention by the ATCo. However, some capacity will be lost, approximately equal to the pilot delay or longer when the departure has to wait for the next missed approach conflict.

Third, some differences are present between the participants regarding the departure capacity. P2 only had seven departures, while P4 had nine. As mentioned above, P4 applied an 'optimistic' separation, while P2 seems to be more conservative. The planning history of P2 suggests that at least when using the TTST, this participant worked more last minute, as also described above. For example, this participant started working with flight 8 at a late stage and therefore not being able to let this flight depart or swap it with flight 7 to not have a required WTC separation (which also did not happen during the baseline).

In general, no large differences can be noted for the departure interval (Figure 19). Naturally, the presence of conflicts influences the separation applied by the participants. Therefore also the interval with the closest conflict is presented (Figure 19b). However, also here no significant differences are present. Furthermore the number of arrivals between the first and last departure (Table IV) did not differ much. The result of P4 can be explained with the 'optimistic' separation applied. In Figure 11 it can be seen that during the baseline the departures were more 'squeezed', resulting in a lower number of arrivals. With the TTST, this participant was the only one to let the first flight depart within a missed approach conflict and therefore had an extra arrival between the first and last departure. In summary, possibly the low number of departures and short duration of the scenarios lead to the capacity result not being very different. Based on these results, hypothesis 3, stating that the departure interval would decrease, can be rejected.

B. Workload

The ratings given by the participants with the *Rating Scale Mental Effort* (Figure 21), show that with the TTST the workload was perceived higher. The relatively low workload for the baseline can be explained since the participants are very familiar with controlling these types of scenarios and the current EFSS. Furthermore, the scenario contained only one arrival and one departure runway (1 + 1), while during traffic peaks there are three active runways (2 + 1 or 1 + 2). However, the TTST transforms the EFSS into a planning tool, meaning a big change in use and the introduction of new types of information. This was also pointed out by most participants: more experience with the current EFSS, while sometimes still getting used to working with the TTST. P1 summarised the difficulties encountered with the tool by stating that the current EFSS is used as a 'notebook', while with the tool strips start moving and therefore the system is 'messing up' the notebook (which also explains the negative responses in Figures 13 and 18). These factors explain the relatively higher workload.

On the other hand, the workload for arrival flight strips might decrease, because of the automated arrival strip sequence. With the TTST, the participants did not have to sort these strips themselves. The resulting decrease in average drag action per flight and average duration per action can be seen in Figure 22, and with the tool mainly includes dragging the strip down to the *working area.* This result is also reflected in the feedback from the participants (Figure 18), where three participants found the time axis for arrivals a useful addition. One participant called it 'really convenient', since 'you do not have to check the order' of arrivals which 'on a daily basis can save quite a bit of time'. This is partly compensated by the increase in drag duration of departures, due to the planning character of the tool and the appearance of the strip upon taxiing. In other words, instead of 'puzzling' with arrivals, more actions are required for planning departures, which also is reflected in the increase in average drag duration per flight for departures. Despite this, the total average drag actions per flight decreased. Also, the overall average drag duration per flight does not significantly increase.

Also, an important factor in aerodrome control is the time needed to consult the information systems in the tower, since air traffic should be primarily visually controlled. At least, from the time the participants were dragging strips, it cannot be concluded that more 'heads-down' time is introduced with the TTST.

C. Experiment Setup

To be able to connect the results of this research to the real operation, the realism of the experiment setup is an important factor. To achieve this, a replica of the tower screen and the EFSS was built, the scenarios contained real traffic samples and to match aircraft performance, traffic was replayed. Also, the perceived realism by the participants must be considered and it can be concluded that the simulation was realistic (Figure 23). Interesting to note is that not every participant marked the aircraft performance as 'realistic', despite the replay. There could be several reasons for this. First, the performance could only be assessed by looking at the radar screen, while in reality also the outside view is present and therefore could be perceived differently. Second, the participants could really focus on their task, since there were, for example, no ground controllers present and other factors that could distract them, hence the participants had the time to track the aircraft in more detail on the radar screen. Third is the pilot response time. During the simulation, the pilot delay (distribution) after issuing the take-off clearance was the same for all flights, while in reality, for example, it is highly associated with the airline.

D. Recommendations

Based on insights gained during the design, the results and the feedback from the participants, several recommendations were drafted.

First, the limited number of participants and also the limited duration of the scenarios (and the corresponding low number of flights) probably resulted in some statistically insignificant results. The limited duration also influenced the training of the participants. For example, the difference in departure planning with the TTST, showed that not every participant used the tool to the fullest extent. Therefore an experiment with more participants, longer scenarios and more training should be performed.

Additionally, the tower operation is not only limited to runway control. As also pointed out by various participants, to be able to let a flight take off within its departure window, the RC depends on ground control to deliver the aircraft on time at the runway holding point. To achieve better adherence to the departure window (which is needed with TBO) and a more stable and predictable operation, additional tooling for ground control can be introduced. Here, improved taxi predictions can be utilised to support the controllers in their decision-making. Optionally, also the outbound planner can be supported with determining the initial departure planning.

Furthermore, also the interaction between ground and runway control can be taken into account when evaluating the TTST. For example when, based on information provided by the tool, the RC would like to change the departure sequence, while flights are still under control at ground. Potentially, a future support tool for ground can be connected to the TTST for this purpose.

Also within the TTST, improvements can be made. The most important is adjusting the conflict windows. Of the current conflicts, the missed approach and along-SID can be further refined. The missed approach conflict window can, for example, be improved by making use of the data on the projected final approach speed, specific aircraft characteristics and wind conditions at the approach path. The along-SID conflict window can be adjusted with, for example, improved trajectory predictions by making use of more detailed ADS-C EPP reports. Doing so, especially in situations which are difficult for ATCos to comprehend such as with complex wind fields, the TTST can have even more added value since the experiment showed that ATCos do take this information into account in their decision-making.

Based on the observations made with P2, deactivation of *advice* type conflicts could be improved. In the version tested in the experiment, a deactivated conflict would become active when the departure is dragged again, which could lead to the behaviour seen in Figure 16a for flight 4. This process has been improved in a newer version of the TTST. Here, conflicts stay deactivated until the strip is again hovered over the window for more than two seconds. However, this version has not been tested with RCs.

To improve planning the departures, taxi time predictions can be introduced. This may help RCs with determining the take-off time and provides them with a more realistic solution space by taking out solutions before the flight has reached the runway. Additionally, as came forward in Section VI-A, some sort of pilot delay prediction can be introduced, such that flights will depart with a smaller difference from the planned departure time.

Last, it should be investigated what effect the TTST, or tooling in general, will have on visual control at the tower. More specifically, how much 'heads-down' time will be introduced and, when necessary, what mitigating measures should be introduced.

VII. Conclusion

The introduction of Trajectory Based Operations (TBO) will change the operation for aerodrome control, but it will also provide new opportunities for decision support tools due to the availability of new data and information. A support tool called the Take-off Timing Support Tool (TTST) has been developed for runway control at Amsterdam Airport Schiphol. The tool has been incorporated into the already existing Electronic Flight Strip System (EFSS) and provides Air Traffic Controllers (ATCos) with the solution space in time and enables them to improve the planning of departures.

The experiment conducted with the TTST showed a decreasing trend in conflicts and at the same time adherence to the conflict information provided. Regarding the departure planning, mixed results were visible, ranging from last-minute adjustments to a stable planning. This proves that, most certainly with more training, a stable planning in terms of departure time is possible. Furthermore, no significant differences in departure interval nor the interval with the closest conflict were present. Lastly, a significant increase in workload could be observed, mostly a result of the radical change in workflow with the EFSS and the unfamiliarity with the tool.

In conclusion, the TTST is a suitable platform for supporting TBO in aerodrome control. The tool utilises additional data and information that will become available and leaves room for the incorporation of future developments. It also assists ATCos with time-based control and emphasises the departure window, which is part of the four-dimensional trajectory.

In the future, the relationship with ground control, conflict window refinement, and taxi time and pilot delay prediction should be investigated, which potentially can improve departure planning in aerodrome control. Lastly, the effect on visual control in the tower should be investigated.

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II

Preliminary Thesis Report*

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*Has been graded as part of the preliminary thesis report under AE4020 - Literature Study

1

Introduction

1.1. Background

To facilitate air traffic, Air Traffic Management (ATM) has been established. As part of ATM and Air Traffic Services (ATS), Air Traffic Control (ATC) is responsible for maintaining safe separation between aircraft and creating an orderly and efficient flow of traffic. To achieve this, different ATC units have been established, which can be subdivided into Area Control Centre (ACC), Approach Control (APP) and *Aerodrome Control* or Tower (TWR) control. The airport and its vicinity is the work domain of aerodrome or TWR control. This includes being responsible for taxiing aircraft and issuing clearances for take-offs and landings.

Based on forecasts, it is expected that in 2040 there will be a demand for $16.2\ million$ flights in Europe. While taking into account planned capacity growth, this will lead to a capacity shortage of $1.5 million$ flights at European airports. (EUROCONTOL, 2018) Although during the COVID pandemic, the number of flights conducted dropped drastically, a strong growth in air traffic can again be observed, and the numbers are approaching the level of 2019.[1] Therefore the urge to improve the ATM system remains, in order to be able to facilitate the expected air traffic growth. At the same time, as humanity is facing a climate crisis, also aviation must reduce its impact on the climate and environment. Two crucial aspects are the reduction of aircraft emissions and noise pollution. Apart from the development of new aircraft and propulsion systems, also the ATM system plays a role in the task[2]. Therefore, the ATM system must be modernised and the efficiency should be increased. This may, for example, result in facilitating direct routes with minimal additional track miles and therefore reducing aircraft emissions.

1.2. Problem Statement

The European ATM Master Plan (SESAR Joint Undertaking, 2019) lays down the vision of the *Single European Sky ATM Research* to improve the ATM system in Europe. In this, Trajectory Based Operations (TBO) is an important concept to achieve these goals. Within TBO, a Four-Dimensional (4D) trajectory (i.e. latitude, longitude, altitude and time), gate-to-gate, acts as the joint plan for operating the flights. The 4D trajectory is managed through Collaborative Decision Making (CDM) and shared with stakeholders and involved parties. With TBO, the ATM system should become more efficient, thus leading to higher capacity and less environmental impact, for example by shorter, more direct trajectories. TBO relies on extensive data sharing and the availability of new types of data, for example, data links with aircraft, which potentially unlocks new possibilities to predict trajectories and control flights.

Since within TBO, the 4D trajectory describes the flight from the departure gate until the arrival gate, all stages of the flight are included. This means that all types of ATC units need to switch to TBO as well, including TWR control. Therefore research is required into which way TBO can be supported in aerodrome control and how TBO can improve the current operation in the TWR. By using the information available in a TBO environment, a decision support tool can assist the TWR controller in making trajectory-based decisions for flights under its control.

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[1] Source: https://www.eurocontrol.int/publication/eurocontrol-forecast-update-2022-2028, Accessed 27-2-2023

[2] Source: https://climate.ec.europa.eu/eu-action/transport-emissions/reducing-emissions-aviation_en, Accessed 6-4-2023

1.3. Research Objective and Question

Based on the background and problem statement, the following research objective is defined:

Research Objective

Supporting Trajectory Based Operations in Aerodrome Control by designing and creating a decision support tool for Tower controllers.

This research objective can be subdivided into several sub-objectives. The first is to analyse the current *Aerodrome Control* operation at Schiphol Airport. The second is to investigate the TBO concept, the relation with *Aerodrome Control* and the new opportunities it provides in terms of predictions and decision support. The last is to provide and visualize the solution space to TWR controllers with a decision support tool, based on the current operation and the TBO environment.

The main research question, which will be answered in this research, is stated below. In order to answer this research question, several sub-questions have been defined, which are stated below the research question.

Research Question

How can Trajectory Based Operations be supported in Aerodrome Control?

Sub-Questions

1. How is Aerodrome Control implemented at Schiphol Airport?
2. What is Trajectory Based Operations?
3. How can a feasible target take-off time be determined?
4. How can departure time solutions visually be presented to Tower controllers?
5. How does take-off timing support affect the runway capacity and the number of conflicts?

1.4. Report Structure

In Chapter 2, a general description of the ATM system is provided. The first research sub-question is treated in Chapter 3, which describes *Aerodrome Control* at Schiphol Airport. TBO is discussed in Chapter 4, which also answers research sub-question two. These first three chapters all include a section 'Research Focus', which describes the focus of the research with respect to the chapter topic. Based on the information provided in the previously mentioned chapters and the corresponding research focus section, a support tool for TWR control is designed, which is discussed in Chapter 5.

2

Air Traffic Management

Air Traffic Management (ATM) is the ’dynamic, integrated management of air traffic and airspace’, as defined by ICAO (2016). This can be subdivided into three parts: Air Traffic Services (ATS), Air Traffic Flow Management (ATFM) and *Airspace Management*. These parts will be discussed in Section 2.1, 2.2 and 2.3, respectively. In Section 2.4, the focus with respect to ATM will be presented.

2.1. Air Traffic Services

As for ATM, also ATS can be subdivided into several components. These are flight information service, alerting service, air traffic advisory service and Air Traffic Control (ATC) service. Flight information service consists of providing information to flights, such that these can be operated safely and efficiently. This could be, for example, the weather or aerodrome information. Next, the air traffic advisory service consists of providing information for safety purposes, i.e. collision hazards. However, these shall not be interpreted as clearances but as advice, since the completeness of the information can not be guaranteed. Alerting service applies in case of emergencies and also includes search and rescue services. (ICAO, 2016)

Probably the most well-known part of ATS, and ATM for that matter, is ATC. ATC can be split up into several parts as described by ICAO (2001). These are listed below. The division between these services is schematically shown in Figure 2.1.

- Area Control Centre (ACC)
- Approach Control (APP)
- Aerodrome Control or Tower (TWR) Control

The different controllers will issue clearances in order to maintain safe separation between aircraft and to create an efficient and orderly flow of traffic. In the Netherlands, Belgium, Luxembourg and a part of Germany, *Area Control* is split up into *Upper Area Control* and ACC, where the *Upper Area Control* is provided by Maastricht Upper Area Control, which is part of Eurocontrol. Here *Upper Area Control* is responsible for en-route traffic. ACC, APP and TWR are provided by the Dutch Air Navigation Service Provider (ANSP), Luchtverkeersleiding Nederland (LVNL). ACC is responsible for aircraft climbing to the en-route phase of flight and for aircraft descending to the destination airport and when these need to hold when the demand exceeds the runway capacity at the airport. APP controllers will guide arriving aircraft to the final approach to the runway and are responsible for aircraft climbing out of the departure airport. Last, the TWR is responsible for all traffic at and around the airport.

2.2. Air Traffic Flow Management

According to ICAO, 2016 ATFM is ”a service established with the objective of contributing to a safe, orderly and expeditious flow of air traffic by ensuring that ATC capacity is utilized to the maximum extent possible and that the traffic volume is compatible with the capacities declared by the appropriate ATS authority”. It is therefore used to manage the air traffic demand such that it matches the ATC capacity.

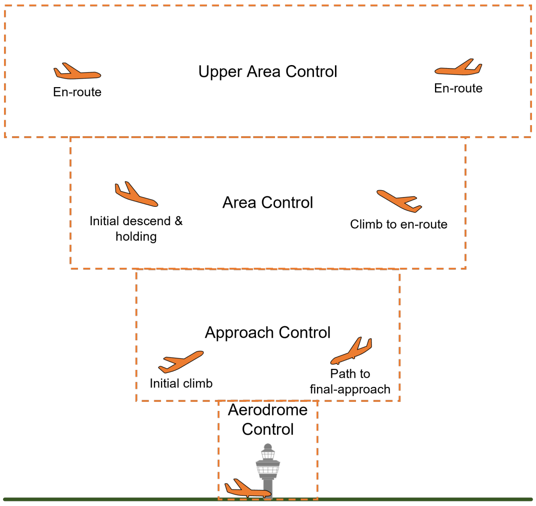


Figure 2.1: Air Traffic Control Division

At airports and in airspaces where the demand could exceed the ATC capacity, ATFM should be implemented. There are three phases of ATFM: strategic planning, pre-tactical planning and tactical operations. Strategic planning happens well in advance before the flights take place, most of the time between two to six months, i.e. for the next season. To ensure the expected demand does not exceed the expected capacity, measures need to be taken to mitigate this, for example by increasing the ATC capacity or rescheduling flights. Pre-tactical planning usually happens one day before the operation. It comes down to fine-tuning the plan made during the strategic planning phase. The tactical operations phase happens on the day of the operation. During this phase, tactical measures are executed, which prevent the demand from exceeding the capacity. Also, the air traffic situation is monitored to check whether the measures have the desired effect. When there are long delays, remedial actions have to be taken. If, despite the measures taken, there is (or will be) an exceedance of capacity the ATFM unit and other ATC units should be advised. Next to this, flight operators shall be informed about expected delays and/or possible restrictions. (ICAO, 2016)

In Europe, the ATFM is provided by the Eurocontrol Network Manager (NM). At Schiphol, Collaborative Decision Making (CDM), in the form of *Airport-CDM*, has been implemented and this is connected to the NM operations centre. NM balances the demand and capacity in the airspace of connected ANSPs, such that the demand will not exceed the capacity of the sectors. This is done by issuing a Calculated Take-Off Time (CTOT), which is a time slot together with a corresponding window (-5, $+10$ min), wherein the aircraft shall depart.

Within CDM the different stakeholders, which are the aircraft operator, main ground handler, de-icing coordinator, pilot, ATC and airport operator, cooperate by sharing information to achieve efficient planning and eventually an efficient operation. For this, the *Milestone Approach* is used as described by Duivenvoorde et al. (2019). There are several milestones specified, which are significant events in the planning phase or during the progress of a flight. At every milestone one or more actions take place. The *Milestone Approach* is suggested by Eurocontrol (EUROCONTROL Airport CDM Team, 2017) however, at Schiphol, not every suggested milestone is implemented. Therefore some milestone numbers are missing from the list below. In the *Milestone Approach* and the CDM process in general, several time parameters are used. An overview of these parameters and their definition are listed in Chapter A.

1. EOBT - 3 hours
2. EOBT - 2 hours
4. Local Radar Update
5. Final Approach
6. Landed
7./8. In-Block
9. Final TOBT update

10. ATC issues TSAT
11. Boarding Starts
13. Actual Start-up Request Time
15. Off-Block
16. Take-Off

The first two milestones are based on the Estimated Off-Block Time (EOBT), which is the expected time the aircraft departs from the gate, i.e. the 'block', and is provided in the flight plan. Milestone one takes place three hours before the EOBT of the flight. At this milestone, the flight plan from ATC is automatically matched to the corresponding outbound flight in the CDM system. Also the Target Off-Block Time (TOBT) is sent to ATC, which is the estimated time at which the ground handling is finished. When the outbound flight does not have a connected inbound flight the TOBT is set equal to the *Scheduled Off Block Time*, which is the slot provided by the Airport Slot Coordinator. When there is a connected inbound flight, the TOBT is calculated with Equation (2.1). The TOBT will be automatically updated when there is a change in the Estimated Landing Time (ELDT) and/or the Estimated In-Block Time (EIBT) however, this process will stop when the aircraft has arrived at the gate (there is an *Actual In-Block Time*) or when the Main Ground Handler Agent sets the TOBT manually. When the EOBT is changed to a time later than the TOBT, it will be overwritten by the EOBT.

At milestone two, which takes place two hours before the EOBT, this TOBT will automatically be updated when there is an update of the EIBT with Equation (2.1). This new TOBT will be provided to ATC. The process of updating the TOBT will continue until milestone six.

$$TOBT = EIBT + Minimum\ Turnaround\ Time \tag{2.1}$$

When the arriving flight enters the Dutch Flight Information Region (FIR), which is milestone four, changes in the ATC flight plan of the ELDT and EIBT are automatically updated in the CDM system. The same holds for milestone five. Also, the flight state is updated to FIR when the flight enters the Dutch airspace and to Terminal Manoeuvring Area (TMA) when the flight enters the TMA. The flight state is set by ATC and is automatically changed in the CDM system as well.

The next milestone happens when the flight is on final approach. When ATC sets the flight state to 'Flight on final', this is also updated in the CDM system.

When the flight has landed, milestone six, both updates of the *Actual Landing Time* and EIBT from the ATC flight plan are also automatically updated in the CDM system. When the *Actual Landing Time* is set, the flight state is changed to 'Flight taxiing'.

After landing, the aircraft will taxi to the gate. When arrived at the gate (i.e. in-block), which are milestones seven and eight, the Actual In-Block Time is set in the ATC flight plan and this is also automatically updated in the CDM system. This update of the Actual In-Block Time will set the flight state to 'Flight in-blocks' and it might lead to an automatic update of the TOBT which is then provided to ATC.

When the main ground handler agent sets the TOBT, considering the current operational situation, milestone 9 takes place. After this milestone, at ten minutes before the current TOBT, the main ground handler and/or the aircraft operator should evaluate the accuracy of this TOBT and update it when necessary.

The TOBT also influences the Target Start-up Approval Time (TSAT), which is the expected time the aircraft can receive a start-up clearance. Milestone ten takes place when ATC issues the TSAT. Before departure, the TSAT is determined using the TOBT, Estimated Taxi-Out Time (EXOT) and TTOT. First the earliest possible TTOT, the TTOT', is calculated using Equation (2.2). Based on several factors, which are the CTOT, Standard Instrument Departure (SID), Wake Turbulence Category (WTC) and runway capacity, an optimal take-off sequence is determined which leads to the TTOT. This is then used to calculate the TSAT with Equation (2.3). 40 Minutes before the TOBT, the TSAT is provided to the pilots of the flight.

$$TTOT' = TOBT + EXOT \tag{2.2}$$

$$TSAT = TTOT - EXOT \tag{2.3}$$

The next milestone (eleven) happens when the boarding starts. Based on the information from the gate agent, the flight state will be set to 'Flight boarding'.

When the pilot requests start-up, milestone thirteen takes place. ATC will then set the *Actual Start-up Request Time* and this time is automatically updated in the CDM system, provided that the request happens within the TSAT-window $(-5, +5\ min)$. The update of the *Actual Start-up Request Time* will lead to a flight state update to 'Flight ready' and the TTOT is manually updated.

When the flight departs from the gate, i.e. off-block, milestone fifteen happens. ATC will set the *Actual Off-Block Time* and this is then automatically updated in the CDM system. This will also lead to a flight state update to 'Flight taxiing'.

Eventually, when the flight takes off, the last milestone takes place, which is milestone sixteen. The *Actual Take-Off Time* will be set by ATC and this will then be automatically updated in the CDM system. The flight state will be set to 'Flight airborne' when this time is set. (Duivenvoorde et al., 2019) The Milestone Approach together with the flight states is schematically shown in Figure 2.2. In this figure, also the interaction with the different Air Traffic Controller (ATCo)s is shown. A more detailed description of the different ATCo working positions in the TWR is provided in Chapter 3.

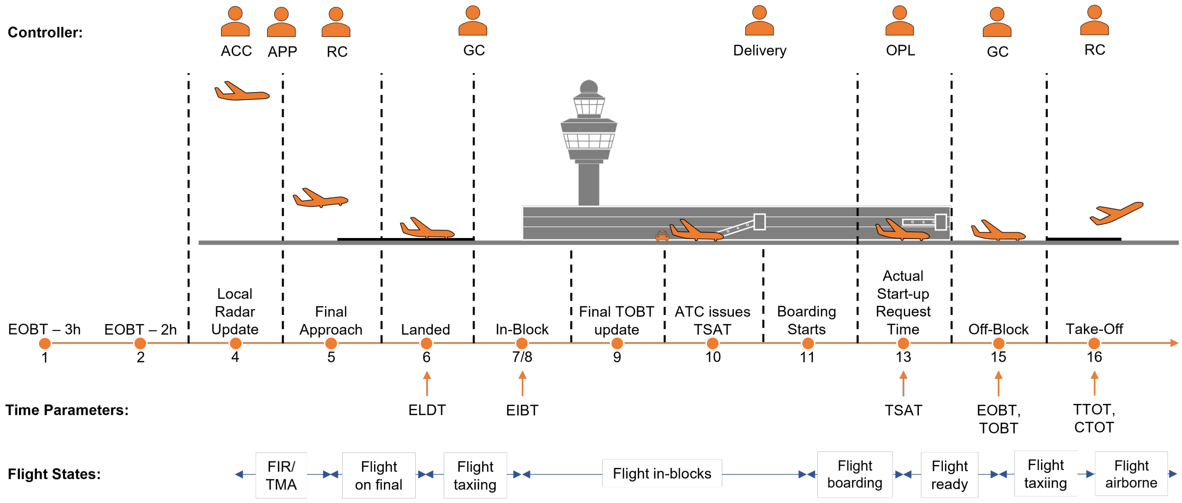


Figure 2.2: Airport - Collaborative Decision Making Milestone Approach

As stated before, the CDM system is connected to the NM operations centre. This is done with the Departure Planning Information (DPI) connection. This connection consists of sending DPI messages. (Duivenvoorde et al., 2019) These messages contain several time parameters:

- Scheduled Off-Block Time
- EOBT
- TOBT
- TTOT
- TSAT
- Taxi Time

With the DPI messages, these time parameters will be set in the Enhanced Tactical Flow Management System (ETFMS) of Eurocontrol. The two main functions of ETFMS are to determine the demand in the sectors which are connected to the NM based on flight plan information provided by the aircraft operator, and calculate and distribute the slot times, i.e. the CTOTs.

There are different DPI message types. The first message type is the *Early-DPI* message which is used to verify that the EOBT and the *Scheduled Off-Block Time* match. This message is used for milestone one.

The *Target-DPI-target* is used to communicate a new or updated TOBT and information about when the flight could depart. This message is used for milestone two, but could also contain information on milestones three to nine.

The next message is the *Target-DPI-sequenced* message which is used to communicate the TSAT and provide information about when the flight departs according to the planning. This message is used for milestone ten, but it may also contain information from milestones twelve and thirteen.

The *A-DPI* message is used to communicate that the flight is under the control of ATC. This message type is used for milestones fourteen and fifteen.

The last message type is *C-DPI* which is used to inform about an interruption of the flight progress. It will result in the cancellation of the latest information provided by a DPI message and the flight plan will be suspended. At Schiphol this message is used for an expired TSAT, return to the stand, invalid flight plan or a cancelled flight.

As described above there is a system of information sharing between the different stakeholders. A schematic overview of sharing the different time parameters between the stakeholders is shown in Figure 2.3.

