MSc Thesis

Investigating the effect on ATFM delays of changing the T-DPI-s horizon for regulated flights

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Delft University of Technology

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by

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Preface and acknowledgements

The following report is the culmination of the many years I spent in Delft studying Aerospace Engineering. In it are a preliminary report and a scientific article regarding the research I did for my MSc thesis, which investigates a possibility of reducing delays at Schiphol airport.

I would like to thank my supervisors during this project: Jacco Hoekstra, Joost Ellerbroek and Ferdinand Dijkstra for the continued support in the project and all the insightful discussions we had over the course of it. The three of you, together with Evert Westerveld, are the reason I stuck around in the field over the last few years; I plan on staying in it for at least a bit longer.

My heartfelt gratitude goes out to the VSV 'Leonardo da Vinci' for all the opportunities and amazing people I got to work with over the years. I would also like to thank my former colleagues at Aerospace Engineering.

To all my friends and family: thank you for the continued support! I could not have reached this point without you. Special thanks go out to the Caldera for all the experiences over the years. I would like to thank Ted for the one-sided discussions and not changing my code too often. It is a pity my father couldn't be there to witness my graduation, but I'm very happy that my mother and brother are here, and I would like to thank them for all the support over the years. Finally, my partner Manouschka; thank you for putting up with me over the course of this project. I can imagine it wasn't always easy, but words can't describe how happy I am to have you around.

Jan Post
Amsterdam, October 2023

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
AAS	Amsterdam Airport Schiphol
A-CDM	Airport Collaborative Decision Making
A-DPI	Actual Departure Planning Information
AGHT	Actual Ground Handling Time
AIBT	Actual In-Block Time
AIR	Airborne (status in CDM)
AIRAC	Aeronautical Information Regulation And Control
ALDT	Actual Landing Time
ANSP	Air Navigation Services Provider
AO	Aircraft Operators
AOBT	Actual Off-Block Time
API	Application Programming Interface
ARC	Archival System at NMOC
ARDT	Actual Ready Time
ASAT	Actual Startup time
ASRT	Actual Start Up Request Time
ATC	Air Traffic Control
ATFCM	Air Traffic Flow and Capacity Management
ATFM	Air Traffic Flow Management
ATOT	Actual Take-Off Time
ATS	Air Traffic Service
BRD	Boarding (status in CDM)
CASA	Computer Assisted Slot Allocation
CDM	Collaborative Decision Making
CFMU	Central Flow Management Unit
COBT	Calculated Offblock Time
COVID	Coronavirus Disease
CSAT	Calculated Startup Time
CTO	Calculated Time Over
CTOT	Calculated Takeoff Time
CTOT*	Calculated Takeoff Time from model
DDR	(EUROCONTROL) Demand Data Repository
DPI	Departure Planning Information
E-DPI	Expected Departure Planning Information
ECAC	European Civil Aviation Council
EIBT	Estimated In-Block Time
EHAM	ICAO code for Schiphol Airport
ELDT	Estimated Landing Time
ENV	Environmental Database at NMOC
EOBT	Expected Off-Block Time
ETO	Estimated Time Over
ETOT	Expected Takeoff Time
EXIT	Estimated Taxi-In Time
EXOT	Estimated Taxi-Out Time
FC-FS	First Come, First Served

Abbreviation	Definition
FIR	Flight Information Region
FMP	Flow Management Position
FPL	Flight Plan
GH	Ground Handler
GUI	Graphical User Interface
IFPS	Initial Flight Plan Processing System
KDC	Knowledge and Development Centre Mainport Schiphol
KLM	Koninklijke Luchtvaart Maatschappij / Royal Dutch Airlines
KNMI	Koninklijk Nederlands Meteorologisch Instituut / Royal Netherlands Meteorological Institute
LVNL	Luchtverkeersleiding Nederland / Air Traffic Control The Netherlands
MGH	Main Ground Handler
MTTT	Minimum Turn-round Time
NEST	Network Strategic Tool
NM	Network Manager
NMOC	Network Manager Operations Center
PB	Push Back
RDY	Ready (status in CDM)
RSG	Royal Schiphol Group
SAOC	Schiphol Airline Operators Committee
SIP	Slot Improvement Proposal
TACT	Tactical System at NMOC
TAX	Taxiing (status in CDM)
T-DPI	Target Departure Planning Information
T-DPI-s	Target-DPI-Sequenced
T-DPI-t	Target-DPI-Target
TMA	Terminal Manoeuvring Area
TOBT	Target Offblock Time
TSAT	Calculated Startup Time
TTOT	Target Take Off Time
US	United States

Part I

Scientific Paper

Investigating the effect on ATFM delays of changing the T-DPI-s horizon for regulated flights

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Abstract

As aviation recovers to pre-pandemic levels large amounts of Air Traffic Flow Management delay also return, as the traffic at airports and in airspaces reaches their old levels. These delays have a yearly cost of around 500 million euros in the European Civil Aviation Conference area and are detrimental to the experience of passengers. This paper proposes a change in the interaction between the A-CDM process at Schiphol and EUROCONTROL's Network Manager, varying at what point the slot improvement process for regulated flights is stopped; providing more transparency in the network with this change. The resulting change in ATFM delay is investigated by modelling these two systems and freezing the slots at a set time, using historical input data to accurately model the turnaround process. The results generated using the described methods are inconclusive. More data and an additional implementation of using the CTOTs calculated by the model in the simulated turnaround are needed in order to make statistically sound conclusions on whether changing the T-DPI-s horizon has any effect. Nevertheless, this paper still presents insights and a novel framework for continued research into the subject.

1 Introduction

Amsterdam Airport Schiphol is one of the airports with the highest Air Traffic Flow Management (ATFM) delays, both cumulative and per flight. ATFM delays are handed out by the European Organisation for the Safety of Air Navigation (EUROCONTROL) at the request of Air Navigation Service Providers (ANSPs) when an airspace is projected to go over capacity. If an airspace is over capacity the safety cannot be guaranteed, and a hard limit is put on the capacity of the airspace based on the amount of traffic that can safely be coordinated within it. Because of environmental reasons, these delays are applied on the ground, before departure, instead of holding aircraft while airborne where possible. These ground delays are made possible by sequencing and issuing take-off slots to flights still on the ground. If a flight follows this slot, no airspace is projected to go over capacity. The delay between the estimated take-off time calculated from the filed flight plan and the time in the slot is defined as ATFM delay. In Europe these slots are issued by EUROCONTROL; different parts of the world have different ways of handling Air Traffic Flow Management, commonly adhering to ICAO DOC 9971 [1]. For an airport, both arrival and pre-departure ATFM delay are tracked as a performance indicator; arrival ATFM delay indicates an actual capacity lower than what is assumed during planning leading to holding (for example due to weather), and pre-departure ATFM delay results in perceived delays for travelers [2][1]. As the amount of flights in the European Civil Aviation Conference area and traffic to and from Amsterdam Airport Schiphol are approaching pre-pandemic levels the amount of ATFM delay is steadily increasing towards previous levels. While both arrival and departure delay are detrimental to the travel experience, only departure ATFM delay (outbound flights being issued a departure slot) has a direct effect on the airport operation, with arrival ATFM delay mainly affecting Air Traffic Control (because of the aforementioned holding patterns before approach). This effect on airport operation is a result of the limited amount of resources on the ground, putting a hard cap on the amount of aircraft an airport is able to accommodate without encountering bottlenecks. Currently, because of a combination of a large amount of flight movements and big connecting banks, consisting of in- and outbound peaks which mainly support the hub function of Schiphol for KLM, periodically Amsterdam Airport Schiphol is out of resources. Therefore, the operations are further disrupted by departure ATFM delay. While departure ATFM delay is just one factor in pre-departure delay, the snowball effect it can have as other processes are also disrupted must

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[1] The release of 2023 consumer complaint data has been delayed but can be assumed to be similar

not be underestimated. Most of the pre-departure delay is reactionary delay [3], meaning that it is a network effect originating in another cause. This means that reducing the original delay is likely to have a disproportional impact on the total amount of delay, reducing the delay in the system beyond the original amount.