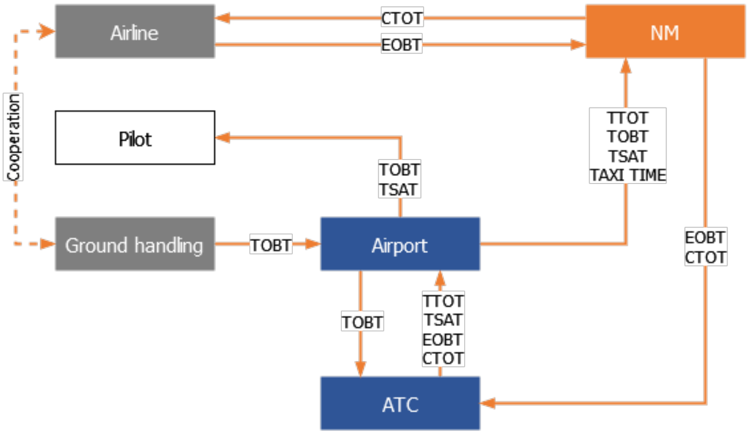


Figure 2.3: Time Parameters Flow

2.3. Airspace Management

Globally, the airspace is subdivided into Flight Information Regions (FIRs). In the Netherlands, there is only one FIR, called the Amsterdam FIR. Within this FIR several controlled airspaces are present and these generally correspond with the area of responsibility of the different ATC services. These airspaces are listed below. (Hoekstra and Ellerbroek, 2020)

- Upper Airspace
- Control Area
- Terminal Manoeuvring Area (TMA)
- Controlled Traffic Region (CTR)

The upper airspace is the work domain of the controllers from *Maastricht Upper Area Control*. This airspace starts from Flight Level 245. ACC generally is responsible for flights within the *Control Area*. For inbound flights, the ACC controllers will guide the aircraft to the *Initial Approach Fix*, which is generally located at the border between the *Control Area* and the TMA. When the demand exceeds the capacity of the runway, ACC will let aircraft hold in stacks close to the *Initial Approach Fixes*. Within the TMA, APP is responsible for the flights. Inbound flights will be guided from the *Initial Approach Fixes* to the final approach. Last, the CTR is the work domain of the TWR, which is the area around the airport. The aforementioned airspaces can be classified, as defined by ICAO (2001), based on the type of flights allowed within this airspace, i.e. Visual Flight Rules (VFR) or Instrument Flight Rules (IFR), and the extent of ATC service provided.

Schiphol has three CTRs, which are shown in Figure 2.5. As indicated in the figure, altitudes are defined for the different CTRs. CTR 1 elevates from the ground up to $3,000ft$. The circular part of this CTR has a radius of $8NM$ and the centre is located at the *Airport Reference Point*. Both CTR 2 and 3 elevate from $1,200ft$ up to $3,000ft$. (LVNL, 2022)

2.4. Research Focus

Within this research, the focus will be on Aerodrome or TWR control and therefore on the operation within the CTR. However, since the ATM system is highly integrated, other parts may not be neglected.

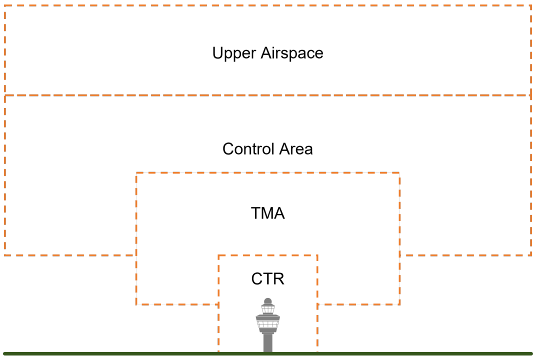


Figure 2.4: Airspace Division

For example, the ATFM process, described in Section 2.2, must be taken into account when looking at outbound flights. When determining the order in which flights are going to depart, the ATFM process has a large influence.

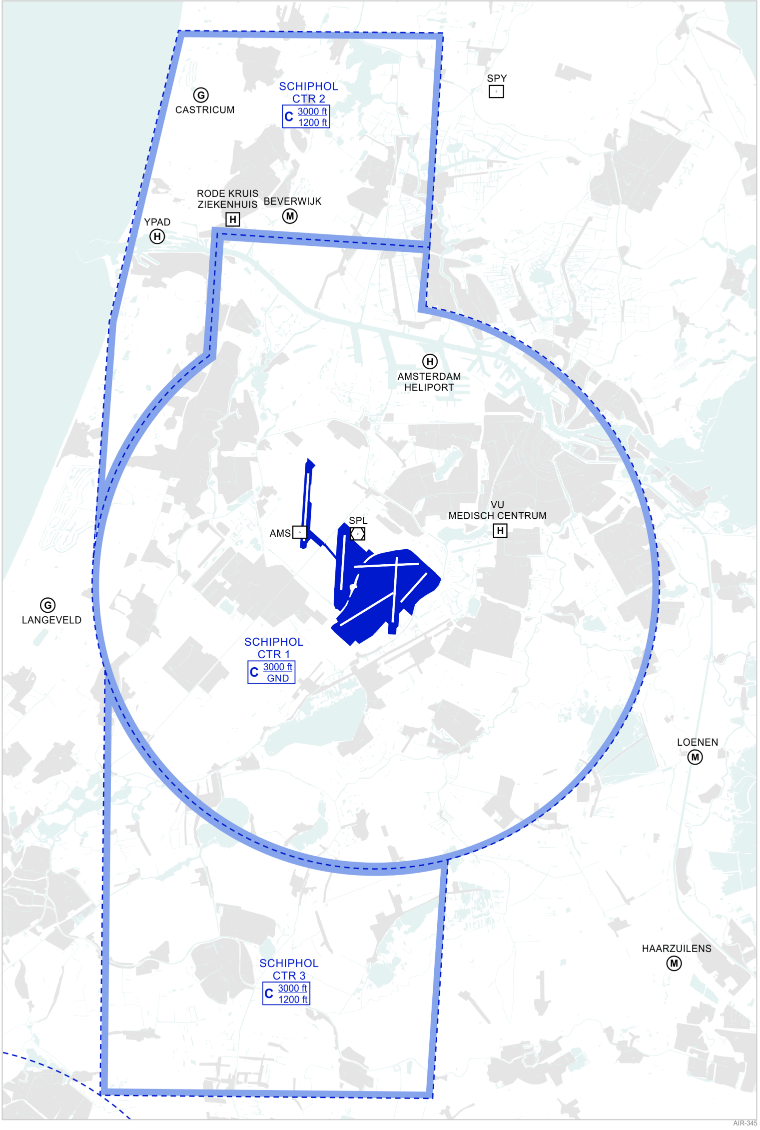


Figure 2.5: Schiphol Controlled Traffic Regions (LVNL ATMP, 2017b)

3

Aerodrome Control at Schiphol Airport

In this chapter, *Aerodrome Control* at Schiphol Airport will be described. *Aerodrome Control* is carried out from inside the TWR. The work domain of the TWR is the Schiphol-CTRs, as described in Section 2.3. First, in Section 3.1, the tasks of TWR controllers at Schiphol are described. The procedures within the Schiphol-CTRs are discussed in Section 3.2. Finally, in Section 3.3, the tools used by TWR controllers at Schiphol are discussed. The focus of this research with respect to the operation within the CTR is described in Section 3.4.

3.1. Tasks of Schiphol Tower Controllers

The TWR at the airport has multiple functions, as defined by ICAO (2016). First, the TWR should provide information and clearances to aircraft which are Under Control (UCO) at TWR controllers to ensure a safe operation. While doing this, a continuous watch on both all flight operations in the vicinity of and on an aerodrome and vehicles and personnel on the manoeuvring area should be maintained by TWR controllers. Second, the TWR should provide alerting services, such as alerting the rescue and fire fighting services. Additionally, the TWR should report failures or irregularities of aids and equipment.

The TWR at Schiphol provides ATS within the Schiphol CTRs and on the manoeuvring area at the airport. This is done by controllers of the LVNL. At Schiphol, the tasks and responsibilities are split up between different TWR working positions. These are:

- Delivery
- Outbound Planner (OPL)
- TWR-Assistant 1
- TWR-Assistant 2
- Ground Control (GND)
- TWR Control
- Supervisor

The interaction of the different ATCos is schematically shown in Figure 2.2. The main tasks of the different working positions are discussed below, as described by LVNL TO (2020).

Delivery

The delivery controller checks the flight plan data and based on this flight plan issues the en-route clearances and CTOT to departing flights. For VFR flights, the start-up clearance is provided. Furthermore, the delivery controller decides together with the OPL and TWR-Assistant 1 if an extra runway is needed, issues new clearances when runway or SID is changed and supports the OPL and TWR-Assistant 1.

Outbound Planner

The main task of the OPL is to create an optimal planning for outbound flights with the support of CDM, which is the process described in Section 2.2. Next to this, the OPL issues in certain cases the start-up clearances or transfers the flights to the GND frequency for start-up and pushback. Also, the *Automatic Terminal Information Service*, QNH and aerodrome information is provided to outbound flights. Together with the TWR-Assistant 1 the OPL determines the TTOT / Revised Estimated Time of Departure (RETD). The OPL also issues new clearances when there is a sudden change in runway or SID and, when needed, transfers the flight back to delivery.

Tower-Assistant
There are two assistant positions at Schiphol TWR: TWR-Assistant 1 and TWR-Assistant 2. The TWR-Assistant 1 collaborates mainly with delivery and the OPL. On behalf of delivery and OPL, the TWR-Assistant 1 coordinates (changes in) flight plan information and CTOTs. In consultation with OPL, the RETDs are determined and the TWR-Assistant 1 enters these RETDs in the TWR system. Together with delivery and the OPL, it is determined if an extra runway is needed. The main task of the TWR-Assistant 2 is to support mainly the Ground Controller (GC) and Runway Controller (RC). This includes, under the responsibility of both the GC and RC, communicating with vehicles and tow trucks at the manoeuvring area and alongside the runways, airport services, external emergency services and other involved services. Under the responsibility of the GC, the TWR-Assistant 2 controls vehicles on the manoeuvring area and lets them cross non-available runways. Under the responsibility of the RC, the TWR-Assistant 2 lets vehicle and tow trucks cross available runways and coordinates the request and return of runways to the airport authority with permission from the RC.

Ground Control
At the GND position, the Ground Controller (GC) is responsible for most ground operations. This includes communicating with flights under its responsibility, issuing pushback and taxi instructions and giving instructions to prevent collisions and unauthorised entry of the runway. The GC will also inform the pilots about weather changes and the status of navigation aids and will assign remote holding positions to aircraft. Operating the taxiway lights is also part of the tasks of the GC.

Tower Control
TWR control is the work domain of the Runway Controller (RC) (or TWR Controller). The main tasks of the RC are issuing take-off and landing clearances and ensuring that the separation minimums are maintained. This includes the separation between departing IFR flights (optionally together with other RCs), arriving IFR flights (together with APP), VFR and IFR flights (optionally together with other RCs and/or APP) and between aerodrome traffic (e.g. in the case of dependent runway operations). For outbound flights, the departure sequence is determined together with GND, where the TWR in the end makes the final decision. For VFR flights, the RC should provide traffic information and vice versa. Some other tasks are providing (or letting someone else provide) necessary and useful information to pilots and drivers of airport vehicles (e.g. weather information), together with TWR-Assistant 2 and GND and optionally with other RCs ensure runway safety, issue clearances to vehicles to enter a runway in use and, together with other TWR/APP officers and the 'flow manager aircraft' from Schiphol, determine the runway configuration.

Tower Supervisor
The last working position is the TWR supervisor. The supervisor has responsibility for the entire TWR process. In particular, the supervisor is responsible for the occupation of the tower, coordinates emergencies and special situations and is the point of contact for the supervisors of APP and ACC and for the airport (Schiphol).

The TWR at Schiphol has two rings, an outer ring and an inner ring. The division of the different types of controllers over the two rings is fixed, however, within a ring, the occupancy of the different consoles may vary. Depending on the traffic demand, the work of the different working positions can be split up amongst several controllers, for example, two RCs. (LVNL TO, 2020) An example of a setup at Schiphol TWR is shown in Figure 3.1.

3.2. Tower Control Procedures at Schiphol Airport

In this section, the tower control procedures at Schiphol Airport will be discussed. During the different stages of a flight, different Air Traffic Controllers (ATCos) will be responsible for the flight. The flight

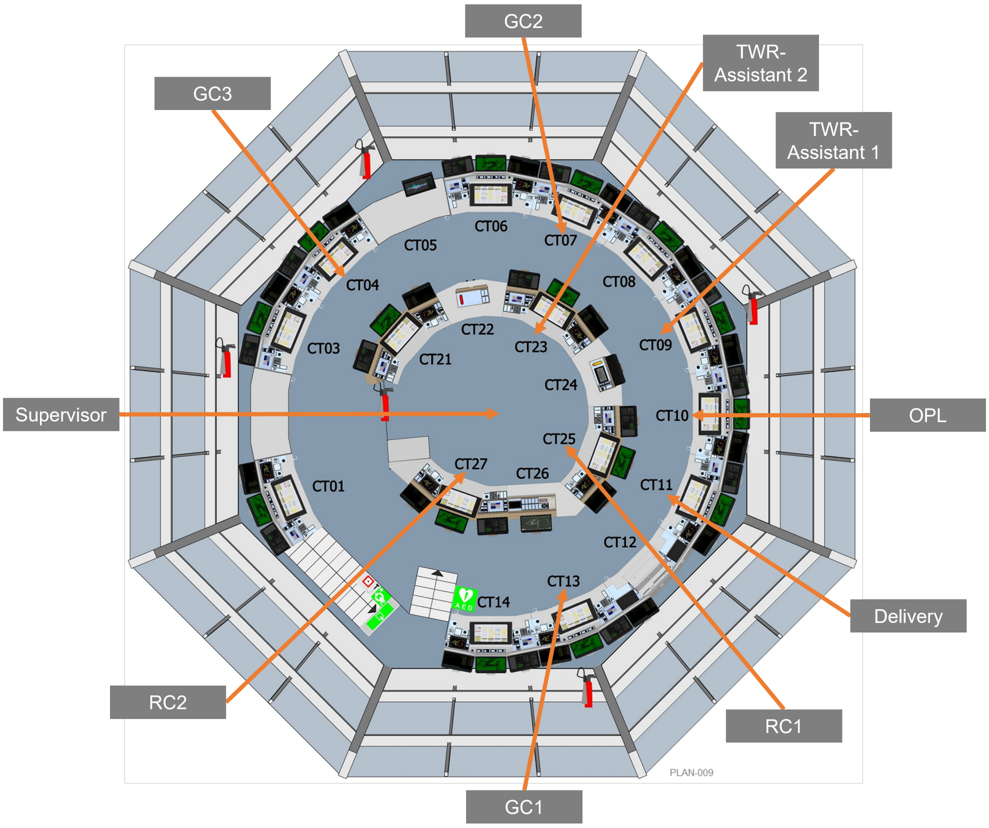


Figure 3.1: Example of a setup at Schiphol Tower. Adjusted image from (LVNL ATMP, 2012)

will be transferred between the different ATCos as the flight moves through the different areas of responsibility. Before the transfer of control can happen, certain conditions shall be met, as defined by (LVNL ATMP, 2017b). First, the flight shall be coordinated with the next ATCo. Second, in case a larger separation minimum applies for the next ATCo position, the current responsible ATCo shall establish is larger separation before the transfer of control. Also, the flight shall be separated from other traffic in the area of responsibility of the current responsible ATCo. Last, the ATCo shall establish transfer of communication (i.e. the pilot changes the frequency). After this, the transfer of control can be executed.

Some procedures described in this section focus on the operation under ”normal” conditions, that is during daytime and with good visibility. It should be noted that during periods of bad visibility or during the night, additional or different procedures with respect to the procedures described in this section may apply. For example, additional requirements on separation minimums (LVNL ATMP, 2017b).

The procedures of the different ATCos in the Schiphol TWR are described in the different subsections. First, delivery in Section 3.2.1. Second, the OPL in Section 3.2.2. Next in Section 3.2.3 the procedures of GND. Finally in Section 3.2.4, TWR control.

3.2.1. Delivery

Before a flight can be operated, a flight plan should be filed to an ATS provider. The flight plan contains basic information about the flight. These are, amongst others, the aircraft identification, flight rules (i.e. IFR or VFR), aircraft type, WTC, departure airport, cruising speed and flight level, the route and destination airport. When filled in, the flight plan should be submitted not more than 120 hours before departure (the EOBT). A revised or new flight plan should be submitted when there is a delay of more than 30 minutes (in EOBT). (ICAO, 2016)

The Delivery controller is the first controller in sequence from a pilot’s perspective for a departing flight. Delivery will check the filed flight plan for the aircraft type, colours of the airline (for visually identifying the aircraft) and the gate or stand. Additional information will be put on the digital flight strip by the controller, such as when a different aircraft livery is used or the number of persons on board.

The Delivery controller will also issue en-route clearances. The en-route clearance is basically the permission to execute the flight. The Amsterdam Advanced ATC (AAA) system, which is the main ATC system used at the LVNL, will provide the en-route clearance to the controller. (LVNL ATMP, 2017b)

ACC is responsible for the en-route clearance provided that the flight departs from an airport within the Amsterdam FIR and it is projected to cross an airspace under the responsibility of ACC. The en-route clearance consists of the callsign, destination airport, SID or departure instructions, runway, cleared flight level, squawk (transponder code) and the CTOT when applicable. In some cases, an intersection start (see Figure 3.2) can be assigned to a flight. In general, jet aircraft always depart from the start of the runway however, there are several reasons to start via an intersection. The first reason is to change the departure sequence to achieve a higher departure capacity. Second, prevent jet blast hindrance for aircraft at other runways. Third, to meet the ATFM regulations. The last reason is to avoid, as much as possible, crossing an active runway. When an intersection start is used, this will be provided to the pilot together with the runway in the en-route clearance. The en-route clearance can be provided to the pilot via voice communication or a data link. An example of an en-route clearance via voice communication is shown below. After the en-route clearance is received, the flight will be transferred to the OPL. (LVNL ATMP, 2017b)

> ”KLM123 Slot 11:05, cleared to EGLL, VAL4E departure runway 18L, initial climb FL060, squawk 2135” (LVNL TO, 2021b)

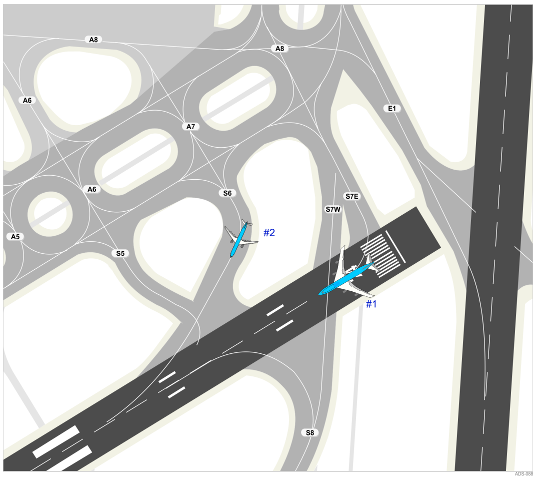


Figure 3.2: Intersection start (LVNL ATMP, 2017b)

3.2.2. Outbound Planner

When a departing flight is ready for start-up, the pilot will contact the OPL. The OPL will then check if the call has been made within the TSAT window $(-5, +5\ min)$. In case the call has been made too early, the pilot has to wait until the time is within the TSAT window and when the call has been made too late, the pilot has to contact the main ground handler agent for a TOBT update. As described in Section 2.2, Equation (2.2) and 2.3, an update in TOBT will lead to an update of the TSAT. (LVNL ATMP, 2017b)

When the call has been made within the TSAT window, the OPL will determine the RETD. These time parameters should be planned within the CTOT window $(-5, +10\ min)$. In case no RETD can be found within the CTOT window, the OPL can refer the pilot to the airline for an adjustment of the EOBT and to the main ground handler agent for an adjustment of the TOBT. When the OPL expects that the flight could depart a maximum of 20 minutes after the CTOT, a CTOT extension can be requested from the NM. The maximum extension the NM can provide is 10 minutes (together with the CTOT window results in a maximum delay of 20 minutes). It could also be the case that a flight requests to depart ahead of schedule, provided that the flight is ready for departure from the gate/stand, no de-icing is needed, the request is made on or after the TOBT and before the TSAT window and the request does not affect the planning of other flights. In this case, the OPL could send a ’ready to depart message’ to the NM. (LVNL ATMP, 2017b)

In some cases after the flight is ATC activated (i.e. the RETD is set), the RETD has to be changed or cancelled by the OPL. By changing the RETD, adjacent ATC centres are provided with an update of the estimated time at which the aircraft will enter their airspace. When the *Estimated Time of Departure* differs more than five minutes from the current RETD, it has to be changed. In case there is an update of the CTOT after ATC activation, the RETD should be changed in case the flight waits somewhere in the 'field' (taxiways, remote holding position, ... etc.) or is should be cancelled when returning to the gate or stand. In case ACC requests a flight plan change, the RETD needs to be changed as well. The RETD will be cancelled when the flight is expected not to depart within a reasonable time. (LVNL ATMP, 2017b)

The actual start-up clearance will only in limited cases be issued by the OPL. These are helicopters, aircraft at taxi-out position (i.e. no push-back is needed), certain aprons and when start-up happens at the gate. In all other cases, the GC will issue the start-up clearance. Before transferring, the OPL provides the QNH and the visibility range at the runway. (LVNL ATMP, 2017b)

3.2.3. Ground Control

As described in Section 3.1 the GC is responsible for most ground operations. In most cases, the GC will issue a start-up clearance to a departing flight, except for the cases where the OPL issues the clearance as described in Section 3.2.2, combined with a push-back clearance. After the start-up and optionally the push-back clearance the GC will provide taxi instructions to taxi from the gate/stand to the departure runway. When the aircraft approaches the runway holding point, the flight is transferred to the RC. (LVNL ATMP, 2017b) An example of a taxi instruction can be found below.

> ”KLM123 taxi via A2 and B to holdingpoint N5 runway 09” (LVNL TO, 2021a)

While providing start-up clearances and taxi instructions, the GC also determines the departure sequence together with the RC. Here the GC prepares the sequence and basically proposes it to the RC. (LVNL TO, 2020) The sequence is the order in which aircraft are going to take-off.

This sequence is normally based on the order in which the aircraft are ready for take-off, however, to optimize the departure sequence (maximum number of departures with the least average delay) a different order may be chosen. Factors that may influence the sequence are the aircraft types (and their relative performances), route after take-off (i.e. the SID), a specified minimum departure interval, the WTC, aircraft with priority or aircraft with ATFM requirements (i.e. the CTOT window). By putting two aircraft with different SIDs behind each other, the separation may be decreased and therefore the departure capacity may increase. (ICAO, 2016) This will be described in more detail in Section 3.2.4. Every runway at Schiphol has several SIDs, where every SID per sector has a fixed point of leaving the Schiphol-TMA (LVNL, 2022).

Also, the WTC is important when determining the sequence. To prevent problems for smaller aircraft behind larger aircraft caused by the WTC, separation minimums are specified for the six different categories, which are based on the maximum take-off weight and the wing span of the aircraft. These categories are shown in Table 3.1. The separation requirements are described in more detail in Section 3.2.4. Whether aircraft use an intersection start, which also affects the WTC separation, should also be considered when determining the sequence. As described in Section 3.2.1, an intersection start can only be used in certain cases. (LVNL ATMP, 2017b)

Finally, the CTOT and its window contribute to creating the departure sequence. During the process of taxiing the GC needs to make sure that aircraft are able to depart within the CTOT window, even if the CTOT changes while taxiing. When delays during taxiing may lead to aircraft not being able to depart within the CTOT window, the GC needs to inform the OPL about this. (LVNL ATMP, 2017b)

Arriving flights will transfer from the RC to the GC by themselves when the aircraft leaves the runway. The GC will then provide taxi instructions to taxi from the arrival runway to the gate/stand. (LVNL ATMP, 2017b) An example can be seen below.

> ”KLM123 taxi via taxiway Q to D2” (LVNL TO, 2021a)

Just like for ”normal” road traffic, there also exist traffic rules for taxiing aircraft. These are described by (ICAO, 2005b). Several rules apply to prevent collisions between two taxiing aircraft. First, two

Table 3.1: Wake Turbulence Category (LVNL ATMP, 2017b)

EU-WTC	**Maximum Take-off Weight [kg]**	**Wing Span [m]**
Super heavy (A)	$> 100k$	> 72
Upper heavy (B)	$> 100k$	$60 < span < 72$
Lower heavy (C)	$> 100k$	$span < 32$
Upper medium (D)	$< 100k$	> 32
Lower medium (E)	$15k < MTOW < 100k$	< 32
Light (F)	$< 15k$	–

aircraft should stop or both move to the right when approaching (approximately) head-on. Second, aircraft on the right have the right-of-way in case two aircraft have a course that is converging. Last, when an aircraft is overtaking another aircraft, the aircraft that is being overtaken has the right-of-way, while the overtaking aircraft should keep a safe separation.

In some cases, a taxiing aircraft is required to stop and hold. At all runway-holding positions, an aircraft shall stop and hold unless the TWR has given the approval to proceed. Also at all lighted stop bars, an aircraft shall stop and hold until the lights of the bar have been switched off.

At Schiphol, there are several large taxiways, as can be seen in Figure 3.3, with corresponding taxi directions. The complete map of Schiphol can be found in Chapter B. In general, at taxiway A the aircraft will taxi clockwise, while at taxiway B aircraft will taxi counter-clockwise. At taxiway C the aircraft will taxi to the north, while at taxiway D aircraft will taxi to the south. However, when a flight will depart from runway 18C the flight will use taxiway D unless other arrangements have been made with the RC. (LVNL ATMP, 2017b)

In some cases, an aircraft needs to cross a runway and therefore it needs clearance from the TWR. In case the runway is active, the GC will instruct the pilot to stop and hold before the runway and will then transfer the flight to the RC, since the RC is responsible for the active runways. While doing so, the GC will inform the RC about the destination of the aircraft. If the runway is not active but available to ATC, the GC itself is responsible for the crossing and will therefore give the clearance. In case a runway is not available to ATC, the airport is responsible for the runway and therefore the GC should receive clearance from the *Flow Manager Airport* from Schiphol. The taxiways to the north and south of runway 18C-36C are considered crossings of that runway. When aircraft are departing from runway 18C or arriving at 36C, the northern taxiway is considered an independent crossing and the southern dependent crossing and vice versa for arriving on runway 18C and departing from 36C. Independent crossings are the responsibility of the GC, while the RC is responsible for the dependent crossings. Since these taxiways are considered crossings of a runway, runway holding positions are in place and therefore clearance is needed from the ATC to use these taxiways. (LVNL ATMP, 2017b)

3.2.4. Tower Control

The TWR Controller / RC is responsible for the take-offs and landings as well as the operations at and around the runways, as described in Section 3.1.