The pre-departure turnaround processes at Schiphol have been part of the Airport Collaborative Decision-Making process (A-CDM) since 2018. This CDM mainly focuses on milestones in the turnaround and pre-departure processes. For departures the critical milestones are the Target Off-Block Time (TOBT), Target Start-Up Approval Time (TSAT), and the Target Take-Off Time (TTOT). In the CDM all updates are bundled and visible for relevant partners in the ground process, leading to a more transparent and predictable process if all partners in the turnaround chain send their updates in timely and accurately. The departure slots sent by EUROCONTROL are one of the key drivers in this update process, as a flight has to oblige to the issued take-off time in the slot in order to ensure safety in an overloaded sector. Because of this obligation the Target Take-off Time may change significantly, leading to substantial changes in the planning. While EUROCONTROL will continue to improve the issued slots (i.e. minimize delay) at some point this process will have to stop, as a set departure time is needed for the off-block, startup, taxi, and take-off sequence. Within European ATFM systems this freeze, where the issued slot can no longer be improved, is when the outgoing message of the Departure Planning Information system switches from a "target" message to a "sequenced" message; indicating the take-off slot is now set. This is also known as the switch from T-DPI-t (Target-DPI-target) to T-DPI-s (Target-DPI-sequenced). At the introduction of the CDM system this point has been chosen to be 10 minutes before start-up. However, it is currently not known what the effect of varying this time will be on the total amount of departure ATFM delay. If increasing this time leads to a decrease in delay this change might prove to be a worthwhile trade-off; furthering the insight in this is the objective of this research.

2 Background

The main driver to limit the amount of Air Traffic Flow Management (ATFM) delay is not passenger discomfort; every minute of delay in the network is estimated to cost the sector about €100 on average [4], with these costs scaling non-linearly. As these minutes of delay can quickly accumulate because of reactionary delays it is important for all partners in the European ATFM network to limit this propagation as much as possible. The total cost of these delays over all European airports in 2019 amounted to a theoretical 500 million euros of damages [5]. Additionally, Amsterdam Airport Schiphol experienced some of the highest pre-departure delays in Europe, both in terms of cumulative delays and delays per flight. These numbers are highly correlated due to the airport's high number of flight movements. It is important to understand the way the systems that form this delay interact and what their functionalities are.

2.1 Network Manager

Airspace in Europe is managed by EUROCONTROL. Their Network Manager Operations Center (NMOC, previously CFMU or Central Flow Management Unit) makes sure that regulations, as set by Air Navigation Service Providers, are implemented. For every regulation a list of slots is generated that contains slots only for the allowed amount of aircraft that can be present in the relevant airspace during the regulation. Only aircraft with a dedicated slot can fly through the area during a regulation. After creation these slots are filled in multiple rounds. First, capacity (slots) are set aside for exempted flights; afterwards, all other planned flights are sequenced into a slot where possible. This slot allocation is performed via a first-come-first-serve algorithm where earlier flights are given earlier slots. In the case there are no longer slots available flights must wait until the end of the regulation in an overflow set or plan a different route. The algorithm that connects the slots to the planned flights is called Computer Assisted Slot Allocation, or CASA.

With the allocation of a slot CASA is able to calculate the delta with respect to the original flight plan (which is the resulting ATFM delay) and a new take-off time that needs to be followed in order to have the aircraft arrive at the regulated airspace at the right time. This new issued take-off time is called the Calculated Take-off Time (CTOT), which is relayed to airport data systems like the CDM.

2.2 CDM

The Airport Collaborative Decision-Making (A-CDM) framework is set up to make data sharing possible between partners at the airport (Air Traffic Control, Aircraft Operators, Ground Handlers, and others) and within the European ATFM network. The CDM contains set data on the turnaround process that is shared. These include, but are not limited to, actual and planned times for milestones in the turnaround, flight states, and information on the aircraft and the

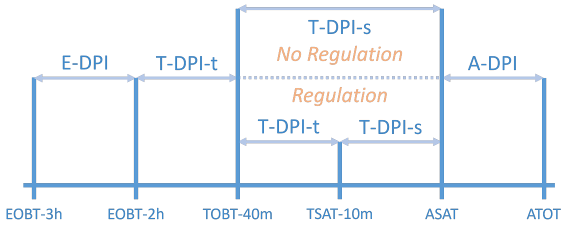


Figure 1: *Timeline of DPI messages*

data linked to it. The way a local CDM instance is connected to the network is through EUROCONTROLs Network Manager via Departure Planning Information (DPI) messages, which are the way data is shared between local fields and NMOC.

Different DPI messages are sent at different times in the turnaround process, as can be seen in Figure 1. These messages are Expected-DPI before turnaround, Target-DPI during turnaround, and Actual-DPI when the turnaround phase is finished and a departure time is sequenced at the field. During the turnaround phase, for unregulated flights, NMOC is informed when the flight is planned to depart 40 minutes before the Target Off-Block Time (TOBT). There is a difference in the process for flights under the influence of a regulation. In this case, the CDM will wait sending out this planning confirmation until 10 minutes before the Target Start-Up Approval Time (TSAT) before sending out a Target-DPI-sequenced (T-DPI-s) message to NMOC.

Currently, the effect of shifting the time at which the T-DPI-s message is sent for regulated flights is unknown. Increasing the time that this message is sent before TSAT may pose a way to reduce departure ATFM delay, as the interaction between the CDM process and the CTOTs issued by NMOC could stabilize. It must also be noted that increasing this time does come with detrimental effects, as the flexibility of the operation is reduced, leading to a trade-off between informing the Network Manager and the flexibility of the operation. This trade-off cannot be completed without information on the effects.

3 Methodology

In order to answer what the effect of varying the time at which the T-DPI-s message is sent for regulated flights is, the Collaborative Decision-Making and Network Manager systems need to be modeled, as they are too complex for an analytical approach. Modelling these systems also enables the analysis of large numbers of flights, making trend analysis possible. This section describes the steps taken to end up at a representative model.

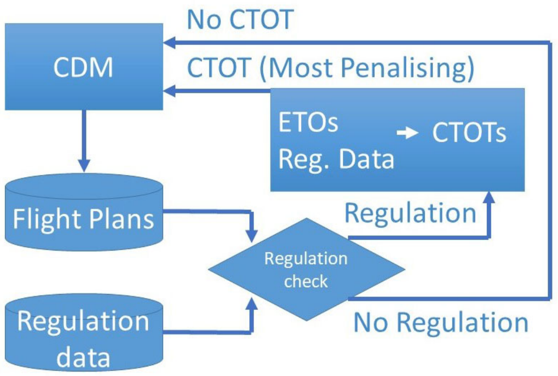


Figure 2: *High-level model description*

3.1 Data

The models could be laid out as seen in Figure 2. While the CDM model processes the updates in a main function, the Network Manager model focuses on checking for regulations and running CASA to issue a CTOT if needed. For this model set-up the use of historic data also becomes a possibility. This approach offers two primary advantages: firstly, it enables recreating the complexity of the CDM using identical inputs, and secondly, it prevents the necessity of large amounts of synthetic data that would have to be produced that behave in the same way as the data recorded in real life. Because of the complexity of the systems, and the fact that an analytical approach is unfeasible, it is unsure whether this synthetic data could feasible be produced with sufficient representative complexity. This approach was thus deemed non-feasible unless no alternative could be found (and would still limit the scope of the project).