Outbounds

As described in Section 3.2.3, the RC will receive the departing flights when approaching the runway holding point. Aircraft should not be allowed to hold closer to an active runway than this point unless prescribed differently by the ATS authority. Also, a line-up and hold clearance shall not be issued to an aircraft at the approach end of the runway when an arriving aircraft did not yet pass the holding point in case the runway is used for both departures and arrivals (mixed mode). (ICAO, 2016)

The GC provides a proposal for the departure sequence, as described in Section 3.2.3. However, the RC can make changes to the sequence, for example by using an intersection start, or by requesting to the GC for a change in the order aircraft arrive at the runway.

An important factor for consideration before issuing a take-off clearance is the separation from other air traffic. There exist several separation requirements, which shall be taken into account for departures.

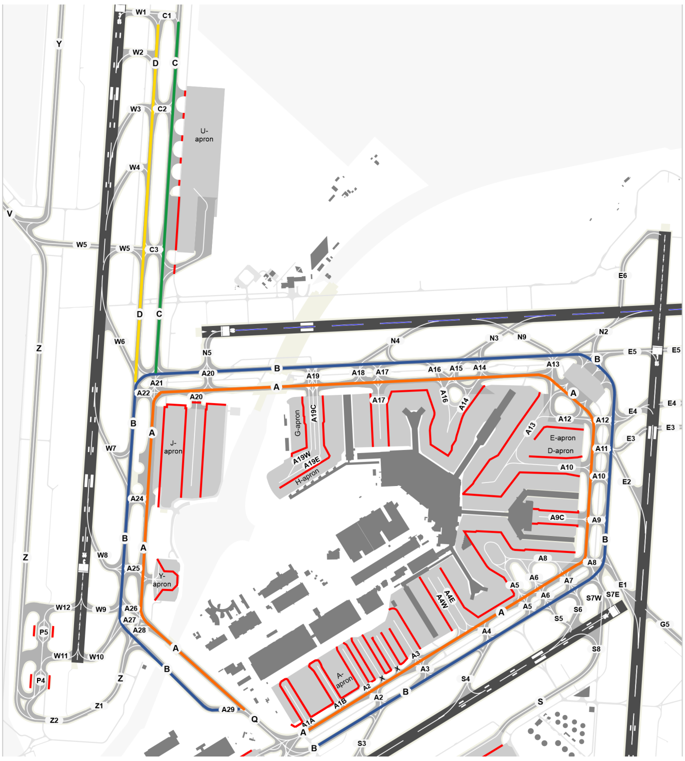


Figure 3.3: Taxiways at Schiphol Centre, with highlighted taxiways A (Orange), B (Blue), C (Green) and D (Yellow). Adjusted image from (LVNL ATMP, 2017b)

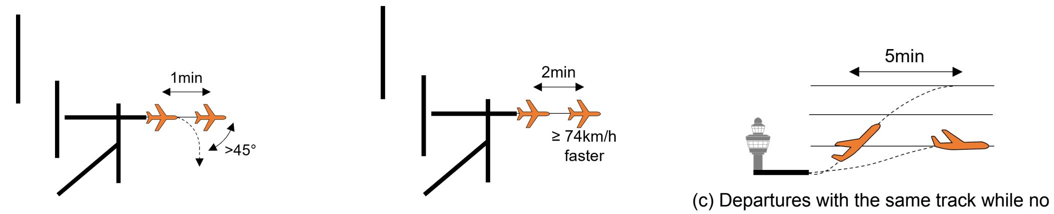
These are brought down to the ones listed below and are described in more detail thereafter.

- Separation minima from preceding and succeeding aircraft
- WTC separation minima
- Separation minima of consecutive ATC units

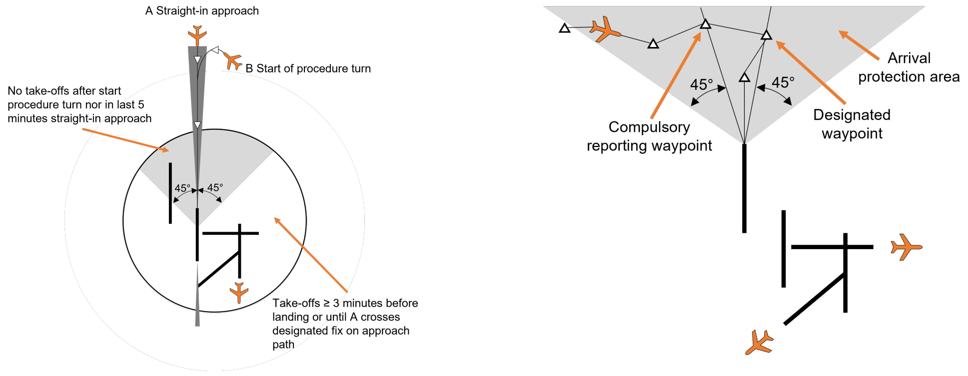
First, several separation minimums have to be applied related to the position of the preceding aircraft with respect to the runway, as defined by (ICAO, 2016). In general, an aircraft may receive a take-off clearance after the preceding departing aircraft has crossed the runway threshold at the runway end or when it started a turn. In case an arriving aircraft preceded the departing flight, the take-off clearance may be issued after the arriving aircraft has left the runway.

Also, some general time-based separation minimums shall be taken into account. For this, two cases are considered, two consecutive departures and a departure preceding an arrival. In the first case, when the track of the succeeding aircraft diverges at least $45°$ from the preceding aircraft, one minute separation is required. When the two aircraft follow the same track and the preceding aircraft is $74 km/h$ faster, two minutes of separation is required. While there is no vertical separation and the succeeding aircraft crosses the flight level of the preceding aircraft, five minutes of separation is required. This is shown in Figure 3.4a till 3.4c. (ICAO, 2016)

For the second case, restrictions apply when the position of the arriving aircraft is taken into account for the take-off clearance. In this case, the aircraft is allowed to take-off in any direction until the arriving aircraft, when following an instrument approach, started the turn procedure or base turn to the final approach or until the arriving aircraft, when making a straight-in approach, is five minutes out. Restrictions for the take-off are applied when the arriving aircraft is in a later stage as described before. These are shown in Figure 3.4d. When the arriving aircraft uses a *area navigation* or *Required Navigational Performance* instrument flight procedure, the departing aircraft is allowed to take-off provided that certain conditions are met. There shall be vertical separation until the arrival has reported that it has passed the compulsory reporting point, the take-off happens before the designated waypoint has been crossed by the arriving aircraft and the departing aircraft does not cross the arrival protection area until separation is established. This situation is shown in Figure 3.4e, where the grey area indicates the arrival protection area. (ICAO, 2016)



(a) Departures with diverging tracks (b) Departures with the same track (c) Departures with the same track while no vertical separation



(d) Departure before arriving aircraft following an instrument or straight-in approach (e) Departure before arriving aircraft with an *area navigation* or *required navigational performance* instrument flight procedures

Figure 3.4: Separation for departing aircraft

Second, the RC should take the WTC into account before issuing take-off clearances. At Schiphol, the *European Recategorisation* for WTC is used. Based on the maximum take-off weight and wing span, the aircraft are subdivided into six categories, which are described in Table 3.1. By using these categories, the separation minimums are specified. These apply when an aircraft is going to depart after an aircraft with a higher WTC. (LVNL ATMP, 2017b) Parallel runways separated by less than $760m$ are considered the same runway for the WTC separation requirements. It should be noted that the parallel runways at Schiphol are separated by more than $760m$.[1]

When aircraft take-off from the same runway or in case the trajectory of the trailing aircraft crosses the trajectory of the leading aircraft at the same altitude or less than $1,000ft$ lower when using crossing runways or parallel runways with more than $760m$ separation (ICAO, 2016), the separations minima are shown in Table 3.2 apply. When an intersection start is used for the succeeding aircraft at the same runway, one minute shall be added to the times specified in Table 3.2. (LVNL ATMP, 2017b)

Table 3.2: Wake Turbulence Category separation minimums (LVNL ATMP, 2017b)

		Succeeding					
		A	**B**	**C**	**D**	**E**	**F**
Preceding	**A**	-	1:40	2:00	2:20	2:40	3:00
	B	-	-	1:20	1:40	2:00	2:20
	C	-	-	-	1:20	1:40	2:00
	D	-	-	-	-	-	2:00
	E	-	-	-	-	-	1:40
	F	-	-	-	-	-	1:20

Third, as described before, the RC shall take separation minima from consecutive ATC units into

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[1] Source: Measured in Google Maps

account. This mostly applies when two succeeding departing aircraft follow the same SID or departure route. Within the area of responsibility of ACC a minimum of at least $5NM$ is required or at least $1,000ft$ vertical separation is required as defined by (LVNL ATMP, 2017a). This has to be taken into account when issuing a take-off clearance. As a rule of thumb, under normal circumstances, that is standard and calm wind conditions, the succeeding departing aircraft may take-off when the distance between the runway and the preceding aircraft is more than $2NM$. Under different weather conditions, the take-off roll might be started later or earlier, where this is based on experience and the judgement of the RC. Another important factor is the expected speed profile. Different airlines apply different speed profiles, and also this has an effect on the separation within the area of responsibility of ACC. Since the speed profile is not known by ATC, there is some uncertainty. The ATCos take this into account based on experience, although often a bit conservative.[2]

Besides the separation minimums described above, the RC should also take additional requirements from APP into account when providing take-off clearances, when present. In case a departing flight will fly a SID after take-off, which almost all departing IFR flights from Schiphol do, the RC does not have to explicitly coordinate these flights with APP. Next to this the RC needs to make sure that the flight will depart within the CTOT window. Also for IFR flights correlation should have happened, which means connecting the flight plan to the correct radar track. If this is not the case, the RC should coordinate the flight with APP. Finally, the RC needs to make sure that the runway and the *obstacle free zone* are clear of obstacles. (LVNL ATMP, 2017b)

Issuing take-off clearances can be done in basically two ways. The RC could first issue a line-up clearance, which means that the aircraft is allowed to enter and hold at the start of the runway or, when an intersection start is used, at the height of the intersection. After some time the actual take-off clearance can be issued. In this way, for example, separation from the preceding aircraft can be ensured. Also, a take-off clearance can be issued without a line-up clearance. In this case, the flight is allowed to enter the runway and directly take-off. The actual take-off clearance consists of several parts. First is the runway (ICAO, 2016). Second is the actual wind information in case this information is significantly different from the *Automatic Terminal Information Service* or when the wind speed is $20kts$ or more. This actual wind information consists of the direction, speed and gusts of more than $5kts$. Third, are the *fast runway visual range* messages when one of these is less than $550m$. Fourth, information about significant weather changes. Last are optional additional departure instructions. An example of a take-off clearance is shown below. When the flight passes through the $2,000ft$ altitude, the flight will transfer to APP by itself. (LVNL ATMP, 2017b)

> ”KLM123, runway 24 cleared for take-off, wind 250 degrees, 12 knots” (LVNL TO, 2020)

Inbounds

Arriving flights will be transferred from APP to the RC when the flight is established on the *Instrument Landing System* or when the pilot reports that the runway is in sight. During the final approach, the RC will provide information when necessary. This information could include sudden occurring hazards, current wind and important changes, current runway conditions and the current *Runway Visual Range*. When the crosswind at the runway is more than $20kts$, including gusts, the RC will inform the pilots about the wind conditions at $4NM$ before the runway threshold for IFR flights or when the aircraft is on downwind for VFR flights. When the *runway visual ranges* are less than $1,500m$, the RC will provide the *fast Runway Visual Ranges* to the pilot until the aircraft is $4NM$ from the runway threshold. When certain information is not shared with the pilot in the arrival *Automatic Terminal Information Service*, the RC will provide this additional information, which could include non- or partly-functioning landing tools, unusable runway exits and wind shear. Before issuing the landing clearance, as for the take-off clearance, the RC needs to make sure that the runway and the *obstacle free zone* are clear of any obstacles. (LVNL ATMP, 2017b)

When the aircraft is at $\geq 2NM$ from the runway threshold or at $1NM$ from the threshold provided that the RC informed the pilot about a late landing clearance, the RC will issue the landing clearance. The landing clearance consists of the runway (ICAO, 2016) and the current wind direction, speed and

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[2] Source: Conversation with a RC

gusts of more than $5kts$ at the runway. An example of a landing clearance is shown below. When the aircraft leaves the runway, the pilot will transfer to the GC by itself as described in Section 3.2.3. (LVNL ATMP, 2017b)

> ”KLM123, runway 06 cleared to land, wind 030 degrees, 10 knots, gust 16” (LVNL TO, 2020)

In case of a missed approach, the RC informs immediately the involved APP controllers. For every runway, only one missed approach path is specified. (LVNL, 2022)

Dependent Runways

When looking at the runway layout at Schiphol (Figure 3.5), dependent runway combinations can be identified. In general, when an active runway combination is dependent, only one RC will be responsible for both runways. These could be two departure runways, two arrival runways or one arrival and one departure runway. When a runway combination is deemed independent, both take-off and landing clearances can be issued independently from each other. (LVNL ATMP, 2017b)

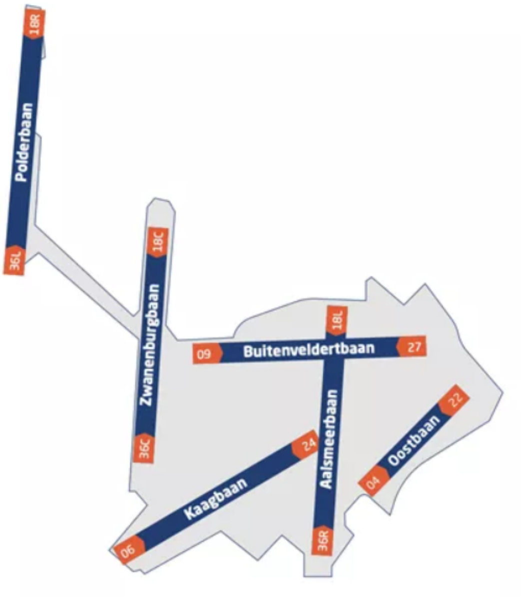


Figure 3.5: Runways at Schiphol, from https://www.lvnl.nl/omgeving/baangebruik, Accessed 23-1-2023

There are two dependent departure runway combinations, which are 24+18L and 18L+09/27. For these combinations, additional limitations on the take-off clearance are specified. These limitations are based on the WTC and the intersection used. For the combination 24+18L, the limitations are set because of the jet blast from the aircraft at runway 24, which influences the take-off from runway 18L. For the combination 18L+09/27, limitations are in place because of the crossing of the two runways and also the jet blast when an aircraft is departing from 18L. When using two parallel runways, that is 18L+18C or 36L+36C, these can be deemed independent based on several requirements, such as good visibility, two RC’s and diverging tracks. In this case, the pilot shall not transfer to APP by itself, however, the RC shall first make sure that the tracks diverge before transferring the flight to APP. (LVNL ATMP, 2017b)

A departure and arrival runway is dependent when the missed approach path raises a possible conflict with the departure. There are several dependent combinations, such as arrival 18C + departure 24 or arrival 36R + departure 09/27. During daytime and clear visibility, the take-off clearance may be issued when the arriving aircraft is established on the final approach track and the RC has informed the arriving aircraft about the departing flight. The RC shall maintain a close watch on the landing aircraft, such that a missed approach can be detected early and therefore the conflict can be resolved on time. During the night and bad visibility, several more additional and strict requirements apply for the take-off clearance. The arriving flight should have landed, the next arriving aircraft shall be established on the final approach track and the distance to the runway threshold shall be $> 2NM$ when the departing aircraft starts the take-off roll. Additionally, the RC shall switch on the *track vector*, which is a line with a length of $2500m$ indicating the track of the aircraft when the ground speed is larger than $80kts$ and is shown on the ground radar screen, which will be discussed in Section 3.3 (LVNL ATMP, 2012). Also here, the RC shall monitor the arriving flight, such that a possible missed approach can be detected early. (LVNL ATMP, 2017b)

Two arrival runways are dependent when the missed approach paths cross each other. Therefore, for example, the combination 06+18R is not considered dependent. Converging arrival runways may be used when there is good visibility, every arrival runway has a different frequency, both are a *Instrument Landing System* approach or one of them is a *Required Navigational Performance* approach and the other one a *Instrument Landing System* approach. When using an *Instrument Landing System* approach, the interception shall happen at least $5NM$ before the threshold and below the descent profile. Last, the RC shall inform the pilots about the converging approach. During the night, certain combinations are not allowed and additional requirements apply for dependent arrival runways, such as that there shall be two RC's. (LVNL ATMP, 2017b)

Runway Safety

Since the RC is responsible for active runways, the RC is responsible for all traffic (both aircraft and other vehicles) at or near these runways. As described in Section 3.2.3, aircraft which would like to cross an active runway or taxi on the runway longitudinally need clearance from the RC. The RC decides whether the flight stays at the frequency of the GC or is transferred to the RC. Also, a vehicle which would like to cross an active runway or drive on the runway longitudinally needs permission from the RC. (LVNL ATMP, 2017b)

3.3. Tools used by Schiphol Tower Controllers

ATCos within the TWR have different tools and surveillance systems at their disposal to control traffic within the CTR. However, as described in ICAO, 2016, *Aerodrome Control* shall mainly be done by visual observation and the use and availability of tools/systems shall not be detrimental to this. In general surveillance systems may be used to monitor the flight path of aircraft on final approach and other aircraft close to the airport, establish the required separation between departing flights as described in Section 3.2.4 and assist VFR flights with navigation.

Console

Every ATCo at the TWR sits behind a console. As described in Section 3.1, the Schiphol TWR has two rings. Besides a few differences, the console at the outer and inner rings are almost identical. The console at the inner ring is shown in Figure 3.6. Several parts are important and/or relevant to this research. The screen indicated with (1) has two functions, a normal PC and the *Closed Circuit Information System* screen. The *Closed Circuit Information System* is a system which contains relevant information for ATCos such as information about the weather, runway use, routes and frequencies. The screens indicated with (2) and (3) are both TWR-screens. This will be described in more detail below. The *voice communication system* panel is indicated with (7), which is used to manage the communication frequencies. Number (12) indicates the intercom panel. The intercom panel enables the ATCo to communicate directly with other ATCos at the other tower (TWR-West) or with APP. The large (touch-)screen at the centre, indicated with (16), is the Electronic Flight Strip System (EFSS). This system is described below in more detail. Finally, number (18) indicates the *airfield lighting control and monitoring system*. (LVNL ATMP, 2012)

Tower-Screen

As described above, the console has two TWR-screens. On top of the screen, the interaction area can be found, which is shown in Figure 3.7. The interaction area is used to adjust the settings of the TWR-screen and it shows some important information. There are several relevant parts. Number (1) indicates the UTC time and (8) the QNH. Runway information is shown in numbers (10) and (11), where the latter one is used to display the *main take-off preference* when there are two runways in use for take-offs. The *main take-off preference* shows the distribution over the two runways based on the sector the aircraft will fly through before it leaves the Dutch airspace. With (2) the configuration can be

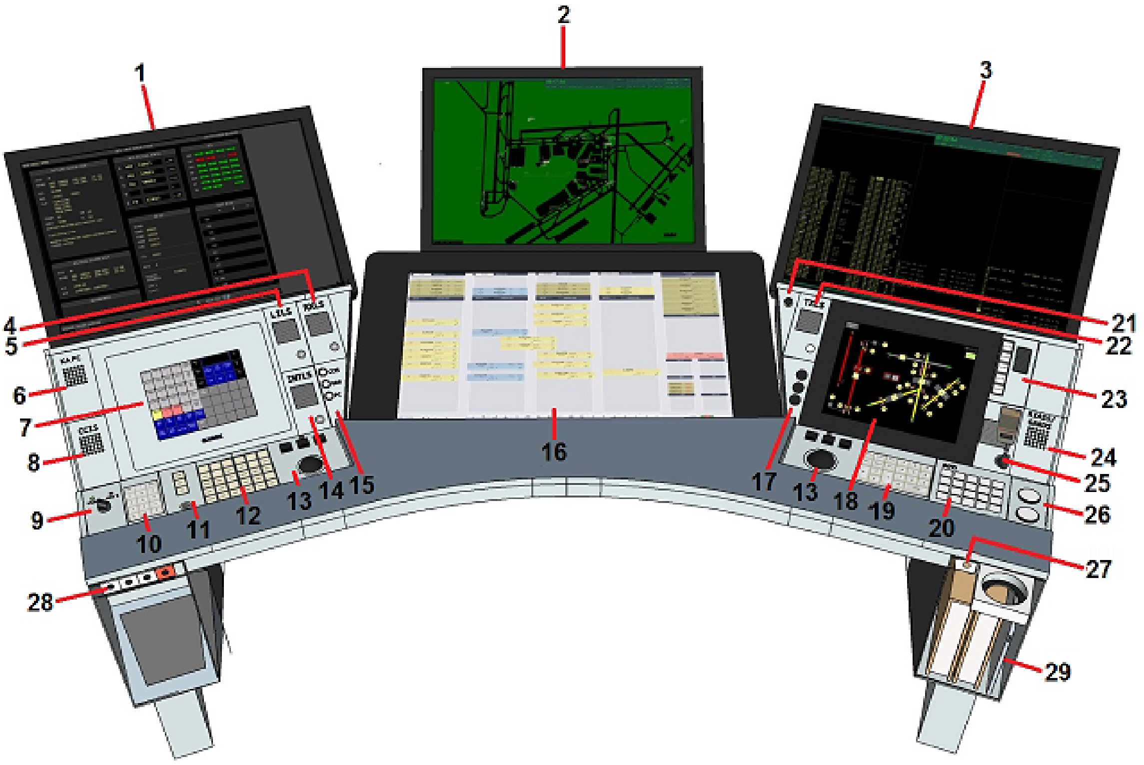


Figure 3.6: Tower console on the inner ring (LVNL ATMP, 2012)

changed based on the different working positions which are described in Section 3.1. The TWR-screen mode can be set with the button indicated with (12). Number (3) is a mode dependent panel and (13) is used to adjust the display settings, such as the brightness. Indicated with (5) and (6) are the Go-Around Detectiesysteem (GARDS) and Runway Incursion Alert System Schiphol (RIASS) menus, which are two warning systems and are described in more detail below. Number (7) indicates the button to activate the backup system, (14) the *runway visual range* button which opens the corresponding window and (15) the button which opens the weather information window. (LVNL ATMP, 2012)

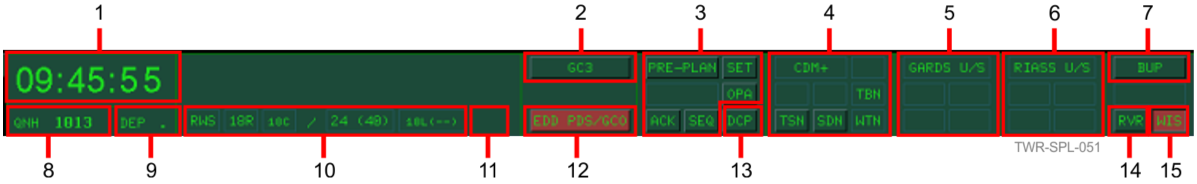
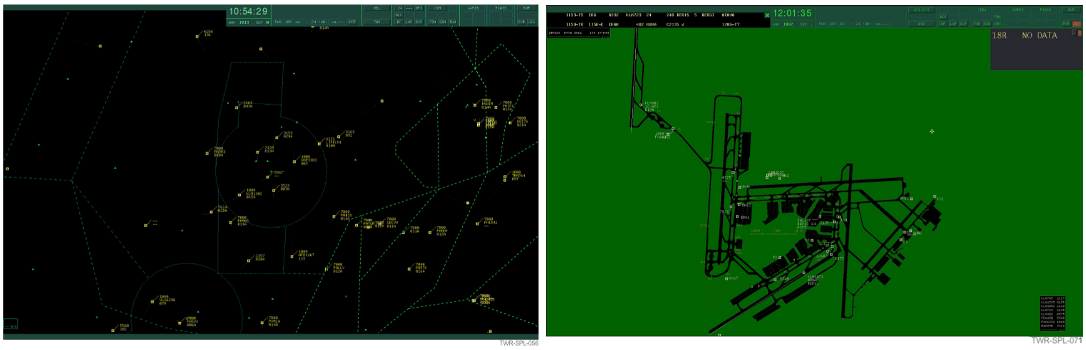


Figure 3.7: Tower-screen interaction area (LVNL ATMP, 2012)

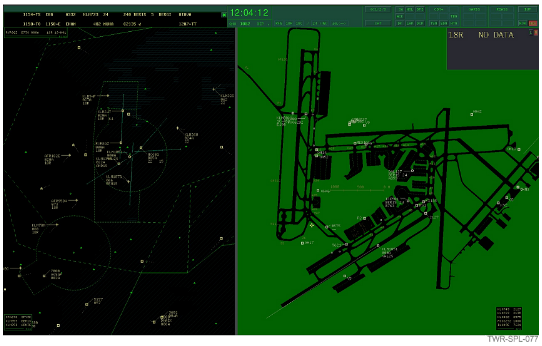
The TWR-screens have basically three different modes. The first mode is the Terminal Area Surveillance Radar (TAR) -mode, which is shown in Figure 3.8a. The TAR-mode is a radar screen which shows the current air traffic situation around the airport, i.e. the Schiphol CTR and TMA. The TAR radar screen has some similarities with the APP radar screen. The second mode is the Airport Surface Detection Equipment (ASDE) -mode. This mode shows the actual traffic situation, both aircraft and vehicles, at the airport. A screenshot of the TWR-screen with the ASDE-mode is shown in Figure 3.8b. The last mode is the *category*-mode. In this mode, the previous two displays are combined. In the *category*-mode it is possible to put the TAR and ASDE display next to each other, both horizontally and vertically. A screenshot of this mode is shown in Figure 3.8c. (LVNL ATMP, 2012)

Electronic Flight Strip System

Every position at the TWR has a large EFSS touch screen. The EFSS is used to keep track of all flights



(a) Terminal Area Surveillance Radar - mode (b) Airport Surface Detection Equipment - mode



(c) Category-mode

Figure 3.8: Tower-screen modes (LVNL ATMP, 2012)

at and around the airport and vehicles. As can be seen in Figure 3.9, it consists of three main parts. Number (1) indicates a ”bay”, (2) a flight strip and (3) the toolbar. (LVNL ATMP, 2012)

To organize the EFSS, different bays are defined, which can be subdivided into three types. *Shared bays* are shared with different working positions and therefore always show the same information. *Transfer bays* are a particular type of shared bays. These are used to transfer the flight from one ATCo to the next one (e.g. from the OPL to the GC). Both the GC and RC also have a *working bay*, which are used for flights that are UCO at the corresponding ATCo. The headers of the bays can have a list box, for example, to select the runway for the corresponding bay, a timer for the WTC or just plain text. These are shown in Figure 3.10. (LVNL ATMP, 2012)

The EFSS display shown in Figure 3.9 is an example of the RC’s layout. The RC can take a runway UCO by selecting the runway in the list box of the *pending area*. The flights for this runway will then automatically show up in this *pending area*. Flights which are transferred to the RC but are waiting to be handled are shown in these bays. The RC will drag the flight strip to the *working area* when the flight is taken UCO. The RC can transfer an arriving flight to the GC by dragging the flight strip to the corresponding GC bay (e.g. GC1). When a departing flight leaves the CTR, the flight strip will be automatically discarded. The same holds for an arriving flight when the AIBT is set or fifteen minutes after the actual time of arrival. When the aircraft operator cancels the flight plan, the flight strip will also automatically be discarded. (LVNL ATMP, 2012)

The strips on the EFSS correspond with a flight or vehicle and contain relevant information. These strips can be placed in the different bays as described above. Depending on the type of flight (e.g. IFR/VFR or departure/arrival) and on the working position the flight strips have different layouts. Flight strips for inbound flights are yellow, while for outbound flights these will be blue. The flight strip can have only one line, which shows only the essential information, two lines, showing a bit more information, and three lines, displaying all information. An example of a flight strip for an outbound flight with three lines is shown in Figure 3.12. There are several important parts and/or relevant parts. Number (1) indicates the departure status, which can be set to the next status by clicking on it. For departures, the different statuses are ”hold short”, which is the start status, ”line-up”, ”take-off clearance”, ”take-off roll” and ”airborne”. When a WTC timer is used, the timer will start when the status is set to ”take-of roll”.