In the end the following datasets were used for this research: a CDM dataset from Schiphol Airport (by LVNL), and datasets on regulations, airspaces, traffic volumes, and flight plans from EUROCONTROL [6]. This CDM dataset is a big table with a new entry row for each update in the process. The dataset on regulations contains starting and end times of a regulation, hourly capacity, and the areas impacted by the regulation. These areas could be coupled, after expansion via a lookup table with traffic volumes and airspaces, to flights that were to be in the effected area in the duration of the regulation. This translation layer also facilitated checking whether flights departing from EHAM were projected to encounter regulations when parameters in the CDM changed.

3.2 CDM

The CDM model will run through the historical updates to imitate how the CDM process would get updated in reality, stepwise. In order to do this the CDM dataset needs to be reduced to updates from

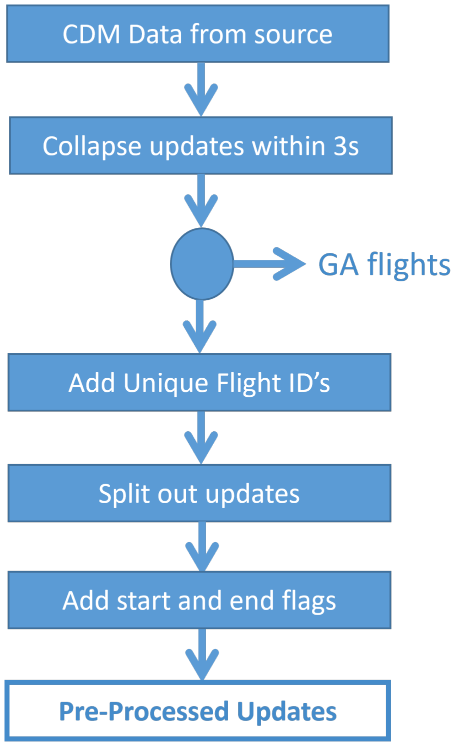


Figure 3: *Data processing flow for the CDM dataset*

one entry to the next for all relevant columns, only containing the relevant updated data. This process is described in Figure 3. As updates trigger updates in other systems down the system interaction chain (for example an off-block time update preceding a start-up time and take-off time update) updates within 3 seconds are combined.

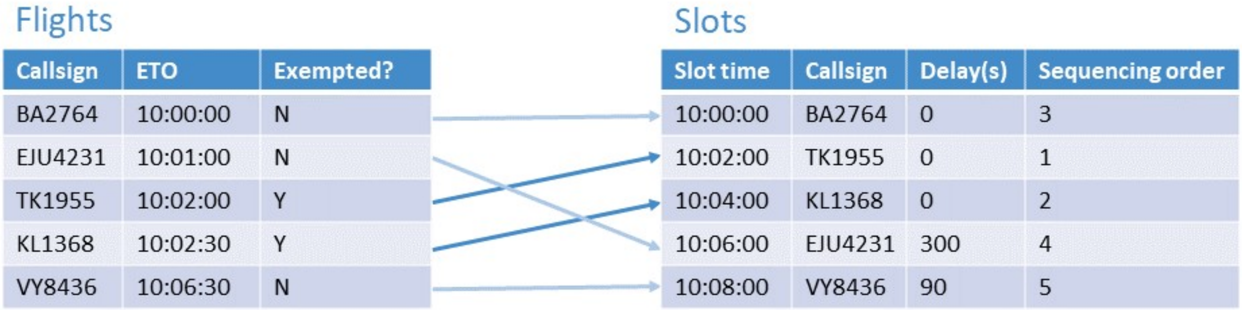
There are a few modifications done to the CDM dataset. First, the dataset was filtered to exclude any flights that fall within general aviation. While these flights are effected by regulations, they do not follow a standard turnaround process, and their presence in the dataset disturbs the research into the main variable. Afterwards a Unique Flight ID, which is not present in the CDM dataset, is coupled to each flight operation. Unique flights IDs were coupled if, for the same callsign, the CDM flights status changed from "AIR" to "null" from one update to the next (indicating a new flight), or if the time between updates was more than 5 hours, which was chosen after experimenting with this limit. Finally, the updates were saved in the format Time of Update, Unique Flight ID, Updated Parameter, and New Value. This way, the CDM could be re-enacted by moving through these updates. The selected parameters (or columns in the original dataset) for these updates were all outbound timing updates and the CDM Flight State. In addition, flags indicating the start and end of updates for a flight were added for debugging purposes.

3.3 CASA

EUROCONTROLs Computer Assisted Slot Allocation (CASA) algorithm works via a first-come-first-serve method where earlier flights are allocated earlier slots. It works via a three round system, where only the last round is able to be delayed on the ground. The first round contains governmental and mission critical aircraft, and the second round contains aircraft that can't be held on the ground at that point (e.g. long distance flights). In this implementation they are assumed to be one category of exempted aircraft, as the first category is almost non-existent in the total number of movements.

```
Data: Set $F$ of flights, each flight $f$ has an ETO
      and exemption status; regulation start
      $t_{start}$, regulation end $t_{end}$, and hourly
      capacity
Initialization:
$n \leftarrow (t_{end} - t_{start})_{seconds} \frac{3600}{capacity}$
$S \leftarrow n$ slots with duration $\frac{3600}{capacity}$ from $t_{start}$
$O \leftarrow$ empty set (overflow set)
for $f \in F$ where $f$ is exempted do
    if $S$ has available slots then
        if slot $s$ containing ETO of $f$ is open then
            Allocate $s$ to $f$ and remove $s$ from $S$;
        else
            Allocate closest open slot $s'$ after
              ETO of $f$ to $f$;
            remove $s'$ from $S$;
        end
    else
        Add $f$ to $O$
    end
end
for $f \in F$ where $f$ is not exempted do
    if $S$ has available slots then
        if slot $s$ directly after ETO of $f$ is open
          then
            Allocate $s$ to $f$ and remove $s$ from $S$;
        else
            Allocate closest open slot $s'$ after
              ETO of $f$ to $f$;
            remove $s'$ from $S$;
        end
    else
        Add $f$ to $O$
    end
end
Result: Two sets of data: $S'$ (set of allocated
        slots with associated flights) and $O$ (set
        of flights without slots)
```

Algorithm 1: EUROCONTROL Computer Assisted Slot Allocation



Flights

Callsign	ETO	Exempted?
BA2764	10:00:00	N
EJU4231	10:01:00	N
TK1955	10:02:00	Y
KL1368	10:02:30	Y
VY8436	10:06:30	N

Slots

Slot time	Callsign	Delay(s)	Sequencing order
10:00:00	BA2764	0	3
10:02:00	TK1955	0	1
10:04:00	KL1368	0	2
10:06:00	EJU4231	300	4
10:08:00	VY8436	90	5

Figure 4: *Example slot allocation by CASA*

The way the allocation works can be seen in Algorithm 1. An example of this is given in Figure 4, which covers a period of 10 minutes with an hourly capacity of 30 aircraft. CASA first creates 5 slots with a length of 2 minutes each. When the slots are created the exempted aircraft are assigned a slot first. For exempted flights, the slot that contains the time they are at the sector (the Estimated Time Over or ETO) is allocated to this flight. If this slot is already allocated, the next available slot is allocated to the flight, until all slots are full or all exempted flights have been allocated. If there are more exempted aircraft than there is capacity the flights will need to be either placed in a holding pattern or rerouted. When all exempted flights have been allocated a slot the rest of the allocation starts, based on a sorted list of the ETOs. Slots are allocated based on the first slot available slot after the ETO. Once all slots are full, or all flights are assigned a slot, the algorithm is finished. In case there were more aircraft than available slots the flights that did not get assigned a slot go into the overflow. In this case the flight will need to be held until at least when their time over the sector is after the regulation. The discrepancy between the ETO and the start of the allocated slot is the ATFM Delay that needs to be assigned to an aircraft to make sure that the traffic in the regulation can be handled safely; this delay is added to a planned take-off time on the ground.