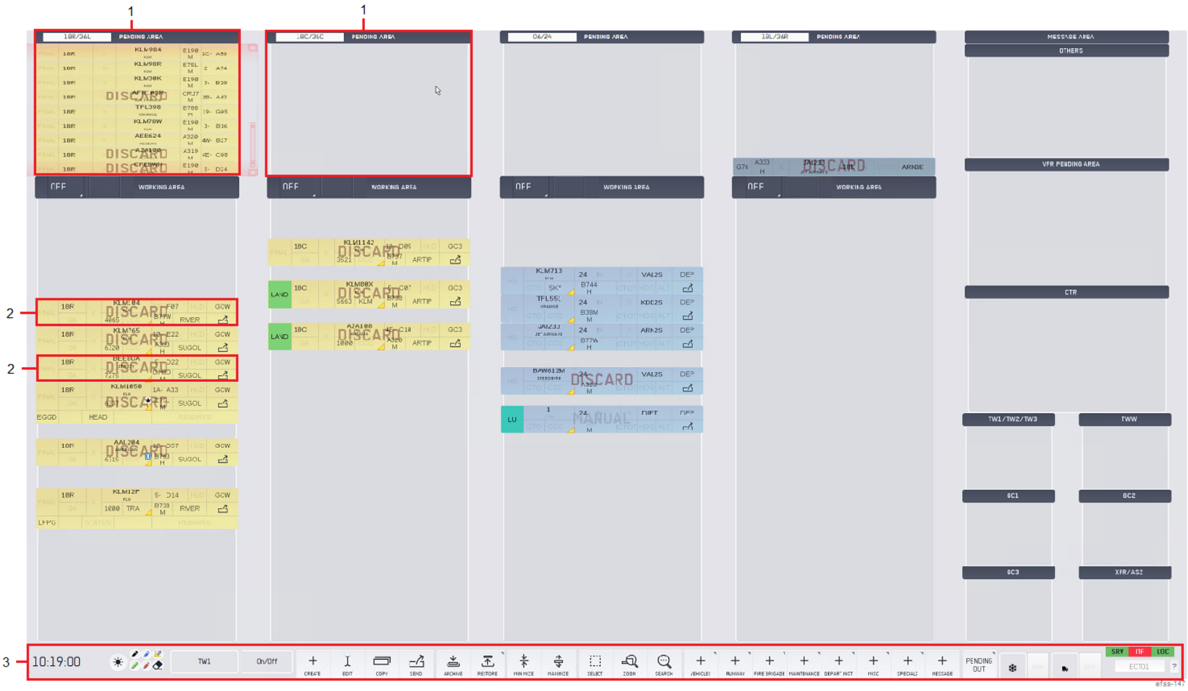
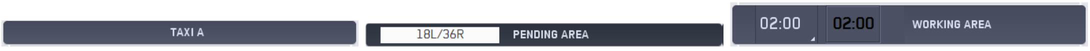


Figure 3.9: Electronic Flight Strip System layout (LVNL ATMP, 2012)

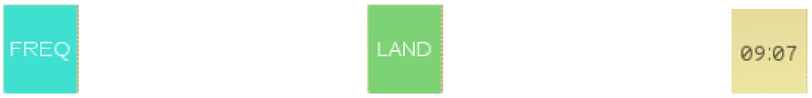


(a) Text (b) List box (c) Wake Turbulence Category timer

Figure 3.10: Electronic Flight Strip System bay headers (LVNL ATMP, 2012)

For arrivals the statuses are "final", which is the start status, "on the frequency", "cleared to land" and "landed". These statuses are shown in Figure 3.11. Number (2) indicates the callsign, (3) the runway, (4) the intersection in case of an intersection start, (6) the SID and (8) the next ATCo in the sequence. The aircraft type and WTC, CTOT, heading and initial departure altitude are indicated with (12) till (15) respectively. Number (8) is used to transfer the flight to the next ATCo in the sequence. Number (17) indicates the destination airport and (18) the squawk. Numbers (20) till (22) indicate the first waypoint, FIR exit point and the requested flight level respectively. (LVNL ATMP, 2012)

(a) Outbound: Line-up (b) Outbound: Take-off clearance (c) Outbound: Take-off roll (d) Outbound: Airborne



(e) Inbound: On the frequency (f) Inbound: Cleared to land (g) Inbound: Landed

Figure 3.11: Electronic Flight Strip System flight status (LVNL ATMP, 2012)

On the bottom of the EFSS display the toolbar can be found. Here the UTC is shown as well as the currently active working position, which can also be changed here. The strips can be created or adjusted with the toolbar. Furthermore, certain settings can be changed here, for example, the brightness. Also, the functionality of the pen can be set here, for example changing the colour or selecting the eraser. (LVNL ATMP, 2012)

Warning Systems

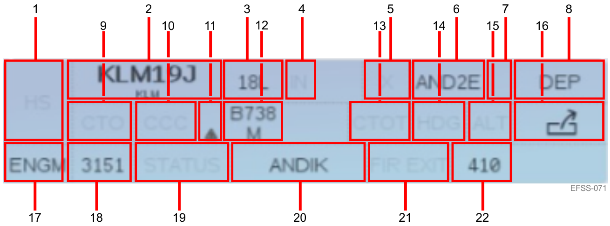


Figure 3.12: Electronic Flight Strip System outbound flight strip for the Runway Controller (LVNL ATMP, 2012)

There are two main warning systems at the Schiphol TWR. These are GARDS and RIASS. The GARDS system detects go-arounds and warns the ATCos about this. This is done by checking if the aircraft follows the landing path, both vertically and horizontally. The warning consists of an audio message, ”Go-around runway [runway number]”, for the responsible RC and an orange square around the track symbol of the corresponding aircraft at the TAR-, ASDE- and *category*-screen. This system only works for IFR flights, the flight needs to be within $4.5NM$ from the runway threshold, the transponder should be functional, the flight plan should be connected to the radar track and the correct runway should be selected for the flight. When GARDS is not functional for one or more runways, this is then shown in the interaction area. (LVNL ATMP, 2012)

RIASS detects runway incursions and warns the ATCos about the danger of a collision because of the runway incursion. In case an aircraft is landing, it ”claims” an area in front of the aircraft which has a width of $90m$ at both sides from the runway centre line in normal situations and $153m$ when there is poor visibility. When there is another aircraft within this area (or a vehicle within $90m$ from the centre line), RIASS will generate a notification. When the arriving aircraft has a speed of $> 58kts$, an alarm will be generated. Between $31 - 58\ kts$ a warning will be generated. A speed of $< 31kts$ will generate no notification. A departing aircraft will ”claim” the entire runway with the same width as an arriving aircraft when the departing aircraft has a speed of $> 41kts$. Also here, when another aircraft (or vehicle within $90m$ from the centre line) enters the claimed area, RIASS will generate a warning. In case of a warning, a white ring will be drawn around the aircraft track symbol at the TAR-, ASDE- and *category*-screen. In case of an alarm, the white ring will blink and the responsible RC will get an audio warning, ”Incursion [runway number]”. RIASS will only generate a notification when the distance between the involved aircraft or vehicles is more than $75m$. (LVNL ATMP, 2012)

3.4. Research Focus

As mentioned in Section 3.1, different controllers are active within the CTR operation. Within this research, the focus will be on the work of the RC. This controller position is chosen based on several reasons. First, the RC bridges the ground and airborne phase of the flight, the take-off and landing. The planning of the ground phase of these flights is based on the departure time, as described in Section 2.2, and therefore at the RC everything comes together. Also, when looking at the division of roles, the RC can be seen as the person with the final responsibility. Furthermore, as described in Section 3.2.4, the RC does not have much influence on arriving flights, except issuing a clearance. On departing flights, however, some flexibility is possible. Therefore, the main focus will be on outbound flights and providing take-off clearances to these aircraft. As Schiphol is a large international hub, the focus will be on regular (flights operated by an airline) IFR flights.

When assessing the current operation, three problems or points of interest can be identified, which could be addressed when designing a decision support tool for RCs. First is the operation regarding dependent runways, as described in Section 3.2.4. Certain runway combinations could cause conflicts. An example is the combination of arriving on 18C and departing from 24 (see Figure 3.5). When an inbound flight on 18C performs a missed approach, and at the same time an aircraft departs from runway 24, a conflict could occur. These situations are also described by OVV (2017) as safety issues at Schiphol. In the past, for the 18C + 24 runway combination, the RC had to intervene to prevent a collision (OVV, 2020) or the *Traffic Collision Avoidance System* was activated (OVV, 2007).

Second, is the uncertainty in the speed profile for departing aircraft. When two consecutive departing aircraft have the same WTC and follow the same departure path or SID while executing a different speed profile, it could be the case that the succeeding aircraft runs into the preceding aircraft when following a faster speed profile. Eventually, this could result in a loss of separation. As stated in Section 3.2, flights shall be separated and therefore conflict free before the transfer of control happens. To prevent conflicts resulting from different speed profiles, the take-off clearance of the succeeding aircraft should be properly timed. Nowadays this happens based on the experience of the ATCo, however ideally this would be based on the speed profile as planned by the aircraft. In this case, one could imagine that the uncertainty decreases and therefore aircraft could depart with a smaller time interval and conflicts may be prevented.

Third is the use of two departure runways during an outbound peak. Since Schiphol is an international hub, inbound and outbound peaks will succeed one another. During an inbound peak, two runways will be used for arrivals and one for departures (in total three runways will be active) and vice versa for an outbound peak.[3] In the current situation during an outbound peak, departing aircraft will be spread over the runways based on the SID, i.e. which direction the aircraft will fly to. In this way conflicts between departing aircraft can be avoided. (LVNL ATMP, 2017b) However, one of the runways will be the primary runway and the other on the secondary, based on how much noise pollution the use of the runway will produce. When the selection of the runway for a flight is based on the SID, one could imagine that not the full capacity of the primary runway may be utilised. When using (almost) the entire capacity of the primary runway, noise pollution can be reduced. However, this may lead to more complex traffic situations and therefore a tool might be used to prevent conflicts and merge traffic streams by, for example, timing the take-off of the aircraft.

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[3] Source: https://www.lvnl.nl/omgeving/baangebruik, Accessed 27-1-2023

4

Trajectory Based Operations

In this chapter, Trajectory Based Operations (TBO) will be discussed. It should be noted that this concept is currently being developed and therefore not finalised. In Section 4.1 the proposed TBO concept is described. The technologies related to the use of TBO are discussed in Section 4.2. The focus of this research with respect to TBO will be discussed in Section 4.3.

4.1. Proposed Concept

The TBO concept is based on three pillars, which describe the main differences with the current operation. These are the Four-Dimensional (4D) trajectory information acting as a joint plan for the flight (Section 4.1.1), managing the trajectory (Section 4.1.2) and sharing the trajectory information with all involved parties (Section 4.1.3).

4.1.1. Four-Dimensional Trajectory Information

In the current situation, the airspace user (e.g. the airline) files a flight plan. The international format is described by ICAO (2016). As described in Section 3.2.1, the flight plan contains basic information about the flight such as the aircraft identification, flight rules (i.e. IFR or VFR), aircraft type, WTC, departure airport, cruising speed and flight level, the intended route and destination airport. This serves as a basis for the ATFM process as described in Section 2.2 and it will be provided to the involved ATS units. Additional information might be added to this flight plan by individual ATS units, such as, amongst others, the runway or SID / *Standard Arrival Route*. Based on their data and assumptions on factors such as the weather and aircraft performance, the ATS units attempt to predict the trajectories for planning purposes, such as human resources. However, in today's environment, the systems of the various stakeholder are not well integrated, resulting in sub-optimal data sharing and management. (Tielrooij et al., 2022)

When moving towards TBO, a 4D trajectory serves as the joint plan for the flight. The 4D trajectory comes down to a representation of the flight trajectory in four dimensions: latitude, longitude, altitude and time. The entire 4D trajectory is planned and managed through CDM and continuously shared with all involved stakeholders. The resulting trajectory is called the *Agreed Trajectory* when an agreement is reached. The flight will be executed according to this *Agreed Trajectory*. Suppose due to certain circumstances the *Agreed Trajectory* needs to be adjusted. In that case, it is the objective that all stakeholders participate in changing and updating the trajectory while sharing relevant data and information. On the trajectory, constraints may be imposed in order to meet particular objectives.

Constraints can be applied in all four dimensions. First lateral constraints could be applied, such as a route (e.g. a SID) or a bound that indicates a maximum deviation. Also, vertical constraints can be imposed in terms of an altitude constraint, range (e.g. ”AT OR BELOW”) or absolute value, that shall be met or initiated (”CLIMB/DESCEND TO”). A speed constraint can be applied as either an absolute value or a range. However, a margin shall be implemented between the maximum/minimum acceptable airspeed and the speed constraint for the robustness of the trajectory. Last, a time constraint may be imposed, which could also be an absolute value or a range, for example, a required time of arrival at a certain waypoint. In general, when applying constraints on a trajectory, a certain level of robustness in the form of bounds or margins shall be implemented to deal with uncertainties and unforeseen circumstances and leave room for separation provision by ATC, such that the need for a revision is limited. These margins may, for example, be based on historical data. Next to constraints, tolerances may be applied to the trajectory. These could be used to trigger an update of the trajectory prediction, notify a certain stakeholder about the trajectory, trigger a trajectory revision or specify the performance limit. (ICAO ATMRPP, 2018)

The main difference with the current way of operation is that the 4D trajectory is continuously evaluated and updated, the information is continuously shared and therefore available to all stakeholders and all parties are involved in the planning, management and updating of the trajectory. (Tielrooij et al., 2022) By applying TBO, it is projected that aircraft can fly more directly to their destination (Figure 4.1) and therefore reduce emissions while also reducing delays and increasing capacity.[1]

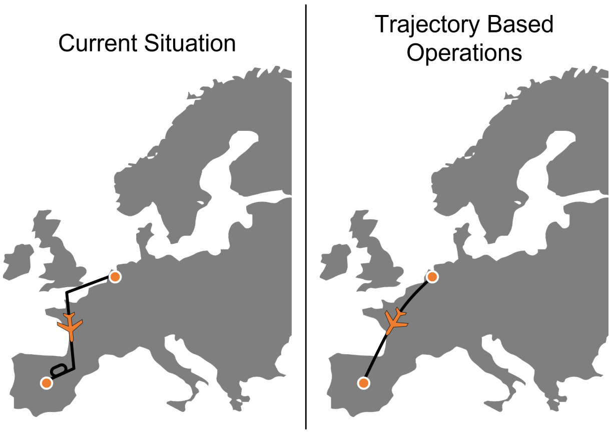

Figure 4.1: Trajectory comparison between current situation and Trajectory Based Operations

4.1.2. Trajectory Management

Since the 4D trajectory acts as a joint plan for the flight, it can be planned in more detail, and all stakeholders are involved, the trajectory must be properly managed. The stakeholders and other factors that influence the trajectory management process are brought down to seven concept components of the ATM system as described by ICAO (2005a). These are listed below:

- Airspace Organization and Management
- Aerodrome Operations
- Demand and Capacity Balancing
- Traffic Synchronisation
- Conflict Management
- Airspace User Operations
- ATM Service Delivery Management

The *Airspace Organization and Management* concept component consists of two parts, as the name suggests. The airspace organization part consists of the establishment of the airspace structure in terms of strategies, rules and procedures. Airspace management is the process of applying the defined airspace structure and selecting suitable ATM configuration for the (expected) traffic demand, which is defined by the airspace organization part. (ICAO, 2005a) As an example, the sector configuration or the reservation of military airspace could be part of the ATM configuration set within airspace management. As described by ICAO ATMRPP (2018), the planned trajectories, i.e. the traffic demand, are used to select the ATM configuration. Once selected, the configuration acts as a constraint on the trajectories.

Within the ATM system the *Aerodrome Operations* component represents the operations at and around the airport, which is i.e. the CTR, as described by ICAO (2005a). Within this component, the

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[1] Source: https://kdc-mainport.nl/2009/08/06/bridget-trajectory-based-operations-en-gb-2/, Accessed 11-1-2023

planned trajectories are used to determine the runway configuration and for surface planning. Contrary, it constrains the trajectories with the selected runway configuration, departure and arrival paths and capacity. (ICAO ATMRPP, 2018)

To prevent demand from exceeding the capacity, the *Demand and Capacity Balancing* concept component is needed. This is a collaborative process, determining if flights can be operated or if changes to the planning need to be made. (ICAO, 2005a) This normally takes place during the strategic phase, but also during the pre-tactical and tactical, of the ATFM process, which is described in Section 2.2. To be able to evaluate the expected demand and capacity balance, the planned trajectories are used. In case of an imbalance, the trajectories or the constraints might be modified. (ICAO ATMRPP, 2018)

Traffic Synchronization happens during the tactical phase of the ATFM process, as described in Section 2.2. This concept component is about establishing and maintaining the air traffic flow safely, efficiently, and in a well-ordered way. (ICAO, 2005a) The planned trajectories are used to detect capacity issues and possible conflicts and their likelihood. Based on this, time constraints with corresponding tolerances might be imposed on individual trajectories, where the tolerances are tighter compared to the ones imposed by the *Demand and Capacity Balancing* concept component. Also during the execution of the *Agreed Trajectory* instructions can be issued originating from this concept component to meet the time constraints of the trajectory for synchronisation purposes.

The *Conflict Management* concept component describes the mitigation of the risk of conflicts and collisions and consists of three layers, which are strategic conflict management, separation provision and collision avoidance. The first layer, strategic conflict management, is provided by the *Airspace Organization and Management*, *Demand and Capacity Balancing* and *Traffic Synchronization* concept components and is mostly applied in the strategic and pre-tactical phases of the ATFM process. The objective is to minimize the risk of conflicts and the need for separation provision, which is the second layer. This layer is applied during flight, i.e. the tactical phase of the ATFM process, and includes maintaining the described separation minimums. Collision avoidance is the last layer of the *Conflict Management* concept component. An example of this is the *Traffic Collision Avoidance System*. (ICAO, 2005a) When planning 4D trajectories, strategic conflict management should be taken into account within the concept components mentioned before, where the risk of conflicts shall be decreased and changes within these components shall not lead to new conflicts. The updated trajectories which are being executed are used to detect conflicts. In case of a conflict, one or more trajectories shall be modified, where the *Conflict Management* component has priority over the other components. The modification of the trajectory should preferably be within the already established constraints and corresponding bounds, however, if this is not possible the trajectories need to be revised.

The flight operations of the user of the airspace, e.g. the airline, is included in the *Airspace User Operations* concept component. The airspace user plans the flight by establishing a flight plan, which starts the process of defining the trajectory. Generic and ATM configuration constraints shall be taken into account by the airspace user preferences when creating or revising a trajectory. These preferences are also an input when establishing the constraints of other concept components. Also, trajectory predictions by the airspace user shall be shared for an efficient collaboration process. In the end, the airspace user shall execute the flight according to the clearances, which shall be in line with the *Agreed Trajectory*.

Within the *ATM Service Delivery Management* concept component the, sometimes conflicting, inputs from the other components are balanced against each other. This is done based on a set of rules for trajectory management, which shall lead to an *Agreed Trajectory*. In this way, this component acts as a central part of the collaborative process.

The different concept components described above collaborate during the planning, revision and execution of the *Agreed Trajectory*. Therefore, the ATM operations need to be properly managed. The process of ATM operation management is schematically shown in Figure 4.2. The ATM operations are split up into two processes which are coupled and are both inputs for a monitoring function. This part monitors the current situation based on the known trajectories, ATM configuration and other general constraints such as the weather. The management of the ATM configuration is determined by both the *Airspace Organization and Management* and *Aerodrome Operations* concept components. Specifically for this management process, the monitoring function shall detect any flow issues which require a change in the ATM configuration, such as sector or runway configuration change. The ATM configuration itself is again an input for the monitoring function. The other part is the management of the trajectories. When there is an issue with one or more trajectories, the trajectory revision process is activated. This revision is a collaborative process. During execution, the trajectories are monitored and updated to provide accuracy. (ICAO ATMRPP, 2018)

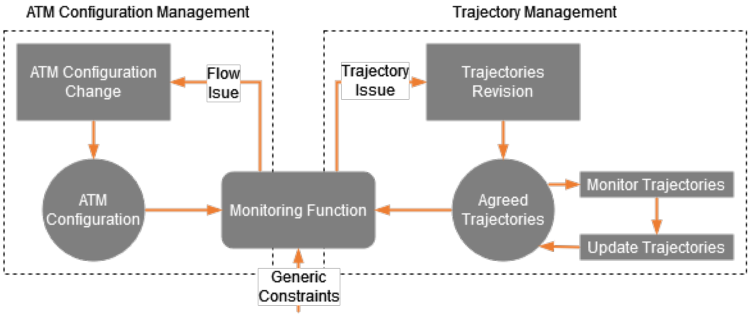

Figure 4.2: Air Traffic Management operation management

The process of creating a (4D) trajectory for a flight starts when the airspace user is planning to operate a flight. In general, the objective is to collaborate across the concept components mentioned before and reach an agreement on the trajectory, which will then be referred to as the *Agreed Trajectory*. In the pre-departure planning phase, the *Airspace Organization and Management*, *Aerodrome Operations*, *Demand and Capacity Balancing* and *Airspace User Operations* concept components interact to construct an *Agreed Trajectory*. During the early phases of pre-departure panning, not all parts of the trajectories can be present for example, the departure runway, as this information might only be available on the day of operation or in terms of hours before departure. Also, with a greater look-ahead time comes greater uncertainty (e.g. weather forecasts), which is why more flexibility might be required during the early stages of the planning or revision might be necessary at a later stage. (ICAO ATMRPP, 2018)

For determining the departure time, together with the *Airspace User*, the *Demand and Capacity Balancing*, *Traffic Synchronization* and *Aerodrome Operations* components collaborate. Here *Demand and Capacity Balancing* defines a departure time with a corresponding window, based on the foreseen demand and capacity. *Traffic Synchronization* on the other hand, interacts with individual trajectories to influence the air traffic flow and therefore applies a departure time with a tighter window. This happens in collaboration with the *Aerodrome Operations* component, which provides gate planning, taxi times and runway allocation. The resulting departure time and window shall fall within the window set by *Demand and Capacity Balancing*, such that no interaction with this component is necessary. (ICAO ATMRPP, 2018)

During the execution of the flight, it is the objective to follow the *Agreed Trajectory* within the constraints and bounds as planned. While executing, the agreed trajectories are monitored and updated with the newest information to improve the accuracy, as seen in Figure 4.2. If due to circumstances, the flight is expected to deviate from the *Agreed Trajectory* outside of the constraint margin, a revision is needed. In general, the modification of the trajectory consists of several parts:

- Proposing
- Predicting
- Evaluating
- Agreeing

The monitoring function determines the need for a revision of trajectories, as seen in Figure 4.2. The process starts with proposing a change to the *Agreed Trajectory* and then predicting the new trajectory. The new trajectory needs to be evaluated across all relevant concept components. If needed, the trajectory needs to be adjusted further. This process continues until an agreement is reached with all components. This process is schematically shown in Figure 4.3. (ICAO ATMRPP, 2018)

As described in Section 3.2.1, currently the flights will receive an en-route clearance. However, with TBO, the route and profile are described in more detail and contain more information as reflected in

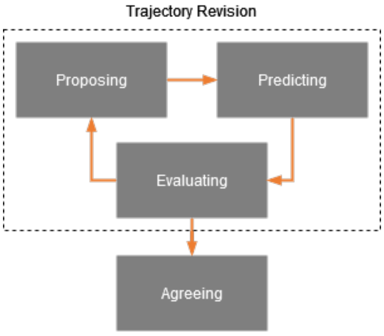

Figure 4.3: Trajectory Revision

the *Agreed Trajectory*. In this way, without further clearances (except for clearances related to runway operations), the *Agreed Trajectory* could be executed. During the planning of the trajectories, the aim of the *Conflict Management* component is to reduce the risk of conflicts and take all influencing factors into account however, it is (most of the time) not possible to generate conflict-free trajectories, because there will be uncertainties and unforeseen circumstances. Therefore, the need for ATC to intervene in the form of clearances remains. These clearances can be open or closed. Closed clearances are clearances in the form of a (4D) trajectory, i.e. a clearance which results in an end-to-end trajectory, either via a revision or within the bounds of already existing constraints. On the other hand, closed clearances do not result in an end-to-end trajectory, for example, a heading or holding command. It is clear that in a TBO environment closed clearances are preferred, however in some cases open clearance might still be needed, for example when holding is necessary. (ICAO ATMRPP, 2018)

Before departure, the airspace user and the ground surface operator shall collaborate to execute the *Agreed Trajectory*, i.e. make sure that the aircraft can leave the stand on time. Within the *Aerodrome Operations* component, start-up and taxi shall happen in such a way that the aircraft is eventually able to depart within the departure window (when specified) as planned in the *Agreed Trajectory*. When adherence to the *Agreed Trajectory* is not possible, due to circumstances such as longer taxi times than expected, ground delays or last-minute runway change, the trajectory shall be revised according to the process described above. (ICAO ATMRPP, 2018)

After departure, the flight will be executed according to the *Agreed Trajectory*, where ATC issues clearances which shall be in line with this *Agreed Trajectory*. Uncertainties and unforeseen circumstances might trigger a revision of the *Agreed Trajectory* when constraints, including margins or bounds, cannot be met. It should be noted that not always all parties need to be involved. For example when adjustments in the area of one ATS unit do not affect the trajectory in the area of other ATS units. As stated before, the *Agreed Trajectory* might not be conflict-free. Therefore, conflict resolution by ATC may still be needed. As described in Section 4.1.1, the constraints preferably have certain bounds or margins for robustness. When resolving conflicts, if possible, these (downstream) constraints and bounds shall be respected and the clearances shall be closed. However, as described before, *Conflict Management* has priority over the other components, meaning deviation from the *Agreed Trajectory* and open clearances might still be needed and may lead to a revision of the trajectory. Also, other factors might influence the *Agreed Trajectory*. For example, bad weather may force an aircraft to fly around this. Also here holds, when constraints, including margins, cannot be met, a revision is required. These two examples are shown in Figure 4.4. (ICAO ATMRPP, 2018)

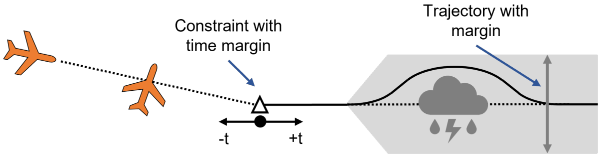

Figure 4.4: Trajectory Margins

As for departures, *Demand and Capacity Balancing* determines an arrival time and corresponding window. If during the planning of the flight, an imbalance between demand and capacity during landing is expected, from the point of view of *Demand and Capacity Balancing* the flight needs to be delayed. However, due to uncertainty and disturbances, in the end, it might not be necessary to delay the departure of the flight. Therefore a controlled departure time might be set with a target landing time. When there is more certainty, it can be determined if a delay is still needed and therefore a revision of the *Agreed Trajectory*. At some point when the flight is approaching the destination airport, the *Traffic Synchronisation* component starts to interact, to create an orderly flow of arriving aircraft. The *Aerodrome Operations* component collaborates for landing time, runway selection and therefore also the arrival path and taxi paths. (ICAO ATMRPP, 2018)

4.1.3. Trajectory Sharing

Since the 4D trajectory, in the form of the *Agreed Trajectory*, acts as a joint plan across all stakeholders for the flight, sharing of this trajectory is vital. For sharing data and trajectory information, existing and new capabilities will be used, which are described in Section 4.2. The information and data to be shared in a TBO environment are listed below.