This CASA implementation works as follows in the model: first, all traffic that is in the relevant (i.e. regulated) sectors is extracted from the flight plan data. If a flight has multiple sectors from the same regulation in the route the first sector entry (chronologically) is taken into account, as this is the entry into regulated airspace. All regulated flights are collected with their ETO and exemption status. A check is performed to see whether the flight from the CDM is already present in this dataset. If it is, the ETO is updated; otherwise another row is added with the input info. It is assumed that as the flights come from Schiphol they won't be exempted. Next the slots are created as described in Algorithm 1. As mentioned it is assumed that both exemption categories can be run simultaneously. After the exempted flights all other flights can be allocated a slot where possible. After allocation the amount of delay is known and this is returned to the main process. An assumption made in this implementation is that in the case of a regulation with a capacity of 0 (an airspace closure) there would be no delay, as the actual flight took place (since historical data is used) and was likely rerouted in a way not present in the dataset. Another assumption made here is that if the flight is not allocated a slot and is put into the overflow the delay assigned is equal to a slot a the end of the regulation. In practice in case of big overflows another regulation is put into effect to handle this traffic safely.

4 Experiment

The following section contains the description of the experiment that lead to the results that will be presented in Section 5 using the methods laid out in Section 3. This experiment was set up to investigate whether the amount of departure ATFM delay can be reduced by lengthening the time before departure where a Calculated Take-off Time (CTOT) slot is finalized. It is proposed that this is the case as the CDM process, which is highly volatile, could be made more stable with these changes. Apart from the experimental set-up, this section also discusses the preprocessing needed in preparation of the experiment, steps taken to improve the runtime of the experiment, and the verification and validation performed in the process.

4.1 Experimental set-up

The experiment works by running historical data through the combined Collaborative Decision-Making and Network Manager models as previously laid out in Section 3. A general overview of the model and the flows through it can be seen in Figure 5. As historical CDM data is run through the model at each Target Take-off Time (TTOT) update the path of the flight (with shifted sector entry times to account for the new take-off time) is checked against the database of regulations. If a flight encounters regulations the needed delay is issued for each regulation. After the delays are returned for all applicable regulations the most penalizing delay is selected, as this is the critical sector in the flight plan from an ATFM viewpoint. From this delay, and the TTOT from the update that triggered the process, a new take-off time can be calculated. As this new time won't be taken further in the CDM process it is called CTOT* to denote it from the original CTOTs that were issued during operation, which are present in the replayed updates. After finishing the run through the historical updates these updates are combined with the CTOT*s issued by the NM model.

After combining these sets of updates they are run through a modified CDM player that registers the CTOT* at a set amount of time before the Target Start-Up Approval Time (TSAT). This is also the CTOT* at a freeze horizon. This way the ATFM delay for different communication time horizons between the CDM and the Network Manager can be extracted and further analyzed. For this analysis, freeze horizons were chosen at TSAT-5 to TSAT-60 in 5 minute increments. When all updates are replayed the run is done and the results can be collected, which is the amount of delay for each flight at each freeze point.

4.2 Preprocessing experimental data

Before the experiment can be run the historical CDM updates need to be loaded and coupled to routing data from EUROCONTROL as the CDM updates contain no information on the filed flight plan. This data on the route is needed in order to check whether changes in the timing will result in the flight encountering regulations. The Unique Flight IDs assigned to flights as described in Section 3.2 are coupled to the IDs assigned to flights by EUROCONTROL by using the callsign and the date. The routing data coupled to the EUROCONTROL ID data contains a list of sectors with entry and exit times. Flights that can not be coupled are dropped (<1% of flights are dropped, which has a minimal effect on the results).

As the TTOT for flights from Schiphol will change the sector entry times, these need to be changed from absolute times to times relative to the take-off, rather than the historical time. This means that the entry time of the first sector will be 0, and the entry times of all sectors afterwards will be their original entry times minus the entry time of the first planned sector, as can be seen in Equation (1). This change to relative times needs to be made in order to check updated sector entry times against regulations.

$$t_{relative} = t_{historical} - t_{start} \tag{1}$$

Finally, the areas that are regulated are put in a format that can be compared to the routing data. There are also "SP" regulations that center on waypoints, but as these can not be resolved as these are not present in the used routing data format they are discarded (these amount to less than 0.1% of all regulations).

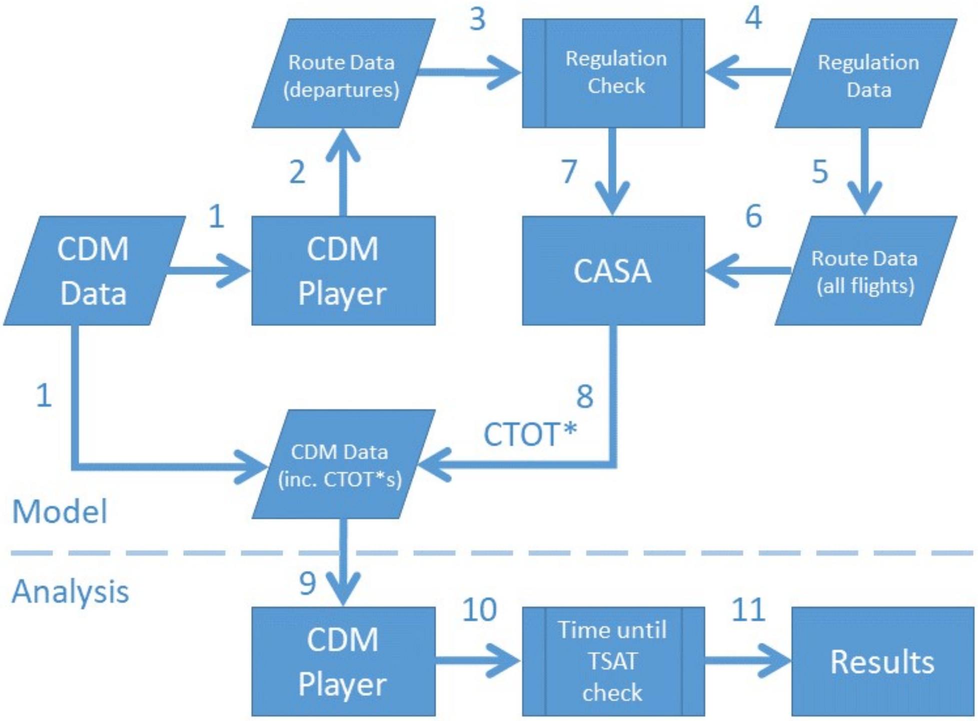
A final processing step is needed for the block "EHAACBAS", which is used to regulate only incoming traffic for Schiphol. The used data on regulations does not contain this distinction, and without adaptations it will regulate all aircraft crossing the Dutch airspace. As these sectors are present in all used flight plans (as all the aircraft investigated depart from Schiphol) these regulations impact all flights. While these regulations are not needed in this research, they are changed to a regulation on EHAM for further research purposes where they may be needed.

4.3 Improving runtime

As running the experiment for a day with low traffic using the original approach took 200 hours this needed to be reduced in order to make the processing of large amounts of days more feasible. To determine whether a multiprocessing implementation was necessary, code optimization needed to be performed. There were 2 changes made with a big impact.