- Environmental factors
- Information supporting CDM
- Information for trajectory prediction
- The Agreed Trajectory

The environmental factors contain information which could affect the trajectory. This includes, for example, weather data and forecasts, airspace configuration or aerodrome capacity. Next, is the information supporting the CDM process, which is part of the trajectory management process, as described in Section 4.1.2. An example is the constraints set by the different components. Third, is the information for the accurate prediction of trajectories, such as aircraft data. Last is the *Agreed Trajectory* itself. (ICAO ATMRPP, 2018)

An important factor within TBO is the trajectory prediction and the accuracy of this prediction. These predictions play an important role in the trajectory management process. Based on predictions of trajectories, trajectory issues could be identified, which may lead to a trajectory revision, as shown in Figure 4.2. Also, when revising a trajectory, the prediction of the proposed trajectory is used to evaluate the solution, as can be seen in Figure 4.3. This prediction is used, for example, to detect any issues with this new trajectory. To get an accurate prediction, sharing relevant data is necessary since this data originates from different stakeholders and parties. As an example, this data could include downlinked aircraft data and weather data and forecasts. The facilitators for sharing information and data for trajectory prediction and TBO in general are discussed in Section 4.2.2. (ICAO ATMRPP, 2018)

4.2. Technologies

There are several technologies and enablers that are needed within a TBO environment. In Section 4.2.1, the sharing platform, System Wide Information Management (SWIM), is described. The information-sharing facilitators are described in Section 4.2.2.

4.2.1. System Wide Information Management

As described in Section 4.1.3, TBO requires extensive data and information sharing. Currently, many stakeholders have their own systems with their own way of data management and limited interoperability. SWIM enables the management and exchange of information and data across involved parties through standards, infrastructure and governance. Instead of individual links between the different stakeholders (e.g. as shown in Figure 2.3), SWIM acts as a central base for data and information publication and acquisition, as schematically shown in Figure 4.5. (Undertaking, 2016) As described by ICAO ATMRPP (2018), SWIM can be seen as the supporting technical infrastructure for the enhanced sharing of information and data.

SWIM is built upon four principles. The first is to separate the providers and consumers of the information and data since most parties are both providers and consumers of data. This is needed because it is not desirable to fix the information streams beforehand, since in certain (unforeseen) circumstances

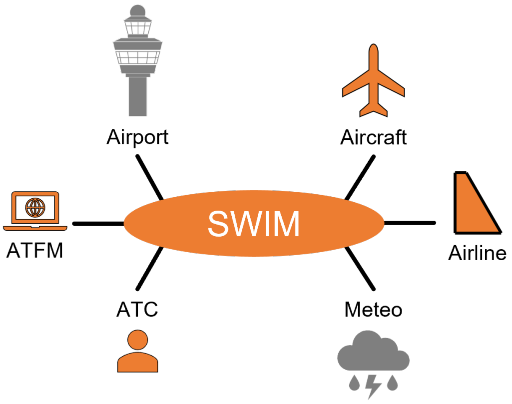

Figure 4.5: System Wide Information Sharing Concept

different parties need different information. The number of both consumers and producers may vary over time. Therefore flexibility in information exchange is needed. Next is the loose coupling of the system. By applying this, the functioning of the different components is not (or only partly) dependent on other components. The third is using open standards and the last is using interoperable services.

4.2.2. Information-Exchange Facilitators

As mentioned before, the TBO concept relies heavily on data and information exchange. For establishing this exchange, several already existing and future information-sharing facilitators are required as described by ICAO ATMRPP (2018) and Tielrooij et al. (2022). These can be subdivided into three groups. The first group are the ground-based information-sharing facilitators:

- Flight and Flow Information for a Collaborative Environment (FF-ICE)
- Performance-Based Communication, Navigation and Surveillance
- Ground-to-Ground Interoperability
- ED-254 Arrival Sequence Performance Standard

The second is air-ground facilitators:

- Automatic Dependent Surveillance - Broadcast (ADS-B)
- Automatic Dependent Surveillance - Contract (ADS-C)
- Controller Pilot Data Link Communications
- Meteo uplink via Aircraft Communications Addressing and Reporting System

The last group is facilitators in the air:

- Flight Management System (FMS)
- Electronic Flight Bag

Flight and Flow Information for a Collaborative Environment

In a TBO environment, FF-ICE will replace the current flight plan template. FF-ICE enables flight and flow information exchange between the different stakeholders, as presented in Section 4.1.2. Based on this information exchange, trajectories can be planned and managed through the process described in Section 4.1.2. The FF-ICE ”flight plan” will be shared using the SWIM network. (Tielrooij et al., 2022)

Compared to the traditional flight plan, FF-ICE will contain much more information, for example, the trajectory information is described in more detail. The data and information is structured in several information groups. These are listed below. Every information group contains several information or data blocks, shown in Figure 4.6. (ICAO, 2012)

- Flight Identifying Information
- Flight Search And Rescue Information
- Flight Permission Information
- Flight Preference Information

- Flight Trajectory Information
- Additional Information

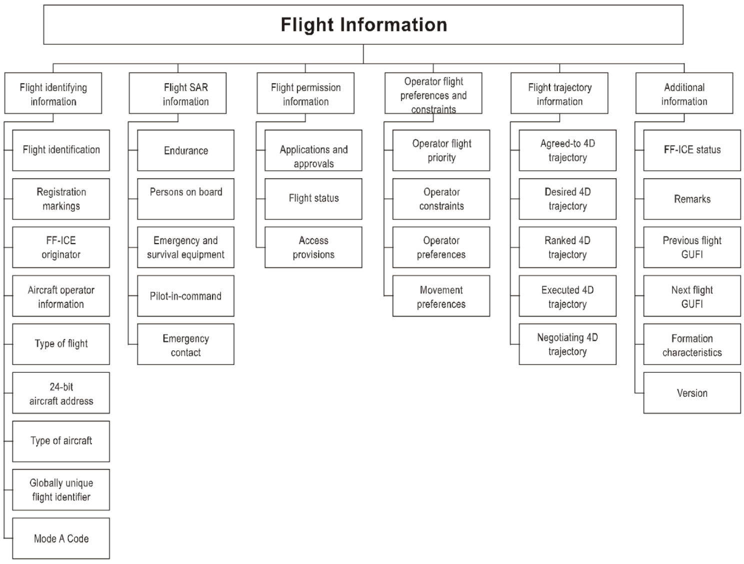

Figure 4.6: Flight and Flow Information for a Collaborative Environment Contents (ICAO, 2012)

The *Agreed Trajectory* is located under the flight trajectory information group. Within FF-ICE, the *Agreed Trajectory* is described in three segments, the departure surface, airborne and arrival surface segment. Every segment contains information and data related to that segment. Several relevant data parts for this research are pointed out.

For the departure surface segment, the first information part is the planning targets, which include the time parameters of the pre-departure CDM process described in Section 2.2, such as the TOBT or TTOT. Related to this are the estimates of the off-block and departure time and corresponding constraints and possible tolerances as part of the 4D trajectory. Next is the taxi path from the stand or gate to the runway, which consists of surface segments with corresponding speeds and arrival times at different nodes. The last information part of the ground segment is the runway information, including the selected runway, the estimated take-off time (based on the end of the taxi path time and take-off roll), corresponding constraint, trajectory tolerances and optionally the airport slot.

For the airborne segment, the 4D path is described in a sequence of elements. For every element, several data types are specified. One of these is the next waypoint and related to this the estimated time of arrival and, if needed, the type of change, such as start-of-climb or to-of-descend, the speed and turn data. Also, lateral, speed and time constraints are specified and optionally tolerances.

The arrival surface segment contains the same elements as the departure surface segment however, the elements are turned around. For example, the taxi path is in this case from the runway to the stand or gate. (ICAO, 2012)

Automatic Dependent Surveillance

Both ADS-B and ADS-C are information facilitators for transporting data from the aircraft to the ground. However, the difference with ADS-B is that ADS-C is based on a contract instead of broadcasting with a fixed interval. Also, with ADS-B only limited data exchange is possible, where the identification, position, altitude and speed, are the most important. With ADS-C, data from the FMS can be sent to a ground station when a connection is established. (ICAO ATMRPP, 2018)

The information and data that can be retrieved with ADS-C, are grouped in data blocks, which are described by ICAO (2016). The different blocks are listed below.

- Aircraft Identification
- Basic ADS-C
- Ground Vector

- Air Vector
- Projected Profile
- Meteorological Information
- Short-term Intent

The *Basic ADS-C* block contains the position of the aircraft in latitude, longitude and altitude as well as the time and figure of merit. The *Ground Vector* contains the track, ground speed and rate of climb/descent, while the *Air Vector* contains the heading, the speed in terms of Mach or Indicated Airspeed and also the rate of climb/descent. Within the *Projected Profile*, the waypoint and estimated altitude and time at the waypoint for both the next and the next+1 waypoint are included. Atmospheric data is included in the *Meteorological Information* block, such as the wind speed and direction, temperature and when available the wind quality flag, turbulence and humidity. Last, the *Short-term Intent* data block contains information about a projected intent point, which are the latitude, longitude and altitude at this point. Also, the time of the projection is included. An additional intent data block is included when there is a change in altitude, track or speed expected, a change point, between now and the projected intent point. This data block contains the distance, track and time to the change point and the altitude at this point.

Another important part of ADS-C for TBO applications is the Extended Projected Profile (EPP) data block, which is part of the baseline 2 version. This information is provided by the *Flight Management System*. The contents are described by RTCA, Inc. (2016), as cited by Guerreiro and Underwood (2018). First, the date and time are included. Next is the sequence of waypoints, with a maximum of 128 waypoints, where for every waypoint corresponding data is provided. The required data are the latitude and longitude of the waypoint. Additionally, it could include, amongst others, the altitude, waypoint name, the estimated time and speed at the waypoint and constraints on the altitude, speed and time. Besides the waypoint data, the message could also include other information, such as the gross mass.

Other Information-Exchange Facilitators

Performance-Based Communication, Navigation and Surveillance are a set of standards and procedures to increase accuracy and efficiency. With *Performance-Based Communication* standards and requirements, it can be ensured that clearances issued, for example, adjusting a trajectory, can be received such that eventually the trajectory can be executed with the required accuracy. This is done by taking several factors into account, such as the time needed to communicate the command. (ICAO ATMRPP, 2018) *Performance-Based Navigation* sets requirements on aircraft performance for executing a particular trajectory or route. By applying this, it is ensured that the aircraft can execute this particular trajectory with the required precision.[2] The last is the *Performance-Based Surveillance*, which lays down the accuracy of surveillance systems. When the prediction of a trajectory is based on surveillance data, the accuracy of this prediction can also be assessed, which is an input for the trajectory management process described in Section 4.1.2. (ICAO ATMRPP, 2018)

The *Ground-to-Ground Interoperability* system, also referred to as IOP, is a system that will be used to share flight objects, which includes the *Agreed Trajectory*, between the different ANSPs.

The *ED-254 Arrival Sequence Performance Standard* is used to communicate trajectory modifications made by arrival managers (a system which sequence arrivals[3]) to upstream ANSPs. (Tielrooij et al., 2022)

The *Controller Pilot Data Link Communications* system is used to send messages, including clearances (e.g. the en-route clearance as described in Section 3.2.2), between ATCos and pilots.[4] The baseline 2 version of this link can be used to upload the 4D trajectory clearance to the aircraft, which is needed for TBO. (Tielrooij et al., 2022)

The *Aircraft Communications, Addressing and Reporting System* is used mainly by airlines to communicate with pilots via messages.[5] Meteorological data could be uploaded to the aircraft with this system. The aircraft's FMS can use this data to improve the accuracy of the trajectory prediction. (Tielrooij et al., 2022)

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[2] Source: https://skybrary.aero/articles/performance-based-navigation-pbn, Accessed 23-1-2023

[3] Source: https://www.skybrary.aero/articles/arrival-manager-aman, Accessed 20-1-2023

[4] Source: https://skybrary.aero/articles/controller-pilot-data-link-communications-cpdlc, Accessed 20-1-2023

[5] Source: https://www.skybrary.aero/articles/aircraft-communications-addressing-and-reporting-system, Accessed 23-1-2023

Both the FMS and the *Electronic Flight Bag* are airborne systems. Complex 4D trajectory clearances can be uploaded into the FMS and the FMS can assist in executing the *Agreed Trajectory*. On the other hand, based on the planned route, the aircraft state and meteorological data, the FMS can provide trajectory predictions. The *Electronic Flight Bag* enables the pilot to interact and collaborate in the trajectory management process. (ICAO ATMRPP, 2018)

4.3. Research Focus

As mentioned in Section 2.4 and 3.4, the focus will be on *Aerodrome Control* and more specifically, on the work domain of the RC. Furthermore, the focus will be mainly on IFR outbound flights. From a TBO perspective, the departure time and corresponding window are important parameters for decisions the RC has to make. As described in Section 4.1.2, both *Demand and Capacity Balancing* and *Traffic Synchronisation* define a departure time and corresponding window, where the window of the *Traffic Synchronisation* component shall fall within the window set by *Demand and Capacity Balancing* and can be set closer to execution (Figure 4.7). When looking at these times, the time set by the *Demand and Capacity Balancing* component is reflected in the CTOT set by the NM and the time set by *Traffic Synchronisation* is reflected by the TTOT/RETD, which are time parameters of the ATFM process as described in Section 2.2.

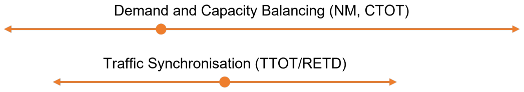


Figure 4.7: Departure time and window

Additionally in a TBO environment, decisions can be based on a 4D trajectory. This holds both for large changes, where a revision of a trajectory is needed and involvement of different parties is required, but also for ”small” tactical changes while staying within the margins of constraints set within the 4D trajectory. The more extensive sharing of information and data, and therefore more accurate trajectory prediction, can support these decisions. When focusing on decisions the RC has to make, i.e. when a take-off clearance should be issued, these decisions can be based on trajectory information. Here, ADS-C data, including the EPP data block, can play an important role.

5

Decision Support in Aerodrome Control

In this chapter, the design of a tool to support the decisions the RC has to make. In Section 5.1, the Ecological Interface Design (EID) principles are discussed. The previous work performed on interfaces for ATC purposes, which forms the basis for the interface design for *Aerodrome Control*, is described in Section 5.2. The design of the interface for the RC, which is called the Take-off Timing Support Tool (TTST), is presented in Section 5.3. Finally, in Section 5.4, the work still to be performed within this research is described.

5.1. Ecological Interface Design

The to-be-developed interface for the RC will be based previous studies that used the EID framework, which was defined by Vicente and Rasmussen (1992). The framework was set up to support the design of interfaces for complex systems where the human interacts with a machine. Borst et al. (2015) describes that within EID, the design of the interface or display is not based solely on the perspective of the human, nor from the technology perspective, but EID focuses on the work domain or ”ecology”. Here ecological interfaces support the *Skill, Rule and Knowledge-Based* behaviour of humans, as presented by Rasmussen (1983) and visualise the solution space, i.e. showing the range of possibilities and taking into account constraints, such as rules or the laws of physics (Borst, 2020).

5.2. Previous Work

The design of the display/tool is based on previous work on displays (using EID) for ATC purposes. Below, the different displays/tools are discussed. Also, the parts that acted as inspiration for the design of the tool are highlighted.

Klomp et al. (2011) proposed a redesign of an interface for inbound planning by ACC ATCos. As described in Section 2.3, ACC controllers will guide arriving aircraft to the *Initial Approach Fix*. Since aircraft approach from different sectors and directions, the ATCo has to merge the traffic streams over this fix. The designed display to support this task is shown in Figure 5.1. The interface displays both a time-space (on the top) and a vertical situation diagram (on the bottom). This displays the trajectory as a white line of the aircraft till the *Initial Approach Fix*. In the time-space diagram on the right, the sequence in which the aircraft are projected to arrive at the fix is shown, where each column represents a single *Initial Approach Fix*. When a flight is selected, the distance (horizontal axis) and the time (vertical axis) are displayed. The light grey area shows the solution space when changing the aircraft's speed and the blue areas show the WTC minimums at the runway. The red contour indicates a conflict zone, where a loss of separation is expected. In the vertical situation diagram, the vertical profile of the aircraft's trajectory is shown. This interface allows the ATCo to determine the sequence and prevent conflicts by manipulating the speed, route and/or vertical profile. The experiment with this interface showed that the inbound traffic streams could be managed safely and efficiently. Also, a trend to better situational awareness could be identified, although not significant.

The aspects of this research that acted as inspiration for the development of an interface to support RCs are related to the planning of the sequence in time. In particular the time axis, in combination with

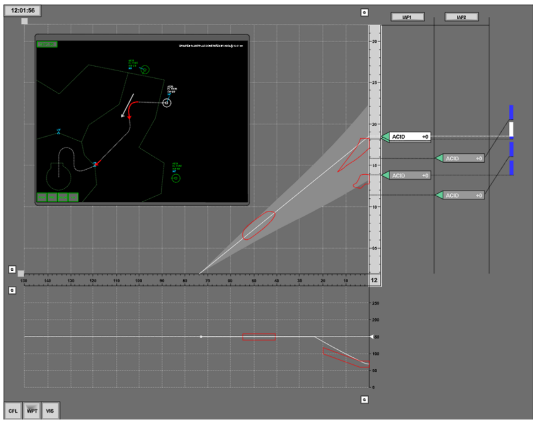


Figure 5.1: Inbound planning interface with a time-space and vertical diagram (Klomp et al., 2011)

displaying the aircraft tags on this axis.

The second research which formed the basis for the design of an interface for RCs is performed by Ottenhoff (2020). Within this research, an interface was developed for resolving conflicts of aircraft flying to a sector exit point, e.g. an *Initial Approach Fix*, while taking into account the effect of wind and trajectory uncertainty. The resulting interface elements in terms of solution space presentation are shown in Figure 5.2. The *Plan View Display* shows the rerouting possibilities with colours for the selected aircraft in case of a conflict. Also, the exit waypoint can be changed, where the black bar at the bottom shows the possible positions while respecting the original required time of arrival. Within the *Vertical Situation Display*, the solution space with respect to the altitude is displayed. The vertical altitude axis includes a grey bar, indicating the viable exit altitudes while catching the required time of arrival at the exit point. The *Time Space Diagram*, shows the conflict resolution options by changing the aircraft's speed. If the ATCo wishes to adjust the exit point arrival time, the black bar on the time axis indicates the possible arrival times, based on the performance limits of the aircraft. The manipulations in all dimensions can be done by placing intermediate waypoints or dragging the exit point (in the *Plan View Display*) or the aircraft tag (in the *Vertical Situation* or *Time Space Display*). A performed case study showed that the interface enables the ATCos to manage both conflicts as well as arrival planning.

The interface designed in this research acted as inspiration for the to-be-developed tool. One of the aspects for this is the bars indicating the viable options, and particularly the bar indicating the possible arrival times in the *Time Space Display*. Also, the possibility of directly moving the aircraft tag along this bar to generate the desired result was deemed a useful aspect.

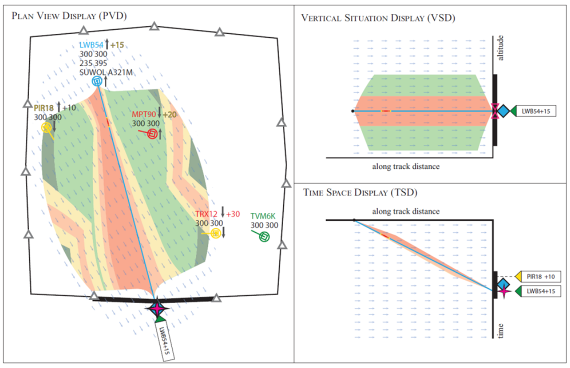


Figure 5.2: Four-Dimensional (4D) trajectory management interface with a plan view, vertical situation and time-space display (Ottenhoff, 2020)

To support fixed approach trajectories and time-based separations at Schiphol Airport during high-density operations, van Selling (2023) designed a new tool-set for APP. The tool included a time-space

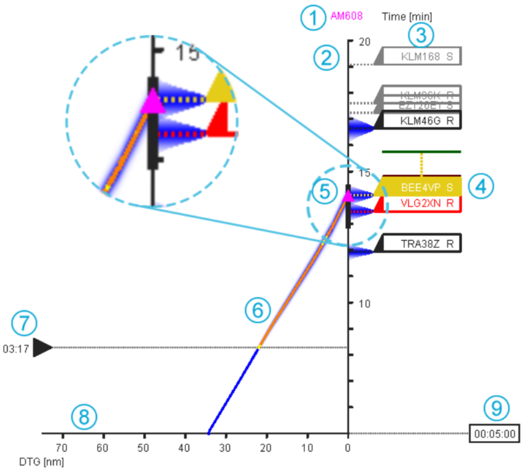


Figure 5.3: Time-Space diagram to resolve conflicts on fixed approach trajectories (van Selling, 2023)

diagram shown in Figure 5.3. When selecting a waypoint on the fixed approach trajectory, on the vertical axis the time before reaching this waypoint is shown for the aircraft on this fixed approach trajectory. On the horizontal axis, the corresponding distance to go is displayed. When dragging an aircraft tag along the vertical time axis, the arrival time can be adjusted and a corresponding speed instruction is suggested to meet this arrival time. The black bar indicated next to (5) shows the possible arrival time range by taking the speed limits into account. In this way, conflicts along the fixed approach trajectory can be resolved and time-based separation can be applied. An experiment performed with the time-space diagram showed that future conflicts were solved in an earlier stage and fewer commands were needed.

For this research, displaying the aircraft on a time axis and displaying the corresponding limits (solution space) were used as inspiration for the design of the to-be-developed tool.

The last interface that was taken into account when designing the tool for RCs is the *Solution Space Diagram*. This tool is discussed in several pieces of research, such as the work from van Dam et al. (2008) or Velasco et al. (2010). The diagram can be used to resolve conflicts. An example is shown in Figure 5.4. The *Solution Space Diagram* consists of a ring around the selected aircraft which indicates possible solutions to resolve conflicts in terms of speed and/or heading instructions. The inner circle corresponds with the minimum speed and the outer circle with the maximum speed the aircraft is able to fly. The red areas indicate combined heading and speed instruction which will lead to a loss of separation. The construction of the diagram for a conflict with one other aircraft is schematically shown in Figure 5.5. By applying this construction to multiple aircraft, a set of triangles become visible within the diagram. It should be noted that this concept can be applied both within the aircraft (van Dam et al., 2008) and at ATC centres (Velasco et al., 2010). An experiment conducted by Velasco et al. (2010) with ATCos showed that the *Solution Space Diagram* could reduce the workload.

An aspect that is used as inspiration for this research is the visualisation of viable solutions to resolve conflicts. Especially that the solution space or viable options are shown directly around the selected aircraft.

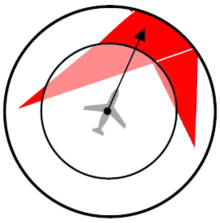
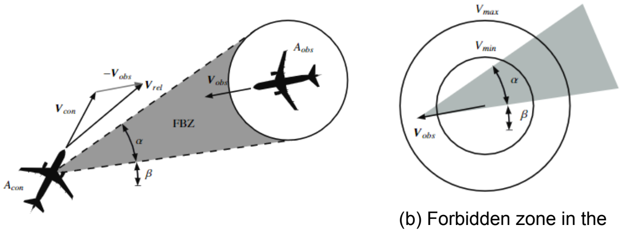


Figure 5.4: Solution Space Diagram (Borst, 2022)



(a) Definition of the forbidden zone

(b) Forbidden zone in the diagram

Figure 5.5: Construction of the Solution Space Diagram (Velasco et al., 2010)

5.3. Take-off Timing Support

In this section, the design of the decision support tool, the TTST, will be discussed. First, the focus of the research will be presented in Section 5.3.1. Next, in Section 5.3.2, the requirements for the tool will be listed. Finally, the design of the TTST will be discussed in Section 5.3.3.

5.3.1. Research Focus

The goal of this research is to support TBO in *Aerodrome Control*. As defined in Section 3.4, the focus will be on the work domain of the RC. Also, three points of interest were identified: missed approach conflicts in the case of converging runways, speed profile differences along the same track, and utilising the primary runway capacity during an outbound peak. For the last option, certain SIDs would be served from both the primary and the secondary runway, allowing more aircraft to depart from the primary runway. This means that traffic needs to be merged upstream. By correctly timing the take-off clearance, upstream ATC units do not have to intervene. However, adequate departure planning is required, such that merging is possible and maintaining a smooth flow without causing delays (i.e. making sure that an aircraft does not have to wait a long time before take-off). This planning process already starts before interaction with the TWR and the RC in particular. There also exist large uncertainties, for example, missing passengers or delays in baggage loading, which makes the planning process complex. This problem requires much involvement of the other working positions at the TWR as well as of the departure planning and therefore is deemed to be not suitable for the scope of this research.