First, the process of iterating through all regulations in the CDM for each flight could be reduced to only the regulations that could be encountered in the route, which can be extracted from the filed flight plan. An additional preprocessing step was incorporated to accomplish this. After coupling the EUROCONTROL ID this could be used to retrieve the planned route, which was then compared to the regulations that were to occur the day of the experiment and parts of the days before and after it. If a sector in the route is present in these regulations it is noted for that specific flight, and during the experiment, instead of going through all regulations, the check only needs to look at the applicable regulations. This resulted in significant decrease (around 1000 times on average) in the amount of regulations that need to be checked.

Secondly, the lookup that is performed in CASA for the relevant flights of the specific regulation was taken out of this function and turned into preprocessing. Each lookup took around 15 minutes as the function needs to loop through multiple large files that contain all traffic in the ECAC area for a day. These extracted flights were saved as cache files, enabling



1. Historical CDM updates
2. New TTOT and Callsign sent at TTOT update
3. New sector entry times for route using TTOT
4. Specifics of regulations
5. Airspaces/sectors/airports in regulations
6. List of flights in regulations
7. If flight is regulated passes on data for slot allocation
8. CTOT* as allocated by CASA
9. Historical CDM updates & CTOT*s
10. CTOT* and TSAT
11. Delay for a flight for a set of freeze points

Figure 5: *High level overview of model layout used in research*

quick retrieval of the data for specific regulations during the experiment. While this preprocessing step added about 50 hours of preprocessing per Aeronautical Information Regulation and Control (AIRAC) cycle, which consists of a set 28 days, the experiment that previously took 200 hours could now be run in 20 minutes. This step paved the way for data analysis on a longer period of time, even without the implementation of multiprocessing.

4.4 Verification & Validation

Throughout the creation of the systems verification and validation have been taken into account. During the set-up of the model and the preprocessing each step has been unit tested with a representative sample. A preprocessed and validated sample was used to check the outcomes of the CDM model, which matched the expected outcomes. Further analysis in the subcomponents that make up the system also showed this behavior. The CASA model was first verified using synthetic data, afterwards the slot allocation was validated with historical data.

After combining the models their interaction was verified to be as expected using another dataset. For verification purposes, the CASA model was adapted to not only return delays but also information on the regulation causing this delay. In the run where the freeze horizon was set at the current time of TSAT-10 the most penalising regulation cause was the same as the historical cause in the EUROCONTROL DDR data in almost all cases, which proves the realism in the simulation. This also validates the realism of the implemented model.

5 Results

This section presents the experimental results, followed by a discussion of these findings in the following section. The outputs of the experiment, as described in Section 4, are CTOT*s issued per flight for different freeze points. Here, freeze points from 5 to 60 minutes before the Target Start-Up Approval Time (TSAT) were chosen with 5 minute intervals. With TSAT-10 as the baseline freeze point the delta to the current situation can be calculated, which can be used to evaluate what the effect of changing this parameter is.

This procedure can be seen for an example flight in Figure 6. This figure shows how the CTOT* is changed over the turnaround of a flight, which is the horizontal axis. The vertical axis indicates the value of the issued CTOT*, which is also a time. As discussed in Section 3 this is the time at which a flight must depart in order not to overload a sector. The jumps that can be seen are a combination of updates to the TTOT and resulting slot allocations performed by CASA. The green line is the historical TSAT of the flight; the black dashed line in front of this indicates the current freeze point at TSAT-10. At this point, the CTOT is finalized and taken into the planning. The other dotted lines in Figure 6 indicate the other freeze points in the analysis; these points range from TSAT-5 to TSAT-60 with 5 minute intervals. Noticeably, there is a big shift in CTOT* approximately 35 minutes before TSAT. If the CTOT* was frozen before this point there would be a drastic difference between the take-off times and thus the pre-departure delay, as the flight would be sequenced to leave earlier. However, fixing this horizon for all flights at this point would drastically reduce the flexibility of the process.

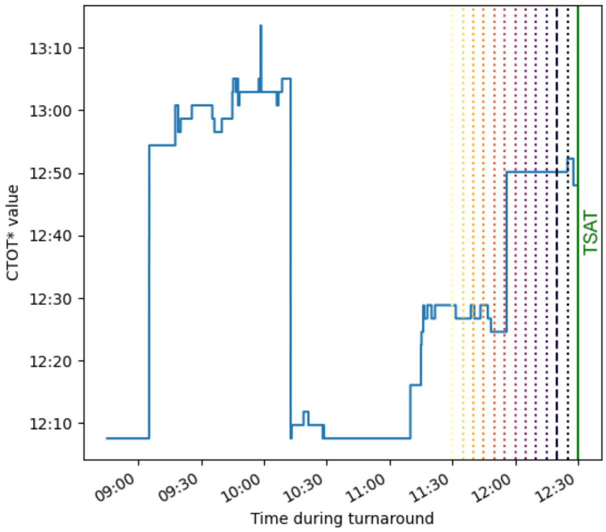


Figure 6: *Timeline of CTOT* value over turnaround for an example flight including freeze horizons and TSAT*

This analysis is expanded from one flight to multiple days in order to signify trends. In aviation the Aeronautical Information Regulation and Control (AIRAC) system is defined in order to force collaboration on the same set of dates. Each AIRAC cycle consists out of 28 days; the first and last day were not taken into analysis to prevent transition issues between multiple AIRACs, leaving 26 days at the center. For each flight, the delay delta compared to the original situation (TSAT-10) can be calculated for other freeze points. This analysis, over the modified AIRAC1901, can be seen in Figure 7. This figure displays not the total amount of delay but the amount of delay that is different compared to the baseline at TSAT-10, which can be seen as a horizontal line centered at 0. It can be observed that changing the freeze point to TSAT-35 or TSAT-40 will lead to the biggest reduction in delays. Freezing point values closer to the baseline also lead to lower cumulative delays, while values before TSAT-40 increase the cumulative delays.

AIRAC1901 runs from January 3rd 2019 to January 30th 2019 during the off season. It can be observed that in many parts of these days, the difference between freeze points does not change (meaning they have the same amount of delay), which is caused by the low amount of traffic and regulations in the ECAC area around this time. Therefore, more AIRACs need to be analyzed. AIRAC1907, which runs from June 20th 2019 to July 17th 2019 in the peak season, can be seen in Figure 8. During this period, the amount of flights was 23% higher than in AIRAC1901, and the amount of regulations set during this period was around 4 times as high. A similar effect to AIRAC1901 can be observed in AIRAC1907, with freeze points up to and including TSAT-40 performing better than the baseline.

The next AIRAC cycle, AIRAC1908, also falls within peak season. The results of the analysis of AIRAC1908 can be seen in Figure 9. Unlike AIRAC1901 and AIRAC1907 the previously observed effects are not present here; with all modifications to the freeze time leading to an increase in delays. While there are gradations in the amount of delay, with freeze points close to TSAT-10 performing better, there are no significant outliers that lead to these values being unrealistically high. Based on this, more AIRACs need to be run through the model to form valid conclusions.

There is more information available within the results of the AIRACs that were analyzed. Table 1 shows details on the data of the different freeze points. Flights without any ATFM delay were removed from the analysis to narrow the focus on relevant entries. This table contains the amount of non-zero entries, the percentage of non-zero entries, the mean and median of the dataset, and the standard deviation of this dataset for different freeze points. It can be observed that the differences between data for different freeze points are small, and no conclusions can be gotten from this with any great significance.

This dataset can be shown as a distribution, which can be seen in Figure 10. This figure contains no binning on the output; each entry in the dataset has its own bar. For clarity, this figure displays a subset of the 12 freeze points investigated, specifically the original TSAT-10 and the freeze points TSAT-30 and TSAT-60. When t-tested these samples were proven not to be statistically significantly different.