The focus of this research will be on the timing of the take-off clearance in the case of two consecutive departing aircraft from the same runway in a TBO environment. Here, the timing related to the separation between two aircraft flying the same SID, but with a different speed profile, will be investigated in particular, while also taking the other separation factors, such as WTC, into account. Possibly also the missed approach conflict, when using 18C and 24 simultaneously, will be taken into account. The to-be-developed tool shall enable the ATCo to make trajectory-based decisions, by making use of trajectory information. An important enabler for this is the ADS-C EPP data link.

When implementing a tool with a focus on these problems, several improvements may be possible on certain factors. As described in Section 3.2.4, the timing of the take-off is based on the experience of the RC and this decision is always a bit conservative in case of two consecutive departures flying the same SID and having the same WTC (or when the succeeding aircraft has a higher WTC). When this timing is based on data and the visualisation of this data, a higher runway capacity might be reached. Also the number of conflicts might be decreased (or less intervention is needed by ACC ATCos). This also holds for the missed approach conflict, when included into the tool.

5.3.2. Requirements

The TTST should fulfil a number of requirements. From the perspective of the current operation, the TTST shall take into account the:

- Different separation minimums
- CTOT window
- Constraints from dependent runway operations

From the perspective of TBO, especially the adherence to the departure window is important, since this may have an effect on the entire planned trajectory when departing too early or late. Therefore the TTST shall include the departure time and window set by:

- Demand and Capacity Balancing (CTOT)
- Traffic Synchronisation (TTOT)

Apart from constraints from the current operation and set by TBO, the TTST should leave room for uncertainties when providing departure time solutions. For example uncertainties in:

- Taxi time
- Aircraft ready for departure time
- Pilot response time

5.3.3. Design

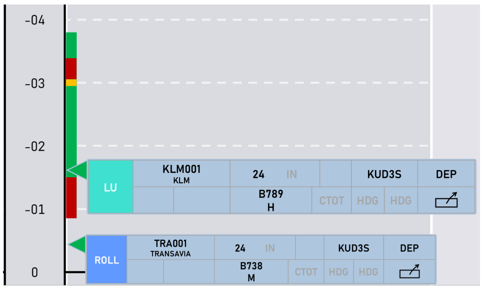
The TTST will be incorporated in the EFSS. There are several reasons for this design choice. First, the current console used at the Schiphol TWR (Figure 3.6) already consists of four main displays. When adding an additional display, the ATCo has to divide its attention to even more displays. This is also related to one of the thirteen display design principles defined by Wickens et al. (1997), which states that the information access cost must be minimized. An additional display would also add additional ”heads-down” time, i.e. not looking outside the window. As described by ICAO (2016), *Aerodrome Control* shall mainly be based on visual observation, with the help of surveillance systems. Therefore the tools and displays must not draw too much attention from the ATCo in the TWR. The second reason is that the EFSS is the main tool used by TWR controllers, which is used to keep track of flights. With this display, already some kind of planning is made for the departure sequence since the flight strips are ordered based on this sequence.

Within the EFSS, a time axis will be added. In the case of dependent runway combinations, the time axis will be placed between the two corresponding bays. In this way, conflicts with aircraft from the other runway can be easily understood. The black solid line indicates the current time. The area above this line indicates the future and the area below the past, both in minutes. Flight strips can be dragged onto this time axis and by doing this select a departure time. The layout of the flight strips itself remains the same. The little triangle next to the flight strip for departures indicates the take-off time and the colour indicates if a viable option is chosen, where green is viable, red is non-feasible and yellow indicates some uncertainty. The example shown in Figure 5.6, shows the combination of arriving at runway 18C and departing from 24.

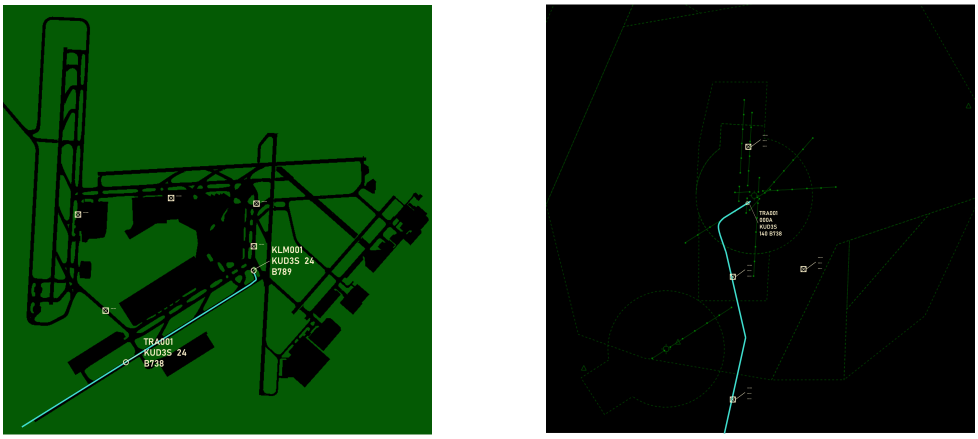
Currently, the RC can take an aircraft UCO by dragging the flight strip to the working area. However, with the TTST, the flight strips can be dragged to the working area with the time axis without taking the flight UCO. When the flight is still UCO at a different ATCo, the abbreviation of this working position is shown in light grey in the flight status part of the flight strip. When the flight is ready for transfer of control, the word ’UCO’ is displayed in black. The flight can then be taken UCO by clicking on the flight status, which will make the flight status white. The other flight statuses stay the same and are described in Section 3.3.

Figure 5.6: Take-off Timing Support Tool

A departing flight can be selected by clicking on the flight strip or on the track symbol and label at the ASDE or TAR screen. When a departing flight is selected, a bar next to the time axis is shown. With colours, the solution space for the departing time is shown, where green indicates a viable option and red a non-feasible option, as seen in Figure 5.7a. With this method, restrictions on the take-off time, due to, for example, the WTC or conflicts, can be made visible. The trajectory of the selected aircraft is shown both at the ASDE (Figure 5.7b) and TAR (Figure 5.7c) screen.



(a) EFSS



(b) ASDE (c) TAR

Figure 5.7: Selected flight with the Take-off Timing Support Tool

As described before, a red area at the time axis indicates a non-feasible option for take-off. The conflicting aircraft will get a red border around the flight strip, as seen in Figure 5.8a. It should be noted that this could also be an inbound flight, for example in case of a missed approach conflict. When there is a conflict along the trajectory, this is shown in red at the TAR screen (Figure 5.8b).

(a) EFSS (b) TAR

Figure 5.8: Conflict in the Take-off Timing Support Tool

5.4. Future Work

After this preliminary phase, some work has to be performed. This consists of two main parts. First is the implementation within the Java-based *SectorX* ATC simulation software. This software is specifically built to perform human-in-the-loop experiments with newly developed interfaces and tools for ATC purposes. Within *SectorX*, there is already a framework to add different ”styles”. For this research, the style ”LVNL-TWR” will be added. Alongside this, several parts have to be implemented in the software. These are listed below, where the first four items form the baseline, as these parts are already used by TWR controllers. It should be noted that when implementing the TTST, some improvements to the design might be made.

- TWR-screen Interaction Area
- TWR-screen TAR mode (adaption of the *SectorX* radar screen)
- TWR-screen ASDE mode
- (Part of) EFSS
- TTST

As part of a simulation, aircraft need to be modelled. This research requires modelling of taxiing aircraft, the take-off roll and the initial climb. It is foreseen that this will, where possible, be based on real data (i.e. replaying actual air traffic). The data will originate from two separate sources, the ground radar and the radar for airborne traffic. Since the data formats coming from these two sources do not match, some pre-processing will be necessary to link the two data streams. The ”replay” of air traffic can be initiated with commands from the ATCo. For example, when an aircraft has lined up, the replay is paused until the ATCo issues the take-off clearance.

To make the TTST work properly, predictions of aircraft trajectories need to be made. Since the actual trajectory of an aircraft within *SectorX* is always known, the prediction of the trajectory and the corresponding accuracy can be engineered. Where possible, these predictions will be based on data modelled after ”real-life” data. As stated before, ADS-C, in particular baseline 2 (which includes EPP), is an important data source for this purpose. For example, the arrival trajectory can be down-linked in much detail, which can be used to prevent missed approach conflicts during converging runway operations (e.g. the combination of departing from runway 24 and arriving at 18C at Schiphol Airport, as described in Section 3.4).

Eventually, the tool needs to be tested. For this scenarios need to be developed. As stated before, when possible, real air traffic data will be used for this, which also adds more realism to the simulation. The actual experiment will be performed with a number of participants. These participants will be professional ATCos from the LVNL. The experiment will start with a training scenario, such that the ATCos can familiarise themselves with the *SectorX* simulator. Next, the participants will conduct a part with the TTST enabled and a part without the tool, such that the use of the TTST can be compared to the current way of operation.

It should be noted that normally, TWR controllers mainly use the outside view to control air traffic, however within the time frame of this research it is not possible to simulate this. Therefore, during the experiment, the participants will only be able to use the displays. This is, however, still a relevant situation for the RCs. When there is bad visibility at Schiphol Airport, the ATCos have to rely on the radar displays (LVNL ATMP, 2017b). As briefly stated in Section 3.2, additional separation minimums and other procedures apply in this situation. However, during the experiments, these additional rules will be neglected.

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III

Master of Science Thesis Appendices

A

Experiment Design

This appendix contains the design of the experiment conducted, to be able to evaluate the TTST. First, in Section A.1, the goal of the experiment will be presented, followed by the experimental setup in Section A.2.

A.1. Experiment Goal

To answer the main research question, ”How can Trajectory Based Operations be supported in Aerodrome Control”, a new support tool, the TTST, has been developed. Therefore the goal of the experiment was to evaluate the use of the TTST by professional ATCos. In particular, whether the ATCos would plan further ahead, rather than pure tactical control of air traffic, and if the additional data available in a TBO environment, which is visualised in the tool, would be taken into account when controlling the traffic. Additionally, feedback from the participants was gathered to be able to improve the tool.

As follows from the experiment goal described above, the following hypotheses were drafted and tested with the experiment:

- When using the TTST, the departure will be strictly around the missed-approach conflicts as set within the tool, because the conflict is visualised and is therefore not up to the ATCo to determine the separation, as is the case in the baseline.
- When using the TTST, after transfer by ground control, there will be fewer interactions with outbound flight strips, because the departure time can already be planned before transfer of control and only the clearances have to be issued afterwards.
- When using the TTST, the departure time interval will be less, because the departure time is visualised in the tool and the interval is therefore actively managed by de ATCo.

A.2. Experimental Setup

The experiment was conducted using the Java-based SectorX Air Traffic Control simulator, in which also the tool was developed and implemented. During the experiment, the participants were asked to control the air traffic in a simulated scenario. In the following sections the assumptions, variables, apparatus, participants, scenarios, workflow and questionnaires will be described.

A.2.1. Assumptions

Several assumptions had been made to be able to conduct the experiment. These are listed below:

- All aircraft were equipped with ADS-C EPP, or a similar system. As a result, the arrival path could be accurately predicted.
- The departure sequence as proposed by ground control was fixed.
- Transfer of control by ground happened when the aircraft was within 150 m from the runway.
- The pilot delay (distribution) was the same for all departures.
- Arrivals would land, irrespective of whether a landing clearance had been issued or not.

A.2.2. Variables

Independent Variables

- Configuration (Baseline or TTST)

Control Variables

- Experiment environment
- Simulator set-up
- Scenario duration
- Traffic scenario
- Pilot delay

Dependent Variables

- Aircraft states (at a fixed time interval)
- ATCo subjective workload
- Notes of observations made during the experiment
- Mouse activity
- Touch activity

A.2.3. Apparatus

The experiment equipment consisted of several elements (Figure A.1). First, a regular computer screen which functioned as the tower screen. Second, was a large touchscreen below the computer screen which displayed the EFSS. To adjust elements on the tower screen a mouse was provided. Elements on the EFSS could be controlled using a pen. During the simulation, no voice control was possible. Therefore, the clearances could be issued via the flight strips on the EFSS.

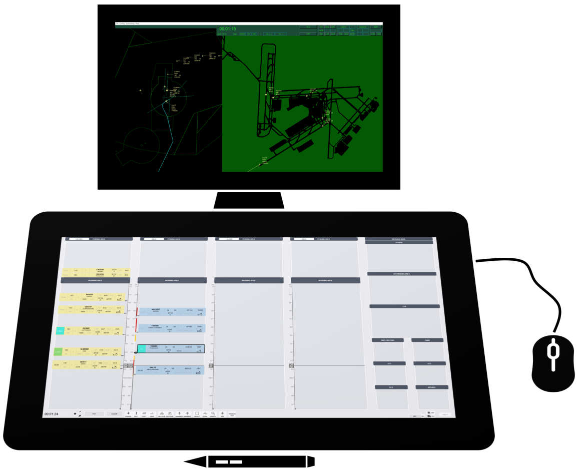


Figure A.1: Experiment Apparatus

A.2.4. Participants

To get the most valuable evaluation of the TTST, the experiment was conducted by at least six qualified Schiphol RCs from LVNL. The ATCos were asked for their age and years of experience to get an indication of the diversity of the participants (Table A.1).

A.2.5. Scenarios

The experiment was structured using a within-participants design. It consisted of four unique scenarios: three training and one measurement scenario. All scenarios ran at 1.5 times the speed. Furthermore, the training scenarios consisted of ten minutes of traffic, while the measurement scenario consisted of fifteen minutes of traffic. Therefore, in total the training would take twice as long as the measurement. Additionally, for an equal comparison, the measurement scenario had a fixed pilot delay, while the training scenarios included a normal distribution for the pilot delay. The participants would run all

Table A.1: Diversity of the Participants

Start Configuration	Age	Years of Experience
Baseline	$\mu = 31.7, \sigma = 4.8$	$\mu = 5.8, \sigma = 3.2$
TTST	$\mu = 31.0, \sigma = 2.9$	$\mu = 6.3, \sigma = 2.1$
Overall	$\mu = 31.3, \sigma = 4.0$	$\mu = 6.1, \sigma = 2.7$

four scenarios both with and without the TTST enabled. To prevent recognition of the scenarios, the flight numbers were replaced. Details of the four different scenarios are presented in Table A.2. The scenarios were replays of real traffic samples provided by LVNL, however with implemented ”pause” moments at the holding point, after line-up and to prevent ”collisions” on the ground.

Table A.2: Scenario details

	S1	S2	S3	S4
Date	26-02-2023	08-05-2023	08-04-2023	05-05-2023
Time	09:20:10 - 09:30:10	13:20:00 - 13:30:00	13:00:00 - 13:10:00	11:47:58 - 12:02:58
Speed	1.5	1.5	1.5	1.5
Duration [min]	6.7	6.7	6.7	10
Runways (Arr/Dep)	06 / 09	18C / 24	06 / 09	18C / 24
Aircraft Count (Arr/Dep)	5 / 7	6 / 5	3 / 5	8 / 8
Aircraft Mix (RECAT)	B,D,E	B,D,E	B,D,E	B,D,E
Surface Wind [° ; kts]	060 ; 15	260 ; 05	050 ; 09	240 ; 04
Pilot Delay [s]	μ=22.3 σ=5.2	μ=22.3 σ=5.2	μ=22.3 σ=5.2	22.3
Type	Training	Training	Training	Measurement

To determine the order of the scenarios and have a balanced structure, a Latin square design was used for the experiment design matrix. This matrix is shown in Table A.3. Runs one up to and including three and five up to and including seven were the training runs, while runs four and eight were the measurement runs. Half of the participants started with the baseline (B) and ended with the TTST (T) enabled and vice versa for the other half.

A.2.6. Workflow

The general workflow followed during the experiment is shown in Figure A.2

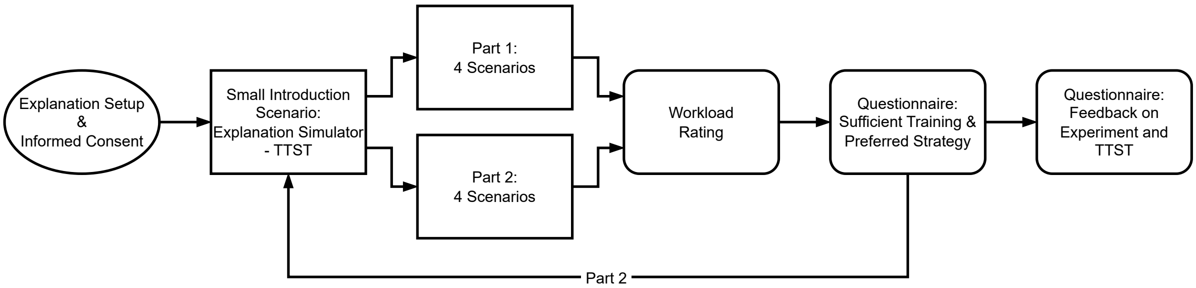


Figure A.2: Experiment Workflow

Table A.3: Experiment Design Matrix, with an indication for Baseline (B) and TTST (T). Runs 4 and 8 are the measurement runs, while the others are training runs.

Run **ID**	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**
27	B-S1	B-S2	B-S3	B-S4	T-S2	T-S3	T-S1	T-S4
45	B-S3	B-S1	B-S2	B-S4	T-S1	T-S2	T-S3	T-S4
68	B-S2	B-S3	B-S1	B-S4	T-S3	T-S1	T-S2	T-S4
13	T-S2	T-S3	T-S1	T-S4	B-S1	B-S2	B-S3	B-S4
89	T-S1	T-S2	T-S3	T-S4	B-S3	B-S1	B-S2	B-S4
56	T-S3	T-S1	T-S2	T-S4	B-S2	B-S3	B-S1	B-S4

A.2.7. Questionnaires

To gather feedback from the ATCos, questionnaires had been created. After every part (baseline and TTST), a small questionnaire was presented. This included two statements to be rated:

1. I was trained sufficiently and the system felt familiar.
2. I was able to handle the traffic in accordance with my preferred strategy.

Afterwards, a larger questionnaire was presented to gather general feedback from the participants. This included the following parts:

1. General
2. Realism
3. Take-off Timing Support Tool (TTST)
4. Comparison between the current way of working and the Take-off Timing Support Tool (TTST)
5. Future of tower control

B

Experiment Briefing

This appendix presents the steps and script followed during the experiment for every participant.

Experiment Briefing

Steps of the briefing:

1. Welcome and appreciation for participation
2. Explain set-up:
    - 8 Small scenarios, including a sheet with runway combination, weather and RECAT table
    - 4 without tool & 4 with tool (or vice versa)
    - Each version starts with small introductory scenario
    - Questionnaire after every version and after the experiment
3. Sign informed consent
4. Small introductory scenario:
    - Baseline <I-BL>:

        <Pause simulation>
        - *Explain* Strips similar to “real” strips

        <Play simulation>
        - *Show* Outbound flights controlled with flight status in strip: line-up & take-off
        - *Explain* Inbound flights will also land without clearance, only pilot initiated go-around (except for missing clearance)
        - *Show* Strips can be transferred with send icon and only with ROLL or ATD / LAND or ATA
    - Take-off Timing Support Tool <I-TTST>:

        <Pause simulation>
        - *Explain* Time-axis next to WORKING bay
        - *Explain* Time-axis is in real time (like ASAP)
        - *Explain* Strips (similar layout to “real” strips) placed on time-axis
        - *Show* Inbound strips snap to ETA and then fixed
        - *Show* Outbound strips first snap to TTOT/RETD
        - *Explain* Strips move down with time
        - *Explain* Outbound strips appear in PENDING when starting to taxi
        - *Show* Outbound strips can be dragged to desired take-off time
        - *Show* Outbound strips desired take-off time can be set by clicking on time-axis
        - *Explain* Outbound strips “now line” indicates start of roll
        - *Show* Dragging of time axis
        - *Show* Outbound strip conflicts visualisation when selecting/dragging strip: WTC, 1 minute diverging tracks, missed-approach and same (initial) SID
        - *Show* When dragging over conflicts highlight of conflicting strip with colours from Intelligent Approach
        - *Show* Difference between conflict ban and advice
        - *Show* White line indicating TTOT window

        <Play simulation>
        - *Show* Outbound flights controlled with flight status in strip: line-up & take-off
        - *Explain* No need for WTC timer
        - *Show* Timer
        - *Show* Automatic detection of ROLL/ATD/ATA

        - *Explain* Inbound flights will also land without clearance, only pilot initiated go-around (except for missing clearance)
        - *Show* Strips can be transferred with send icon and only with ROLL or ATD / LAND or ATA

5. Remarks for the simulation:
    - Simulation is 1.5x speed
    - No outside view, similar to bad visibility conditions but no additional requirements
    - EFSS toolbar has no functionality
    - ASDE/TAR has no delay
    - To adjust elements on TWR screen, move the mouse up
    - Arriving aircraft may be assumed landed when a significant speed reduction is observed and eventually when track vector disappears.
    - No conditional clearances
    - There are intersection starts
    - Take-off pilot delay on average is 22 seconds
6. Ask if there are any questions
7. Start run 1 <ID-R1> (Baseline or Take-off Timing Support Tool)
8. Questionnaire run 1
9. Small introductory scenario (see number 4.)
10. Ask if there are any questions
11. Start run 2 <ID-R2> (Take-off Timing Support Tool or Baseline)
12. Questionnaire run 2
13. Final questionnaire
14. End and thank

C

Scenario Briefing Template

The template for the scenario briefing is presented in this appendix. For every scenario, the runway combination, wind information and the RECAT table were provided. The sheets were ordered for every participant according to the experiment design matrix (Table A.3) presented in Appendix A.

Scenario Briefing

ID: <TEMPLATE>

Scenario 1

S1

Baancombinatie

RWS	06	/	09

Wind

06 060 15
09 060 15

RECAT-EU Tabel

Follower		Super Heavy	Upper Heavy	Lower Heavy	Upper Medium	Lower Medium	Light
Leader		A	B	C	D	E	F
Super Heavy	A		1:40	2:00	2:20	2:40	3:00
Upper Heavy	B			1:20	1:40	2:00	2:20
Lower Heavy	C				1:20	1:40	2:00
Upper Medium	D						2:00
Lower Medium	E						1:40
Light	F						1:20

Scenario 2

S2

Baancombinatie

RWS	18C	/	24

Wind

18C	260	05
24	260	05

RECAT-EU Tabel

Follower		Super Heavy	Upper Heavy	Lower Heavy	Upper Medium	Lower Medium	Light
Leader		A	B	C	D	E	F
Super Heavy	A		1:40	2:00	2:20	2:40	3:00
Upper Heavy	B			1:20	1:40	2:00	2:20
Lower Heavy	C				1:20	1:40	2:00
Upper Medium	D						2:00
Lower Medium	E						1:40
Light	F						1:20

Scenario 3

S3

Baancombinatie

RWS	06	/	09

Wind

06	050	09
09	050	09

RECAT-EU Tabel

	Follower	Super Heavy	Upper Heavy	Lower Heavy	Upper Medium	Lower Medium	Light
Leader		**A**	**B**	**C**	**D**	**E**	**F**
Super Heavy	A		1:40	2:00	2:20	2:40	3:00
Upper Heavy	B			1:20	1:40	2:00	2:20
Lower Heavy	C				1:20	1:40	2:00
Upper Medium	D						2:00
Lower Medium	E						1:40
Light	F						1:20

Scenario 4

S4

Baancombinatie

RWS	18C	/	24

Wind

```
18C     240  04
24      240  04
```

RECAT-EU Tabel

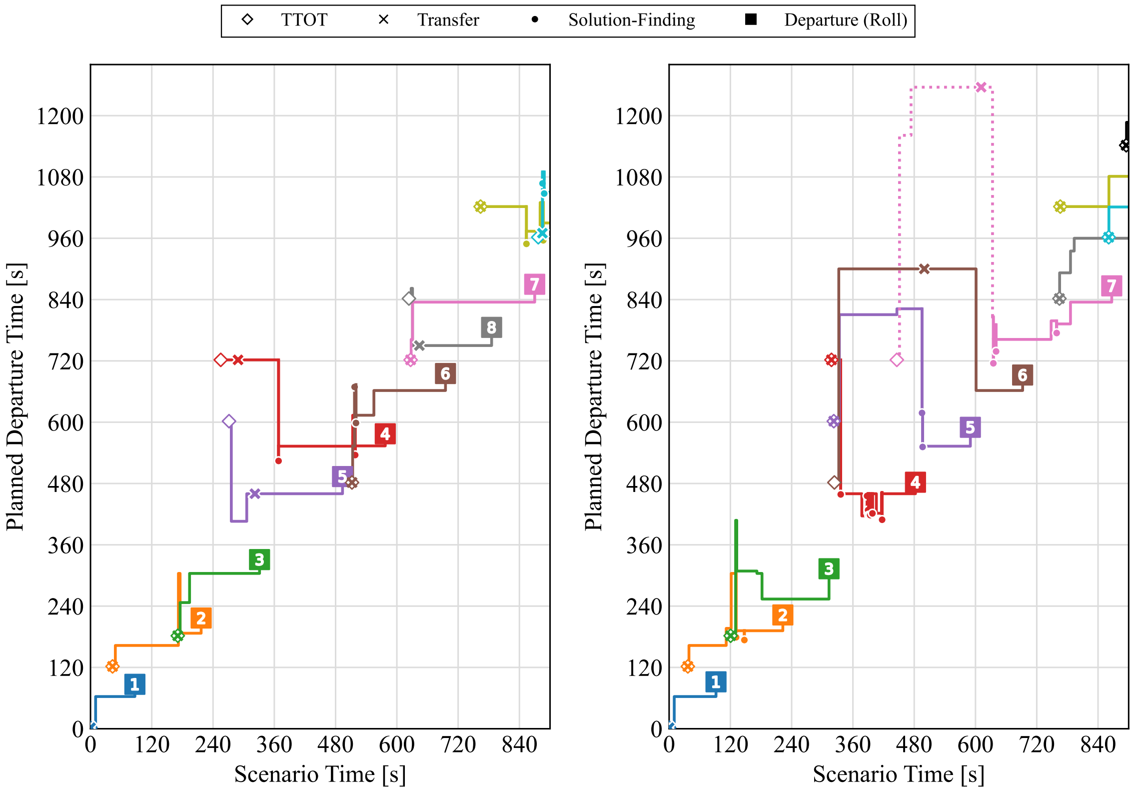
Follower		Super Heavy	Upper Heavy	Lower Heavy	Upper Medium	Lower Medium	Light
Leader		A	B	C	D	E	F
Super Heavy	A		1:40	2:00	2:20	2:40	3:00
Upper Heavy	B			1:20	1:40	2:00	2:20
Lower Heavy	C				1:20	1:40	2:00
Upper Medium	D						2:00
Lower Medium	E						1:40
Light	F						1:20

D

Departure Planning History Results

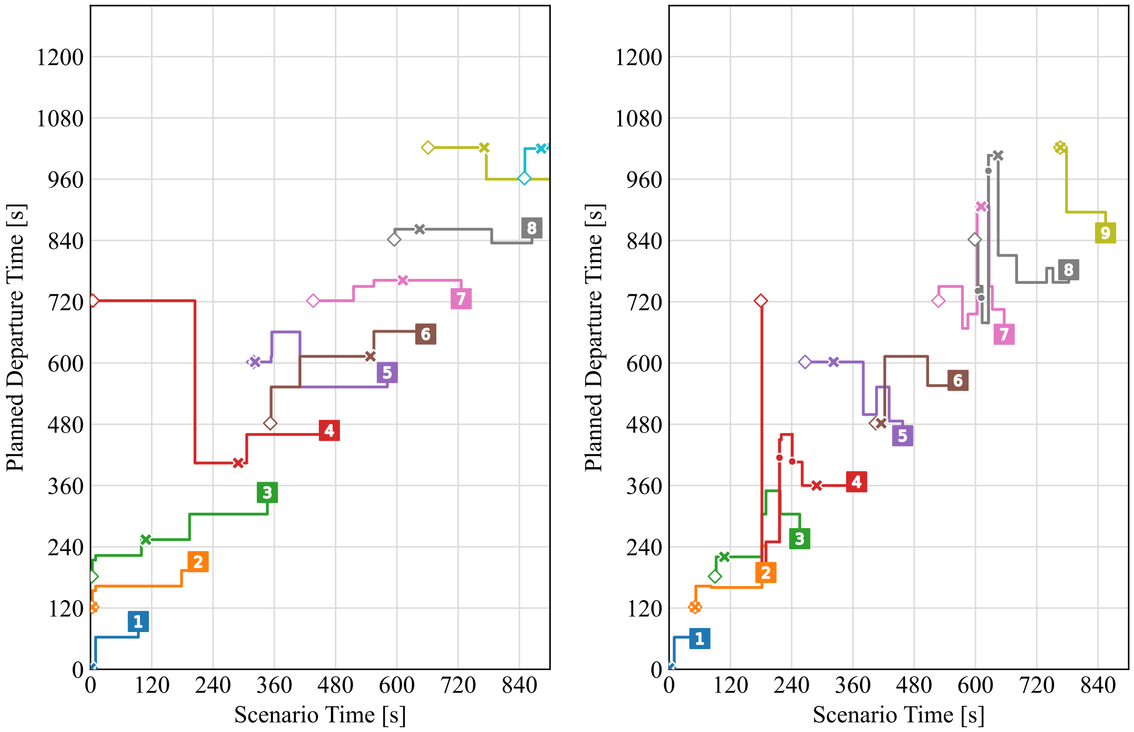
To assess the use of the TTST for planning departures, the planning history for every participant was determined. Figure D.1 shows the history of the planned departure time, as set by the participants. The planning starts when first dragged to the *working area*, which sets the time to the TTOT, and ends when the flight departs. Also included are the transfers by ground control and indications when 'solution finding' was applied. When the former happens before dragging the strip to the *working area*, the marker will coincide with the TTOT marker. A horizontal line means no changes made to the planned departure time. It can be seen that different planning strategies were applied. This ranged from applying many (last minute) changes (P2 and P4) to establishing a stable planning (P3 and P6).