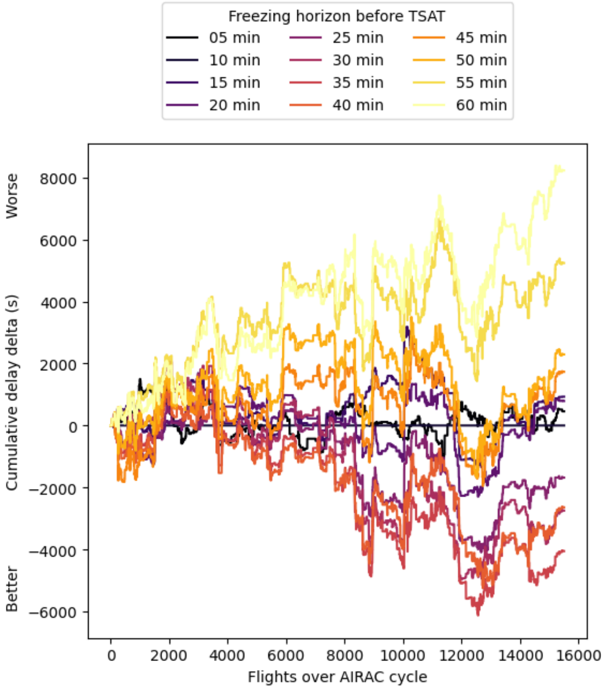


Figure 7: *Cumulative delay delta over modified AIRAC 1901 (04/01/19 to 29/01/19)*

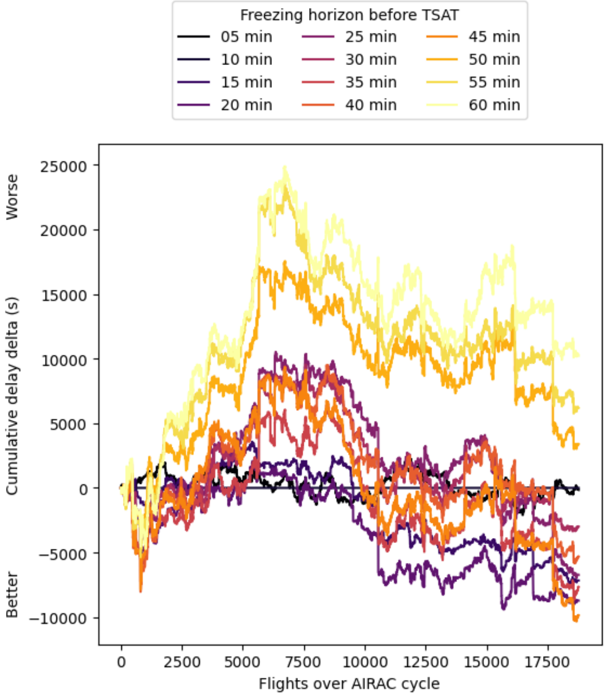


Figure 8: *Cumulative delay delta over modified AIRAC 1907 (21/06/19 to 16/07/19)*

Table 1: *Delay statistics for different freeze points in AIRAC1907. 0's have been removed for all used data.*

TSAT	Count	Percentage	Mean	Median	SD
-05	7485	39.9	217.1	116.0	334.6
-10	7501	39.9	216.7	113.0	337.0
-15	7504	40.0	215.6	113.0	335.8
-20	7511	40.0	215.2	112.0	335.2
-25	7519	40.0	215.3	112.0	335.9
-30	7522	40.1	215.7	112.0	337.4
-35	7529	40.1	214.9	112.0	331.7
-40	7551	40.2	214.5	112.0	331.3
-45	7545	40.2	214.1	112.0	331.3
-50	7537	40.1	216.1	113.0	335.4
-55	7557	40.2	215.9	112.0	335.6
-60	7558	40.2	216.4	112.0	338.9

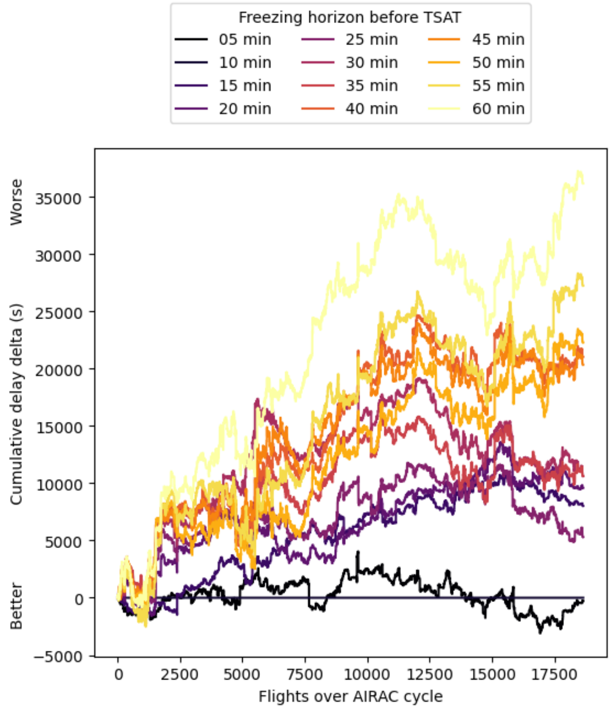


Figure 9: *Cumulative delay delta over modified AIRAC 1908 (19/07/19 to 13/08/19)*

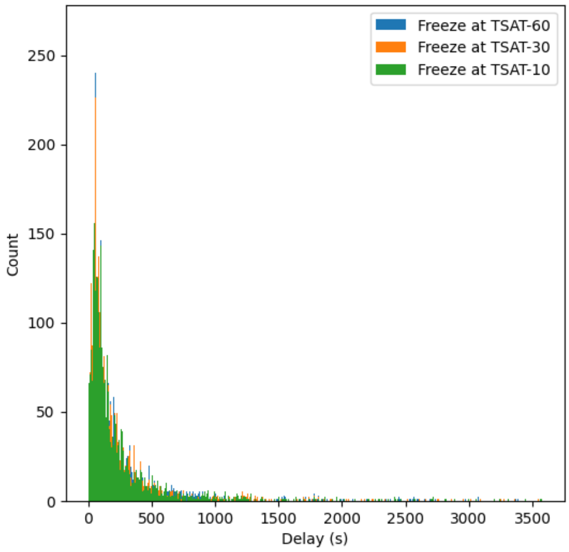


Figure 10: *Delay distribution over modified AIRAC 1907 (21/06/19 to 16/07/19)*

6 Discussion

In this section the results of the experiment performed in this research as seen in Section 5 are discussed. This section is split up into a discussion on the results and a section on the limitations of the methodology (including assumptions made in the process).

6.1 Experimental results

The results presented in the Section 5 show a widely varying effect of changing the T-DPI-s messaging point. While there seems to be a strong indication that values between 20-30 minutes can lead to a strong decrease in the amount of ATFM, the results from AIRAC 1908 contrast this. Based on this data it can be seen that no clear conclusions can be gotten yet based on this sample size, and that more data is needed to indicate actual trends instead of a volatile series.

Something to be noted is that the CTOT* at 10 minutes that is taken as the baseline is simulated and not taken from real data. While the specific regulations resulting in the most penalising delay generally match between the simulation and the historic data as is discussed in Section 4.4, the delays don't match because of a difference in definition. It is unknown how EUROCONTROL actually defines the delays in the dataset, but it seems to be the variance between some reported TTOT and the actual take-off time, taking the CTOT into account. The Slot Tolerance Window, which is the margin a flight has with respect to the issued departure slot at the field, could be another variable on top of this.

In this experiment the delay coupled to a CTOT* is defined as the time difference between the ETO and the starting time of the slot allocated by CASA. In practice this will be the same as the TTOT that triggers that update and the CTOT* value. These values were observed to be around a factor 10-20 smaller than the values listed by EUROCONTROL, with some heavy tails in the distribution as can be seen in Figure 10. These peaks of delay are usually triggered by regulations with a very small capacity, where small amounts of flights in the slot allocation process can lead to big differences. For this reason, it is hard to say whether the results from this research can relate to the actual situation; it seems as there are just to many variables in the process to be able to focus on an independent variable.

6.2 Limitations & assumptions

The complexity in the turnaround process leads to the fact that simply changing a variable is not representative for the changes in the entire system. In fact, by decoupling the CTOT* from the turnaround process (as it was not feasible to fully model it to the needed fidelity within time constraints here), it is still hard to say how this method relates to the situation in real life. There, once a CTOT is issued, this takes precedence over values in the turnaround process, and the CTOT needs to be followed. Because of this, in the data, once a CTOT is issued all historical target times related to the take-off will shift as well, leading to "contaminated" data. However, dropping each flight that is regulated in the dataset is not feasible, as these are the flights that are investigated in this research. This dichotomy of issuing slots but not taking them into account in the rest of the turnaround process leads to a situation where it is unknown what would have happened in the rest of the turnaround process.

The assumptions made in the approach taken here may also have an effect on the seen results, but it is hard to quantify these as these assumptions were put in place to make this research viable in the first place. The following assumptions were made to facilitate the research:

- Independent Slot Allocations
- Independent Departure Sequencing
- Set Flight Plan
- Discrete Time
- Exemption Categories

Independent Slot Allocations:
The most significant assumption is that only the ETOs for departures from Schiphol result in changes in the slot allocation. In real life, the ETOs of all flights in that regulation would get updated, leading to shifts in the allocation as slots free up (for example because of a longer turnaround process, leading to a new TTOT for a flight). This continuous recalculation process leads to the Network Manager sending out Slot Improvement Proposals (SIPs) when new slots open up, in order to most efficiently use the available capacity. As this modeled system is predetermined apart from the slots for the updated flight no other flights will send out updates on the feasibility of their assigned slot and thus no SIPs will ever be sent out, as the other slots are not dynamic.

Independent Departure Sequencing:
As in the previous assumption this independence of the rest of the system is also present in the assumption that the flights departing from EHAM will not interfere with each other; in the lookup that leads to the slot allocation as done by CASA only the ETO of the input flight is changed; if there are more flights in that list originating from EHAM they are assumed to have a set ETO that is based on the historical flight

plan data. This assumption was made since flights are sequenced at EHAM and will not arrive at the sector at the same time, meaning that they cannot interfere. However, for long regulations or regulations with a low capacity their ETOs and slot allocation will impact each other. The effect can still be assumed to be minimal due to the spacing in outbound planning.

Set Flight Plan:
Flights are also assumed to have a set course in the model that cannot be changed. In reality new routes can be filed by the airline to avoid congestion and airspace closures before take-off (until the introduction of FF-ICE, which will open up in-flight rerouting). While this dynamic routing could theoretically be coupled to the existing code, it is unknown if there is data present on when routes for flights were filed and what these routes were. In order to prevent aircraft from experiencing prolonged delays resulting from airspace closures, when the actual flight could proceed as scheduled, workarounds were needed, such as the assumption that regulations of capacity 0 lead to no delays. In real life this is obviously not the case, but flights would be rerouted rather than left delayed for multiple hours if the option was present. Another factor of this is that changes in the take-off time may lead to changes in the runway planning and resulting changes in the taxi time, shifting the ETO of a flight. For simplicity, it is assumed that these are set, but in real life these changes may have drastic effects on the planning. For example, a KLM Cityhopper flight departing from the B-pier at Amsterdam Airport Schiphol can have a taxi time as short as 1 minute when taking off from runway 24 or as long as 20 minutes when taking off from runway 36L. While this could be modeled, achieving a representative outcome would require the implementation of a pre-departure sequencer would need to be in-place that would be representative for the sequencer as used at Schiphol in order to guarantee a result as realistic as possible.

Discrete Time:
Compared to the real-life situation as described in Section 3 there are also slight modifications to the process. In order to make the simulation possible the AIRAC period, which contain 28 days, are split up to form discrete periods of 1 day; this mainly affects the night operations as certain flights are not taken into account anymore. However, as there is little traffic during this time the impact of this is assumed to be minimal.

Exemption Categories:
Another assumption made in adapting to the simulation is the combining of the exemption categories; governmental & critical missions and long-range flights. Since there are very limited flights of the first category it is assumed this combination has no effect on the results.

7 Conclusions

This article has presented the findings of a study exploring the effects of changing the time before TSAT at which a T-DPI-t message changes into a T-DPI-s message for regulated flights at Schiphol airport. In order to come to representative findings a model of the Airport CDM and the Network Manager were made, which were fed with historic data to capture the nuances of the operation. Using synthetic data was, apart from being less representative, also seen as an unrealistic option as the analyses and processes needed to get realistic synthetic data eclipsed the scope of the project; as of this point there has not been sufficient research in order to conclude anything into the possibility of this task.

There are several steps that could be taken to immediately expand the research presented here. The first and most impactful step, as mentioned in Section 6, is to run the model on datasets of more AIRACs. Apart from extending the dataset this will open up more possibilities on the research side as well; analyzing multiple years could prove whether the changes investigated here would have the same effect at any point of the year or whether the effect is coupled to the amount of traffic, which is seasonal.

The current limiting factor in facilitating this expansion is the computational time needed to run the simulation. Even with all the improvements made to limiting this the process of analysing delays for a single AIRAC cycle, spanning 28 days, still requires three to five days on a modern processor (as of 2023). Reducing the computational time needed for this analysis is needed to open up the way to a broader analysis. As the code has already been optimized where possible the fastest way to achieve this would be to implement multiprocessing, making sure that computers can utilize their full resources. However, it will need to be investigated where this can easily be adapted and checks and balances will need to be added to (parts of) the code as the updates are run chronologically. If the hardware is available the model can also be run for different datasets on separate computers, as the AIRACs are independent.

Another way to expand the scope of the research performed on this thesis is to run it for the data of other airports. Since only data from Schiphol was accessible within LVNL, as they are the Dutch ANSP, any conclusions gotten from the data cannot be proven to be globally applicable. Data from comparable airports would need to be analyzed in order to see what the effect of changing the T-DPI-s horizon would be in their operation. This may also prove that the change will have different effects globally depending on different characteristics of these airports.

The effect on the network of changing this parameter should also be investigated. The operations at (CDM connected) airports have an effect on the network, and changing the freeze point for one airport will result in effects at other airports. In fact, several equilibria will have to be explored, as with a hypothetical change introduced at one airport proving advantageous, other airports might follow, leading to a dynamic situation in the network.

Ultimately, the most important addition to this model would be to expand on the turnaround process. Actually taking the CTOT*s into the CDM process would provide a transparent understanding of the impact of altering the freeze point, as opposed to treating it as an as-independent-as-possible variable (as discussed it is hard to say whether the variable is actually independent or if it mainly depends on other factors and the result is a random function). However, modelling the turnaround process to this degree of fidelity is not an easy task and based on current research it is unknown if this is feasible.

Something to note regarding the turnaround process is that in recent years the prediction of turnaround processes has moved away from mathematical models and towards video analysis. At Schiphol this approach has quickly proven viable, and the system is able to detect delays early in the process. If the CDM milestones, for example the TOBT, can be accurately predicted using this system the stability improves drastically and setting the freeze point earlier may prove trivial in order to set the planned operations far in advance.

As mentioned in Section 6, the results generated using the described methods are inconclusive. More data is needed in order to make statistically sound conclusions on whether changing the T-DPI-s horizon for regulated flights has any true effect. Adding complexity to this matter is that the underlying flight operations are only somewhat comparable over multiple years; but with multiple years worth of data a statistically significant result should be able to be found if present.