A similar plot can be constructed for the original EFSS. Figure D.2 shows for every participant the vertical position of departing flight strips relative to the first appearance in the *pending area*, which corresponds to the transfer by ground control. It also displays the departure time and sending the strip (removing it from the EFSS). In general, it can be seen that strips are first dragged down to the *working area* (large vertical segment) and sometimes are moved down a bit further to make room for the strips above. Several participants mainly put the strips at the top of the *working area* (P1, P3 and P5), while others mainly put them at the bottom (P2, P4 and P6). It should be noted that the position in the *working area* itself does not have a specific meaning. However, just like with the TTST, the order (from bottom to top) of the strips represents the departure sequence.



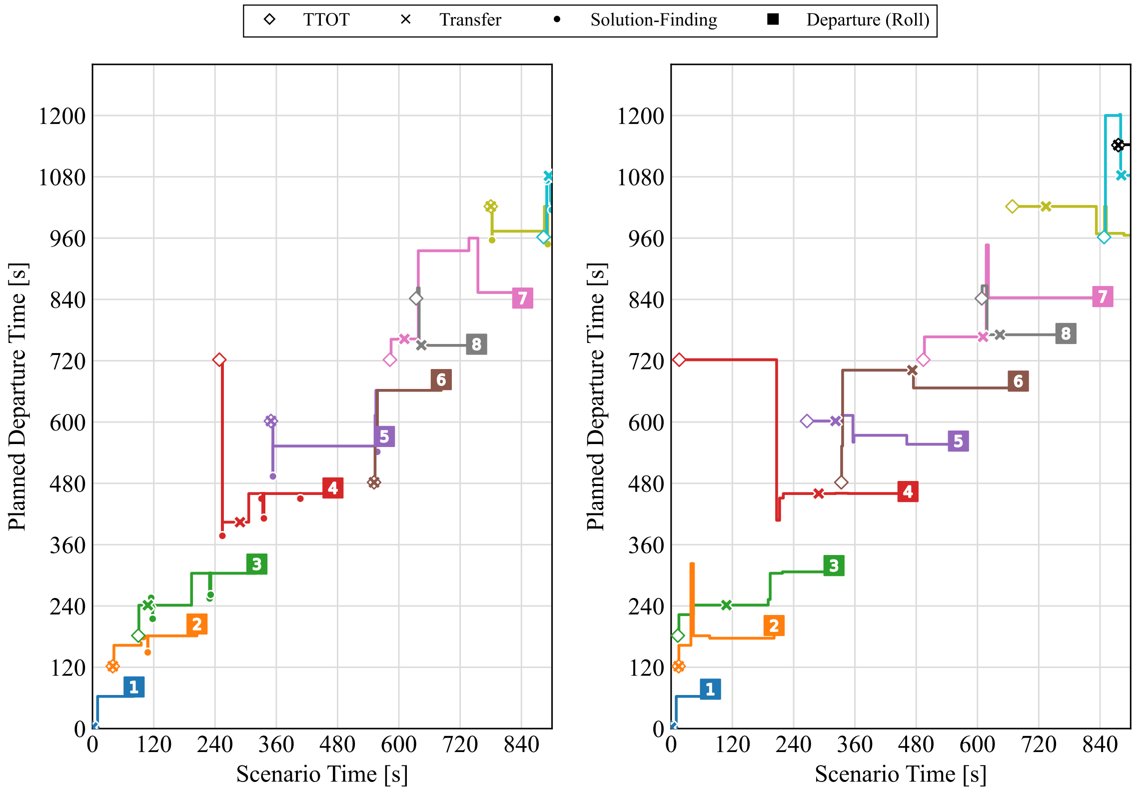
(1) Participant 1

(2) Participant 2



(3) Participant 3

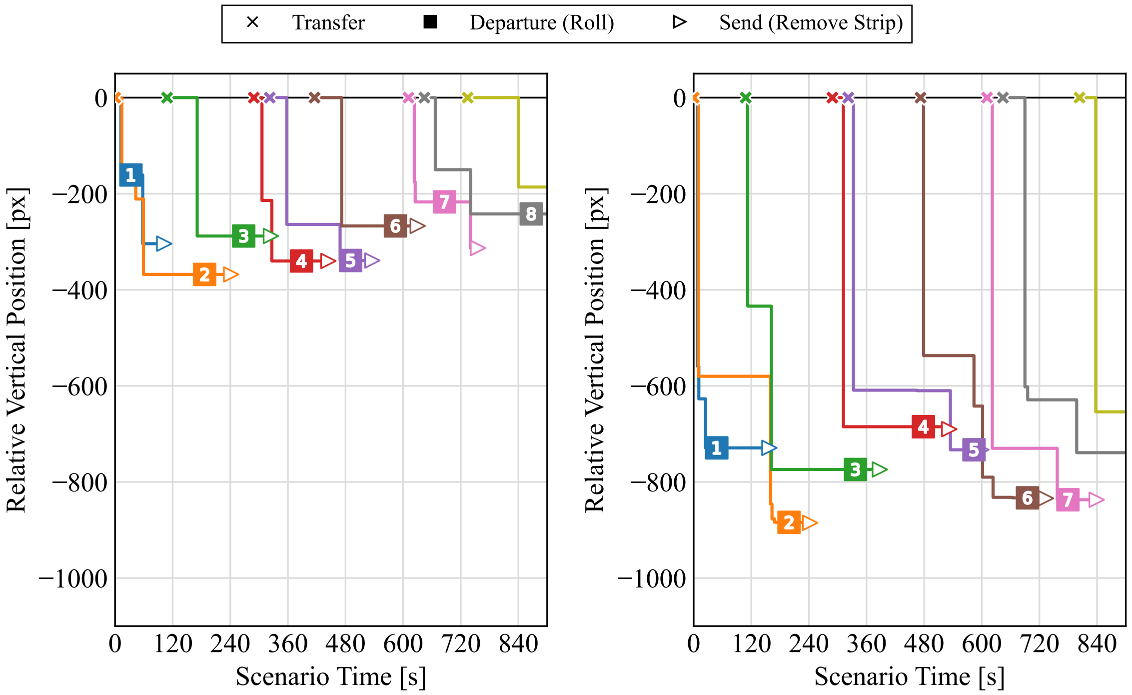
(4) Participant 4



(5) Participant 5

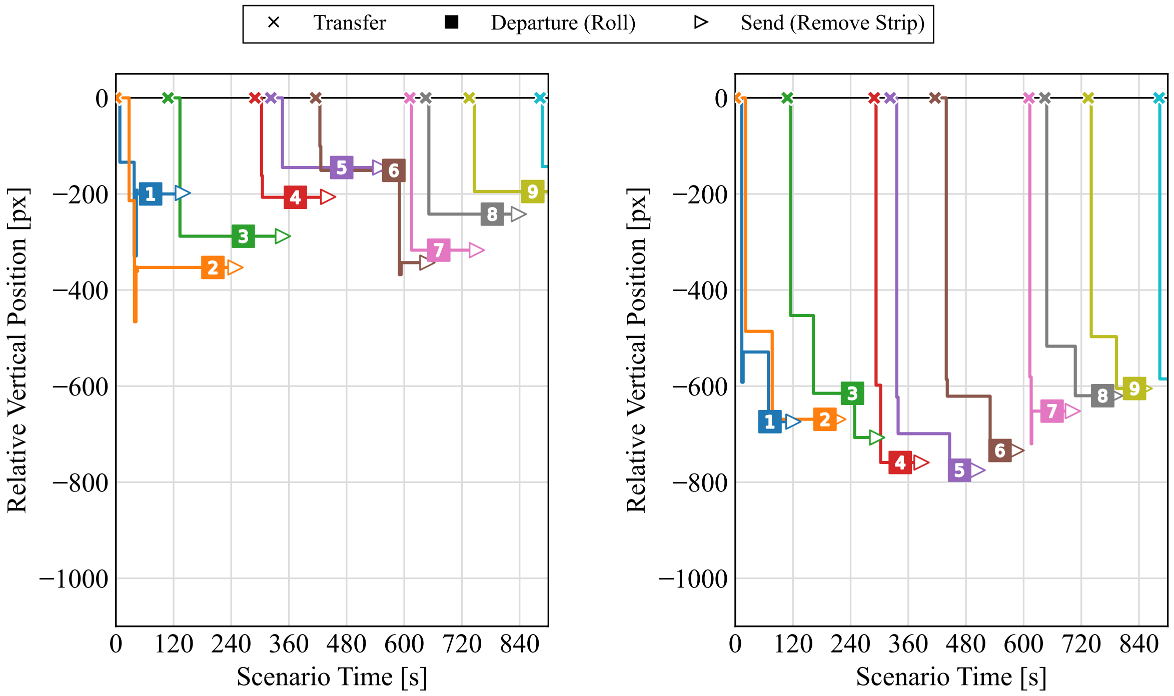
(6) Participant 6

Figure D.1: Departure planning history, starting when dragged to the *working area* (TTOT) and indications of transfer by ground control, solution finding (releasing within a conflict) and the start of the take-off roll. A dotted line means dragged back to the *pending area*.



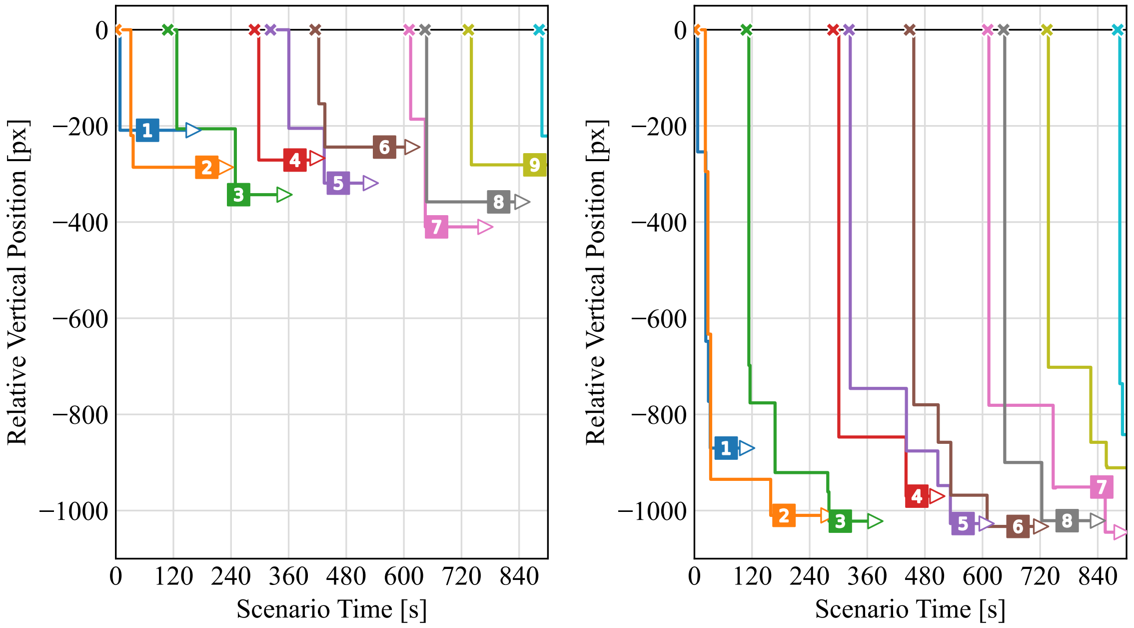
(1) Participant 1

(2) Participant 2



(3) Participant 3

(4) Participant 4



(5) Participant 5

(6) Participant 6

Figure D.2: Vertical strip position, relative to the first appearance in the *pending area* and including indications for transfer by ground control, departure and sending the strip (remove from the EFSS)

E

Questionnaires Results

This appendix presents the results of the three questionnaires. The small questionnaires after the baseline and TTST parts are presented in Sections E.1 and E.2, respectively. The results of the final questionnaire used to gather feedback, are presented in Section E.3. Please note that the remarks made by the participants are all in Dutch since all participants were from the LVNL (Dutch ANSP).

E.1. After Baseline

The results of the questionnaire after the baseline (Figure E.1) show that everyone was trained sufficiently and could apply the preferred strategy.

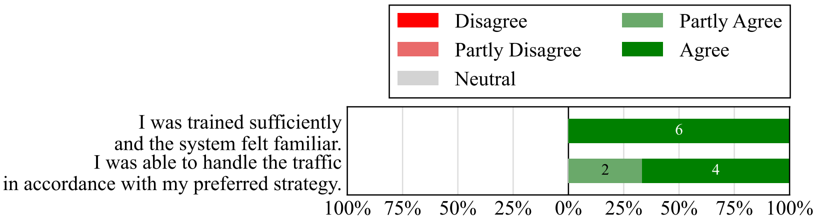


Figure E.1: Training and Strategy for the Baseline

Remarks corresponding to applying the strategy by the participants:

- ”Verplichte roll voor het wegzetten”
- ”Je kan niet ‘spelen’ met factoren als ready for a roling departure etc..”

E.2. After Take-off Timing Support Tool

Figure E.2 shows that in several cases the training was not sufficient enough, mainly because of the radical change in use and workflow with the EFSS as became clear from the remarks. This resulted also in sometimes not being able to apply the preferred strategy, due to the unfamiliarity with the system.

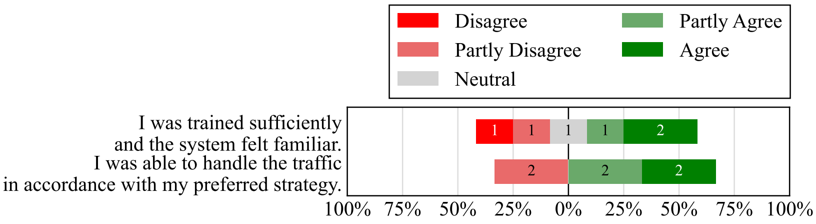


Figure E.2: Training and Strategy for the TTST

Remarks corresponding to the training by the participants:

- ”Betekenis kleuren. Het plaatsen van outbounds. Timer.”
- ”Vooral in het begin even bezig met het ondervinden van hoe conflicten worden gepresenteerd in EFS. Na een tijdje heb je door welk conflict op welke manier wordt aangegeven, welke je zelf zou kunnen ‘overrulen’ en hoe je het systeem op de juiste manier gebruikt.”
- ”Nieuwe systeemondersteuning en andere werking van systeem (eerst uco dan line up bijvoorbeeld). Hele nieuwe werkwijze en bijbehorende denkwijze, dus werkt nog niet echt lekker. Merk dat ik terug val op huidige werkwijze en niet echt bezig ben met de systeemadviezen.”
- ”Veel ‘head down’ werken. Controleren of de kleurcodes kloppen bij het gevoel dat ik had.”

Remarks corresponding to applying the strategy by the participants:

- ”Systeem geeft andere strategie aan met voorgestelde vertrektijd”
- ”Het verkeer wordt volgens de regels correct gerestrict, maar neemt een aantal punten uit de praktijk niet mee. Zo klimt een airbaltic met langzamere snelheid uit dan de klm ervoor, dus kan je eerder starten. Dit wordt initieel geblokkeerd door je strippen. Met twee seconden de strip op de juiste plek houden kan je binnen de 1.40 minuut starten, maar dit vergt wel een extra handeling waarbij je langer naar EFS kijkt en niet naar je verkeer buiten kan kijken. Verder is 1 minuut startseparatie met verschillende SID’s van 09 best lang.”
- ”Vaak kwam het idee van het systeem overeen met mijn eigen ideen. Echter door een andere werking is het mogelijk net even anders gegaan dan als ik deze situaties in het echt tegen kom. Daarbij komt dat ik ‘buiten’ bijna niks gezien heb en ontettend veel naar efs aan het kijken was.”

E.3. After Experiment

The questionnaire started with three general questions: the age, years of experience as RC and if the participant takes a possible go-around into account when issuing take-off clearances. The latter one was answered with ‘yes’ by all participants. The age and years of experience are presented in Table E.1.

Table E.1: Diversity of the Participants

Start Configuration	**Age**	**Years of Experience**
Baseline	$\mu = 31.7, \sigma = 4.8$	$\mu = 5.8, \sigma = 3.2$
TTST	$\mu = 31.0, \sigma = 2.9$	$\mu = 6.3, \sigma = 2.1$
Overall	$\mu = 31.3, \sigma = 4.0$	$\mu = 6.1, \sigma = 2.7$

Presented below are the answers to the other questions. After every figure, the remarks made by the participants corresponding to these answers are stated.

Realism

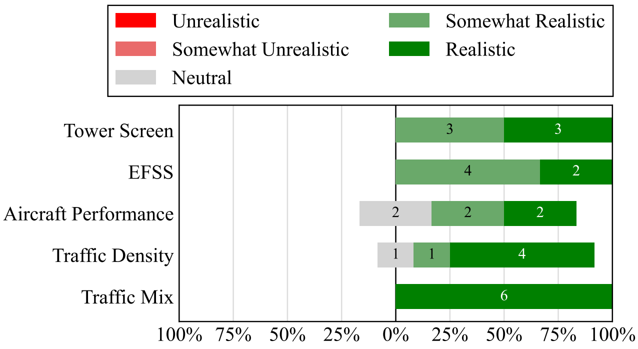


Figure E.3: How realistic was the simulator?

Remarks by the participants (Figure E.3):

- ”Dichtheid van het verkeersaanbod is in de praktijk natuurlijk ook wisselend. Het was nu gewoon verkeer wat lekker doorloopt, maar afhankelijk van het moment van de dag/week/omstandigheden kan natuurlijk alles. Over het torenscherm en EFSS geen onrealistische dingen gezien, alleen een aantal functies die niet zijn ingeschreven, vandaar enigszins realistisch.”

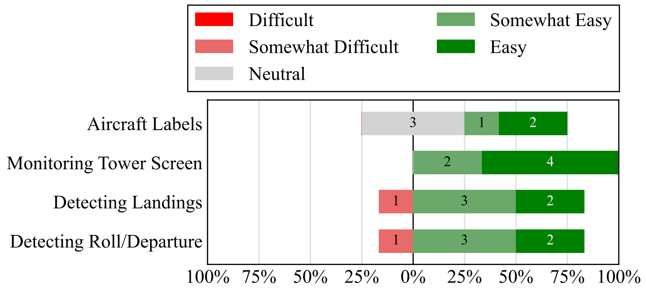


Figure E.4: How was the use of the simulator?

Remarks by the participants (Figure E.4):

- ”Het verplaatsen van labels in het scherm niet geprobeerd, vandaar neutraal ingevuld. Het detecteren van start de take-off roll is hier iets duidelijker te zien dan in de praktijk. Dan begint de take-off roll buiten en zie je na een korte vertraging langzaam ook het plotje in beweging komen, maar zeker het begin van de roll is in de praktijk wat moeilijker op het scherm te zien. Bij elke radar update zie je hem dan hele kleine, subtiele stukjes bewegen, waarbij het in de simulatie wat meer grof aanvoelt.”
- ”Landingen en vertrek kijk je in het echt naar buiten ipv op een scherm. Ook anticiperend vertrekklaring geven kan je doen door buiten vast te kijken hoe de landing gaat.”

Take-off Timing Support Tool (TTST)

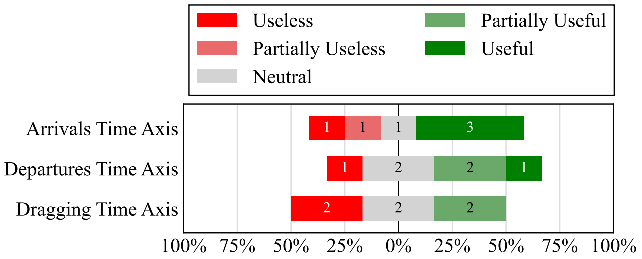


Figure E.5: How useful was the time axis?

Remarks by the participants (Figure E.5):

- ”Meeste tijd besteed ik door naar buiten te kijken of in dit geval naar ASDE en TAR plaatje te kijken”
- ”Tijd-as bij inbounds is echt super handig. Je hoeft dan niet meer te checken in welke volgorde de inbounds komen, wat op een dag bij elkaar opgeteld best wat tijd kan schelen. Tijd-as bij outbounds is na wat gewenning erg handig. Je ziet duidelijk welke conflicten er zijn door de verschillende kleuren en met het langzaam naar beneden schuiven van de strippen weet je precies wanneer je kan starten. Even wennen, maar na een half uurtje al top. Verslepen van de tijd-as is handig, maar niet cruciaal. Heel verder onder de 0-tijd kom je toch niet, dus vermoedelijk zet iedereen die toch op ongeveer dezelfde plek.”

- ”Inbound verdwijnen er vluchten als je ze naar beneden sleept. Als je op deze manier wil werken moet je naar mijn mening alleen vluchten laten zien welke binnen 4? minuten gaan landen. het naar benenden slepen heeft geen toegevoegde waarde naar mijn mening. Daarnaast vond ik het vervelend werken dat vluchten dus aan de boven of onderkant verdwijnen.”
- ”Geef handig weer wanneer de inbounds komen.”
- ”De specifieke minuten waren niet zo interessant vond ik, maar het verloop wel. Dat een kist op minuut 13 landt, maakt niet zoveel uit, maar dat die over 83 seconden op de grond staat is wel juist nuttige info.”

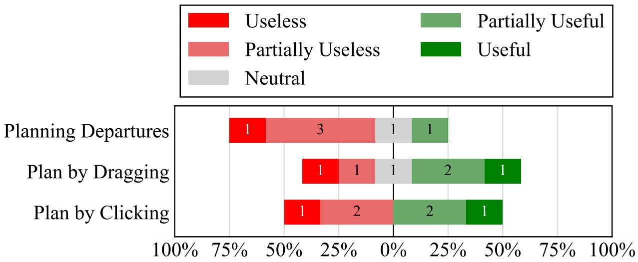


Figure E.6: How useful was planning of the departures?

Remarks by the participants (Figure E.6):

- ”De enige keer dat ik tijd gebruik bij outbounds, is bij Wake Turbulence timen”
- ”Het vooruit plannen van de vertrektijd op basis van de TTOT heeft niet mijn voorkeur. Strippen komen dan op volgorde te liggen van hoe de outbound planner ze inplant en niet op basis van hoe de ground controller ze overzet. In de praktijk geven zij eigenlijk altijd eerst de strip die volgens hen als eerste start, en daarna de tweede. Wanneer je de strippen dan bovenin de working area sleept komen ze weer op TTOT tijd te liggen en kan de volgorde dus veranderen. Zeker met slechte TTOT stelling tijdens sommige momenten van sommige OPL’ers (dit probleem is helaas moeilijk op te lossen) kan dit verwarrend werken. Wanneer je echter de strippen zelf in de juiste volgorde legt op ongeveer de juiste tijd komt het allemaal goed en werkt het systeem uitstekend mee.”
- ”Ik wil op de toren eigenlijk alleen outbounds krijgen welke klaar zijn voor vertrek. in principe krijg ik van ground al een goede sequence. Soms vragen ze nog of er 1 voor moet. Er zijn zoveel variabelen onderweg naar de baan, dat het ook niet nuttig is outbounds eerder dan dat je ze van ground krijgt al te laten zien.”
- ”Vooral bij WTC conflicten handig”
- ”Ik kijk toch vooral naar hoe het verkeer zich ontwikkelt, dwz buiten kijken hoe het gaat en daar de planning op aanpassen. Ver vooruit werken met outbounds heeft niet altijd zo veel zin.”

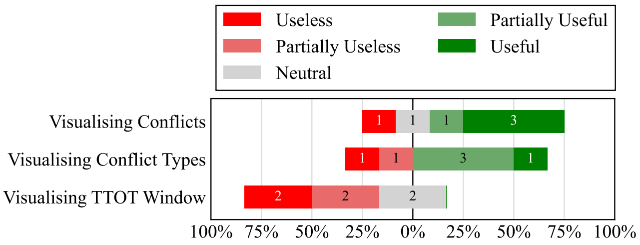


Figure E.7: How useful was the visualisation of conflicts?

Remarks by the participants (Figure E.7):

- ”Visualisatie projecteer ik op wat ik buiten zie of in dit geval op ASDE en TAR plaatje in mijn hoofd”

- ”Uiteraard vraagt de visualisatie van de verschillende conflict types met korte werktijd nu soms nog even een dubbel check, omdat je in de tijds-as soms verschillende restricties en kleuren ziet. Na wat gewenning al een stuk makkelijker natuurlijk. De visualisatie van het TTOT window is aan de voorkant heel goed te zien door de aflopende timer. Je ziet heel duidelijk dat je over bijvoorbeeld 5 seconden mag. Wat misschien nog een toevoeging zou zijn is een iets duidelijkere visualisatie van het einde van de TTOT-window. Een voorbeeld: Een kist zit op 5,5 NM final 18C wanneer een DAL A333 start van baan 24 op een BER departure. Na deze start staat een TRA klaar voor een KDD departure baan 24. Er is nu duidelijk dat wanneer de DAL gaat rollen er na 1.40 minuut gestart mag worden vanwege de wake turbulence. Op het moment dat de 1.40 voorbij is, zit de inbound dus op 1,5 NM final 18C. Je kan dan nog starten, maar uit de visualisatie is niet heel makkelijk in één oogopslag te zien hoelang nog. Op een gegeven moment schuift de TRA strip natuurlijk naar een tijdsslot na de landing van de inbound.”
- ”Prima om conflicten te laten zien, echter denk ik door de meerdere opties dat dit er voor zorgt dat je alleen nog maar naar je efs scherm kijkt ipv naar de daadwerkelijke vlegtuigen. Zelf zie ik meer bijvoorbeeld een automische timer tussen outbounds in je efs baai en dan ergens anders mogelijk nog ondersteuning voor je in- en outbound conflict.”
- ”Vooral WTC handig”
- ”Ik vond het interessant om te zien wat de bepaalde conflicten waren. Het TTOT-window is daarentegen voor TWR nutteloos. Nu heb je de info ook niet namelijk.”

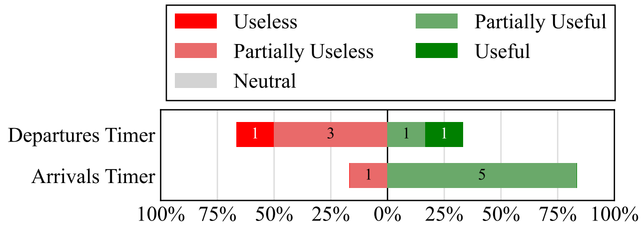


Figure E.8: How useful were the timers?

Remarks by the participants (Figure E.8):

- ”Voor Wake Turbulence is een timer nodig om outbounds te timen”
- ”Zoals eerder benoemd inbound perfect. Outbound dus nog wat tweeken mogelijk met langzamere uitklimmers. Verder is 2 vliegtuigen op dezelfde SID 1.40 soms net wat lang. Als de voorste naar 250 KTS gaat vliegt hij meer dan 4 NM per minuut, dus heb je na 1.15 minuut al de 5NM seperatie. Ik aim dezelfde SID’s meestal op 1.25/1.30 minuut na elkaar.”
- ”Niet relevant, komen zoals ze komen.”
- ”Te veel klokken in beeld zorgt voor teveel met je hoofd naar beneden werken. In het echt moet je de landing of go around toch in de eerste plaats buiten waarnemen.”

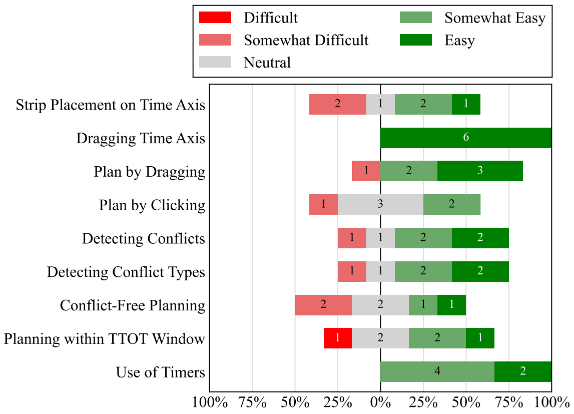


Figure E.9: How was the use of the TTST?

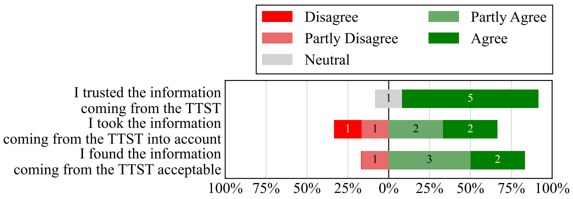


Figure E.10: Rate the following statements.

Remarks by the participants (Figures E.9 and E.10):

- ”Als je ergens binnen een bepaalde separatie wil starten (bijvoorbeeld binnen de 1.40 minuut op dezelfde SID) moet je iets langer vasthouden, wat extra aandacht vraagt. Wat mij betreft wel acceptabel omdat dit voorkomt dat je strippen binnen timers legt.”
- ”Niet relevant, komen zoals ze komen.”
- ”TTST zat voor mijn gevoel bij het waarnemen van landingen aan de (extreem) veilige kant. Daar ben ik dus wel licht vanaf geweken.”

Comparison between the current way of working and the Take-off Timing Support Tool (TTST)

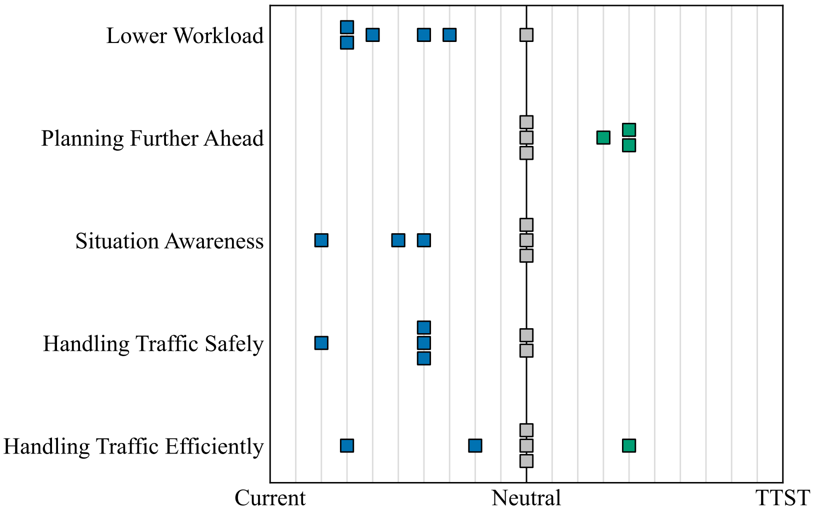


Figure E.11: Compare the current way of working with the TTST.

Remarks corresponding to the lower workload (Figure E.11):

- ”TTST paste mijn ‘kladblaadje’ ongevraagd aan”
- ”Moeilijk te vergelijken nu. Door relatieve onbekendheid met het systeem ben je iets meer met EFSS bezig dan normaal. De verkeersdrukte was niet dusdanig dat met of zonder TTST werken echt invloed heeft op afhandeling.”
- ”vertrouwd, duidelijk. TTST was nog veel zoeken. Heel veel informatie beschikbaar, daardoor niet altijd even duidelijk waarom er iets gaande was naar mijn mening.”
- ”Meer ervaring met huidige systeem. Veel bezig met checken wat de verschillende kleurcodes betekenen ipv alleen met het monitoren van vliegtuigbewegingen.”
- ”Vooral het bekend zijn met de huidige werkwijze. Op TWR kijk je zoveel mogelijk naar buiten en wil je over het algemeen zo min mogelijk bezig zijn met systemen.”
- ”TTST brengt nog veel nieuwe info met zich mee, waardoor je meer in EFSS gefocust bent dan ‘buiten’”

Remarks corresponding to planning further ahead (Figure E.11):

- ”De inbounds liggen direct beter gepland en geven de gaten beter weer waarin je kan starten. De outbounds kan je hiermee ook veel verder vooruit plannen. Nu kijk je vanaf 8NM final en dichterbij hoe de gaten zich ontwikkelen, de tool laat dit al wat eerder zien.”
- ”Verder vooruit plannen is niet nodig op de toren. We hebben het er nog over gehad om bijvoorbeeld alleen inbounds te laten zien die binnen 4 minuten landen, en outbound alleen wat door ground is over gezet.”
- ”Inbounds worden direct in correcte volgorde gelegd door het systeem. Dat scheelt veel handelingen.”
- ”Door de tijdlijn van TTST heb je snel een inzicht wanneer je waarschijnlijk kan gaan starten.”

Remarks corresponding to the situation awareness (Figure E.11):

- ”Werklast niet dusdanig dat dit veel impact heeft.”
- ”Vertrouwde werkwijze en systeemondersteuning.”
- ”Awareness was bij beide prima. Door meer ervaring met het huidige systeem, voelde dat meer in control.”
- ”Het heeft denk ik vooral te maken met het hanteren van een werkwijze die je gewend bent. Kost weinig denkwerk.”
- ”Komt vooral door de nieuwigheid en dat je daardoor in je scherm gezogen wordt.”

Remarks corresponding to handling traffic safely (Figure E.11):

- ”TTST leidde vaak af en zorgde voor meer head-down tijd”
- ”Werklast niet dusdanig dat dit veel impact heeft.”
- ”Vertrouwde werkwijze en systeemondersteuning.”
- ”Te veel leunen en getriggered worden om te starten vanwege de timers, zou kunnen zorgen voor ongewenst gedrag.”
- ”Ik zou zeggen even veilig, ook met de tool probeer ik me goed bewust te zijn van wat ik aan het doen ben en niet blind op de tool vertrouwen.”
- ”Komt vooral door de nieuwigheid en dat je daardoor in je scherm gezogen wordt.”

Remarks corresponding to handling traffic efficiently (Figure E.11):

- ”Bij de outbound strippen moest ik heel goed opletten wanneer de outbound strip veranderde van GND1 naar UCO. Geen duidelijke visuele trigger wanneer je de kist op je ”frequentie” zou moeten hebben. Daarbij vaker het stripbord bij outbounds moeten opruimen of aanpassen.”
- ”Verkeer kan nu nog beter op de seconde nauwkeurig worden afgehandeld door automatische detectie van de roll, wat een positief effect heeft op de capaciteit.”
- ”Teveel bezig bij ttst met nieuwe systeemondersteuning ipv met de situatie”
- ”In beide situaties kan verkeer efficient worden afgehandeld.”

Future of tower control

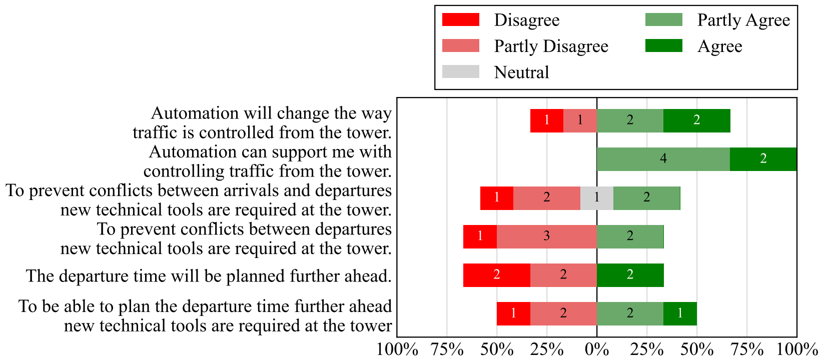


Figure E.12: Rate the following statements.

Remarks by the participants (Figure E.12):

- ”Ik denk dat veel torenverkeersleiders de startcapaciteit redelijk maximaliseren, dus daar zit niet per se de winst. In veiligheid qua startseparatie niet direct door de timers, maar wel door de tool waarbij mensen de ingeprogrameerde SID zien. Verder is technische ondersteuning en automatisering natuurlijk de toekomst. Leuke tool!”
- ”De planning van outbounds is van diverse factoren afhankelijk. Mix van vertrekroutes, types, de manier waarop inbound verkeer op de afhankelijke baan binnnenkomt en zaken als vliegers die nog een checklist moeten doen of wachten op het cabinepersoneel. Kortom, naar mijn mening te veel variabelen om een betrouwbare planning ver vooruit te maken. Het inzichtelijk maken van de specifieke conflicten kan wel van meerwaarde zijn tov de huidige werkwijze.”

General remarks by the participants:

- ”Een strippenbord is mijn kladblok. Een abstracte weergave van mijn mentale beeld. Het TTST past dit ongevraagd aan. Ik zie interessante toepassingen die het werk van de VKL zouden kunnen helpen en ondersteunen, maar niet voor EFS.”
- ”Leuk om deze ontikkeling te testen. Naar mijn mening zijn delen zekker bruikbaar om ons werk makkelijker te maken.”

F

Code Structure

The *SectorX* ATC simulator, features the possibility to add separate viewports, which can be placed inside a grid of viewports in a frame, or a separate frame. The EFSS, together with the TTST, has been implemented as such a viewport. Figure F.1 presents the global code structure of this element. It contains three main elements: the bay area including the bays, the toolbar and the flight strips. For the bay area and the flight strips, several options have been included, where in general these correspond to the 'classic' EFSS and the TTST.

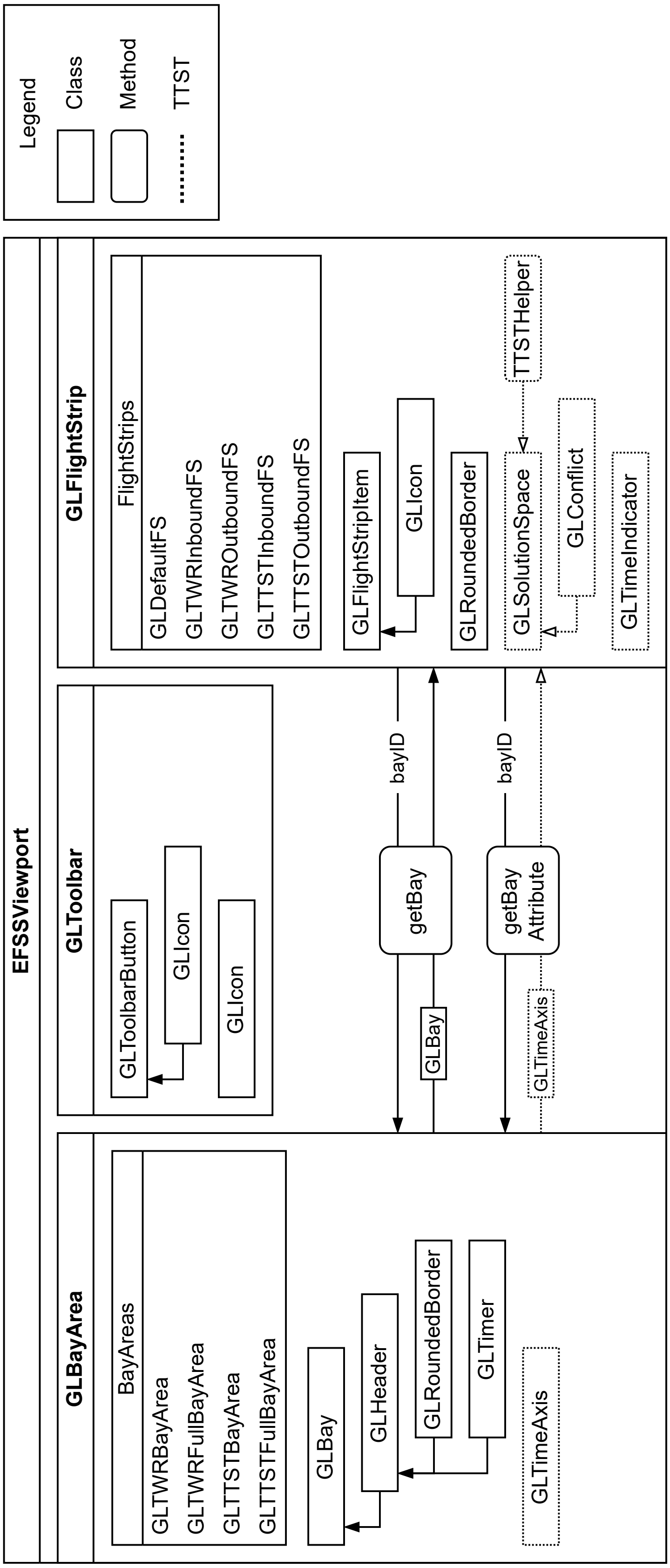


Figure F.1: SectorX Electronic Flight Strip System Code Structure

IV

Preliminary Thesis Report Appendices*

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*Has been graded as part of the preliminary thesis report under AE4020 - Literature Study

A

Collaborative Decision Making Time Parameters

Table A.1: Collaborative Decision Making Time Parameters (Duivenvoorde et al., 2019; EUROCONTROL Airport CDM Team, 2017; LVNL ATMP, 2017b)

Time Variable	**Abbreviation Definition**	**Issued by**	**Based on**	**Window [min]**
ELDT	Estimated Landing Time	ATC/Aircraft Operator/Ground Handling		-
	Definition	Estimated time the aircraft will land		
ALDT	Actual Landing Time	A-CDM System		-
	Definition	The time the aircraft has actually landed		
EIBT	Estimated In-Block Time	A-CDM System		-
	Definition	Estimated time the aircraft will arrive at the gate		
AIBT	Actual In-Block Time	A-CDM System		-
	Definition	The time the aircraft has actually arrived at the gate		
MTT	Minimum Turnaround Time	Ground handling		-
	Definition	Minimum time to turn around the aircraft		
SOBT	Scheduled Off-Block Time	Airport Slot Coordinator		-
	Definition	Slot provided by the Airport Slot Coordinator		
EOBT	Estimated Off-Block Time	Aircraft Operator	Flight Plan	-
	Definition	Expected time the aircraft departs from the gate		

EXOT	Estimated Taxi-Out Time		Taxi Times Table	-
	Definition	Expected taxi time to the runway		
ETOT	Estimated Take-Off Time		EOBT, EXOT	-15, +15
	Definition	Estimated time non-regulated aircraft is going to take-off		
TOBT	Target Off-Block Time	Main Ground Handler Agent		-
	Definition	Estimated time the ground handling is finished, doors are closed and boarding bridge and other equipment is removed.		
TTOT	Target Take-Off Time	TWR System	TOBT, EXOT	-
	Definition	Target time for aircraft to take-off		
TSAT	Target Start-up Approval Time	TWR System	TTOT, EXOT	-5, +5
	Definition	Expected time the aircraft can get a start-up clearance		
CTOT	Calculated Take-Off Time	EUROCONTROL NM	TTOT	-5, +10
	Definition	Slot of aircraft subjected to ATFCM regulations		
RETD	Revised Estimated Time of Departure	OPL	TSAT, EXOT	-5, +5
	Definition	TTOT set in the TWR system		
ASRT	Actual Start-up Request Time	A-CDM System		-
	Definition	Actual time of start-up request by the pilot		
AOBT	Actual Off-Block Time	A-CDM System		-
	Definition	Actual time the aircraft has departed from the gate		
ETD	Estimated Time of Departure			-
	Definition	Estimated time of the departure of the aircraft		
ATD	Actual Time of Departure	TWR system		-
	Definition	Actual time of departure of the aircraft		

B

Schiphol Map

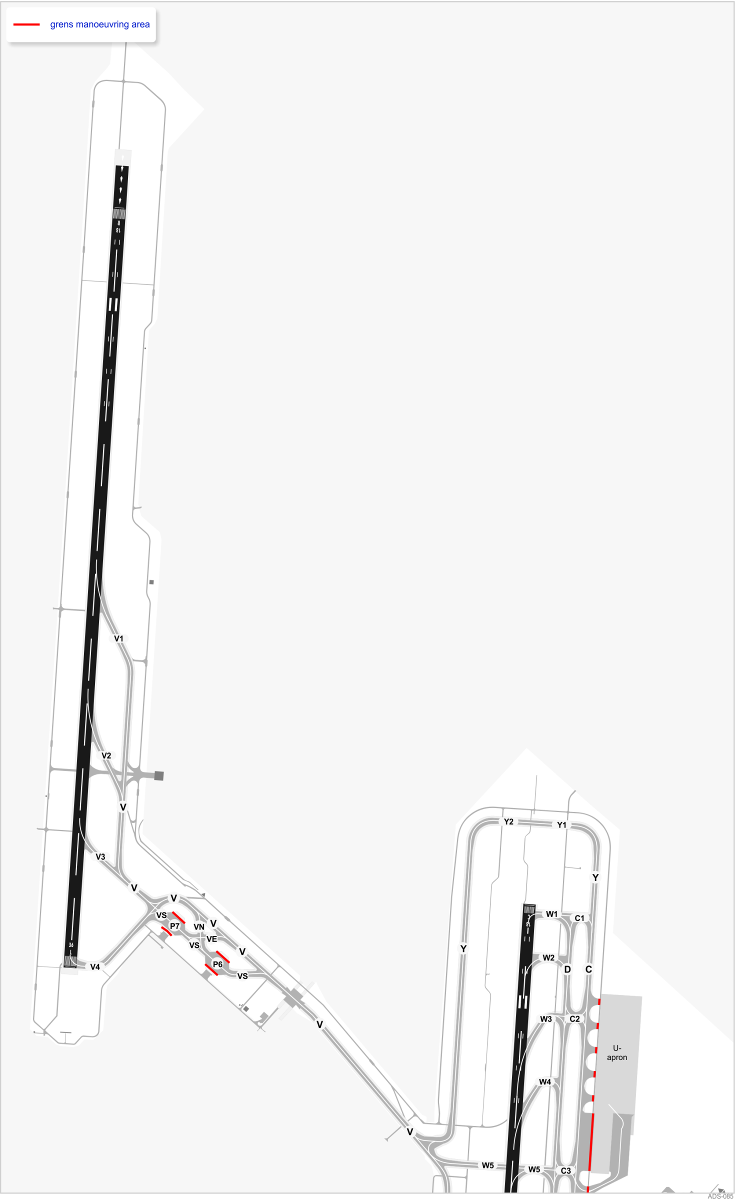

Figure B.1: Map of Schiphol West (LVNL ATMP, 2017b)

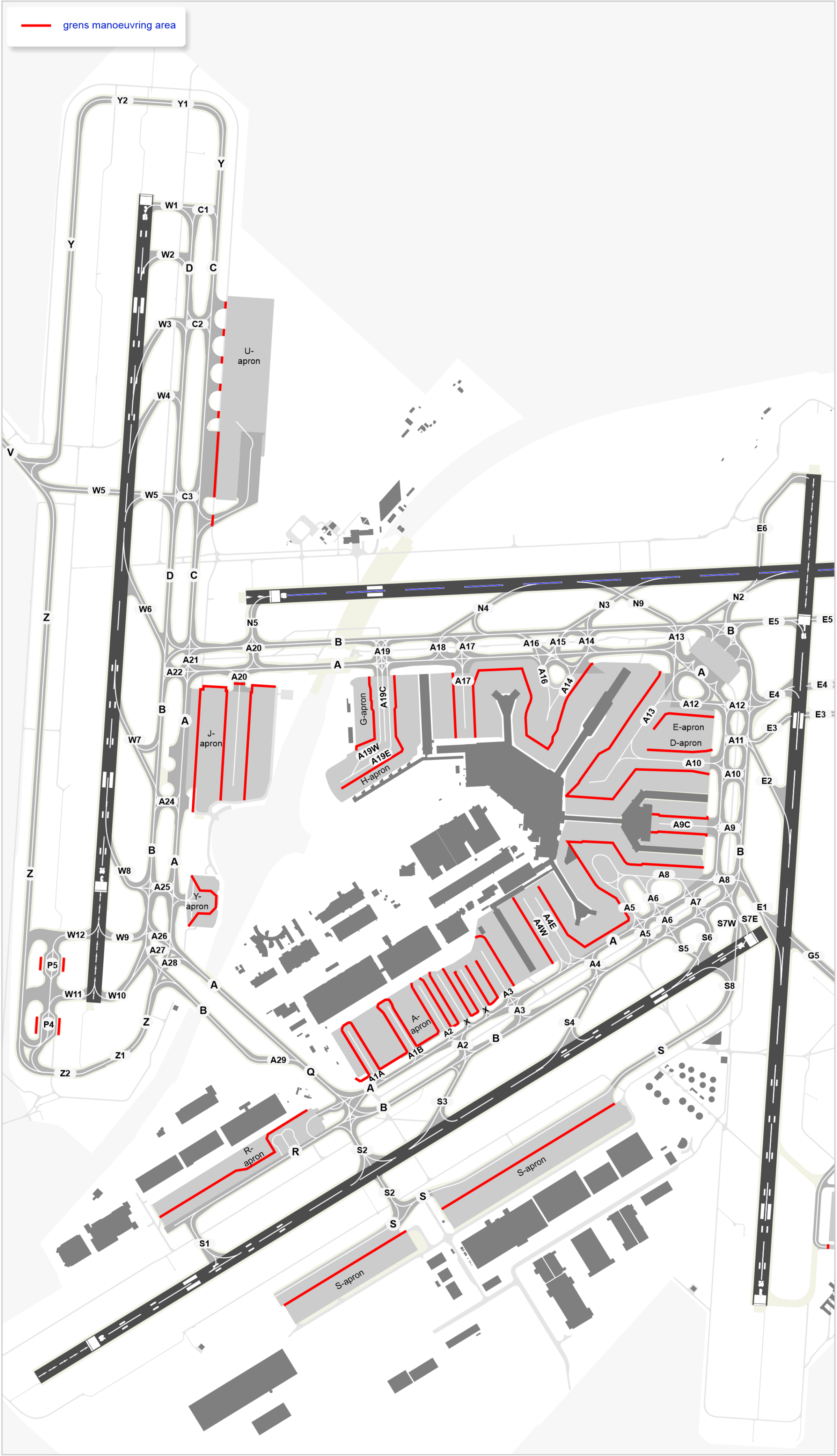

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Figure B.2: Map of Schiphol Centre (LVNL ATMP, 2017b)

Figure B.3: Map of Schiphol East (LVNL ATMP, 2017b)