It is unknown whether the effect this research could have detected would have been present in actual operations, as the CTOT*s are not taken into the turnaround process. Nevertheless, even without a preliminary conclusion on the usefulness of changing the freeze horizon, the methods as developed for this research open the gateway towards more research in this domain by providing a stable foundation that can be used for a multitude of research directions, paving the way towards an objective and transparent understanding of the factors that influence the turnaround process and daily operations.

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Part II

Preliminary Report - Already Graded

1

Introduction

The world of civil air transportation has progressed from having no organization, towards simple landing and takeoff clearance given by local towers, and in contemporary times to complex networks that are interconnected and that are continuously sharing data. These developments in technology have gone hand in hand with the global rise in air traffic and the dawn of air traffic management. All of these developments have lead to a world that has safe and frequent flights to all destinations. On the one hand this is advantageous for many operators, as they can know and act on data that was previously not available. On the other hand, it also means that the network has progressed to an intricate state where disruptions can have cascading effects throughout it, affecting not only the cause but also parts that seem unrelated.

One of these disruptions is Air Traffic Flow Management (ATFM) delay. This is issued to flights in order to avoid reaching the maximum capacity in a sector of airspace when that capacity is reduced. This can be the case due to for example ATC capacity or inclement weather. The European airport with the most ATFM delay has in recent history been Amsterdam Airport Schiphol (AAS) [1]. While the total ATFM delay took a drastic downturn during the COVID-19 pandemic because of the lower number of flights, passenger numbers and flights are currently recovering. As a result of this, ATFM delay is on the way back to pre-pandemic levels and Schiphol is again one of the airports with the most ATFM delay in Europe [2].

ATFM delays are issued by EUROCONTROL's Network Manager Operations Centre (NMOC) on the basis of regulations entered by an ANSP. These delays are utilized in order to hold flights on the ground longer or delay them while en-route. Ground delays are preferred for economic and environmental reasons, as the flight will burn less fuel. In the case of a ground delay, this changed departure time is called a Calculated Takeoff Time (CTOT); the amount of ATFM delay is defined as the difference between the issued CTOT and the original Expected Takeoff Time (ETOT).

This document presents a literature study for a project analysing the change in ATFM delay in case of different time horizons being used in the interaction between CASA and the CDM process at Schiphol. CASA, or Computer Assisted Slot Allocation, is the EUROCONTROL system allocating flights to slots in case of a regulation. The CDM system is a collection of standards and constraints that lead to a better sharing of operational processes and data in order to better inform all the stakeholders in the processes at an airport. These systems, as well as ATFM delay, will be explored in more detail in Chapter 3. The research objective for this study is described in more detail in Chapter 2. The models needed to facilitate this project are described in Chapter 4, and the data needed to feed these models is discussed in Chapter 5. A research proposal based on these explorations can be found in Chapter 6. The conclusion of this report can be found in Chapter 7.

2

Research Objective

The research objective of this study is the following:

> Since 2018 Schiphol is a connected Airport Collaborative Decision Making airport. This means that all the data that is received from handlers, ATC, the airport and the airlines is available for all other partners and within the European Air Traffic Flow Capacity Management network as more information is shared among partners, leading to a more effective way of working. However, regulation by EUROCONTROLs Network Manager Operations Center still happens when sectors and/or airports are projected to go over their allowed capacity. The calculations for handling these regulations and the CDM process have several time horizons that have been chosen in the introduction of the system and the effects of varying these has not been researched. This means that the current congestion in the European skies (and Schiphol in particular, as it is the airport with the greatest amount of outbound delay) might be reduced by tuning these parameters. Research into these topics by modelling the Schiphol and NMOC systems will lead into further insight if it is feasible to decrease the total delay in the network.

This objective leads to the following research question:

> How does the total amount of ATFM delay at Amsterdam Airport Schiphol vary with changing temporal transparency levels between the Schiphol CDM process and the Network Manager?

In order to answer this research question it needs to be split up into multiple sub-questions in order to make it approachable. This needs to be done as the main question is not one that can simply be answered and steps in the process are needed to give the project a structure that can be adhered to.

These subquestions are:

1. *What is the build up of (ATFM) delay at Schiphol?*
2. *How is Airport CDM implemented at Schiphol?*
3. *How does the Network Manager interact with Schiphol?*
4. *How can these systems be accurately modeled?*
5. *Are there uncertainties in these systems and can these be accurately modeled?*
6. *What are the update horizons between the systems?*
7. *Will changing the T-DPI-s message timing result in a change in delay?*

3

Literature Study

The systems needed to support this research are complex and need to be investigated before any other parts of the project can be performed. As the main subject of this thesis is ATFM delay the focus will be here, with a separate focus on the systems in use at the Network Manager and the airport. In Section 3.1 background is given on Air Traffic Flow Management, with ATFM delay discussed in Section 3.2. The network manager and the systems in use there are described in Section 3.3. Finally, the CDM process, as is used at Schiphol, is discussed in Section 3.4.

3.1. Air Traffic Flow Management

Air Traffic Flow Management 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" [3]. In other words, Air Traffic Flow Management is responsible for ensuring a good throughput in (a sector of) airspace. As the effectiveness of ATFM depends on timely and accurate updates, and as aviation and airspace networks have become more complicated, the task of managing these airspaces gains disproportionately from a high degree of technological decision-making assistance to human operators [4].

There is a big difference between the way ATFM is practiced in the US and in Europe [5]. In the US, the main capacity constraints are located at the airports, while the en-route sectors are more critical in Europe [6]. This can partly be explained by a higher population density in Europe, but the main driver that leads to European airports being less congested is the practice of treating them as Fully Coordinated i.e. as having a Declared Capacity that is planned upon and that cannot be exceeded [7]. In reality this means that the only times when the planned flights at an airport exceed the possible capacity is in cases of e.g. severe weather, maintenance or staffing issues where the planned capacity cannot be executed.

As the congestion in Europe is mainly experienced in airspaces instead of locally at airports, a better way of dealing with ATFM is in a centralised approach, rather than a decentralised approach. This is a better way of working towards a global optimum in this case [8]. This can be observed in practice as well, as this change was made in Europe in the 1990s in order to move away from local airline and ATC coordination in order to solve serious delays en-route and at airports [9]. The ATFM services in Europe are currently provided by EUROCONTROL's Network Manager Operations Centre (NMOC) which was previously known as the Central Flow Management Unit (CFMU) until 2011 [10].

A limit on a sectors capacity is called a regulation, as the traffic through it is being regulated. Regulations are set by a Flow Management Position (FMP) at an ANSP by sending EUROCONTROL the info on what sector is will be regulated, the start time of the regulation, the end time of the regulation and the capacity of the regulation. After this, EUROCONTROL will confirm or deny the regulation. EUROCONTROL does not issue regulations on its own for airspace they do not manage, and until a regulation is entered by a FMP, NMOC will not begin processing it.

There are four main systems used at the NMOC [11]: the Tactical System (TACT), which contains the Computer Assisted Slot Allocation system (CASA); the Initial Flight Plan Processing System (IFPS); the Environment Database (ENV); and the Archives System (ARC). These systems and their interactions can be seen in Figure 3.1. The IFPS takes in flight plans filed by airlines; when received, it checks, corrects and distributes them to relevant ATC units. The Environment Database holds information of all the needed data in the process, e.g. all air routes. The Archives System holds past traffic data for information and assistance. Finally, TACT is at the heart of the entire process. It uses the data provided by the other systems and parties in Figure 3.1 in order to monitor ATFM regulations, hand out departure slots (via CASA), and provides assistance for the system operators in making decisions.

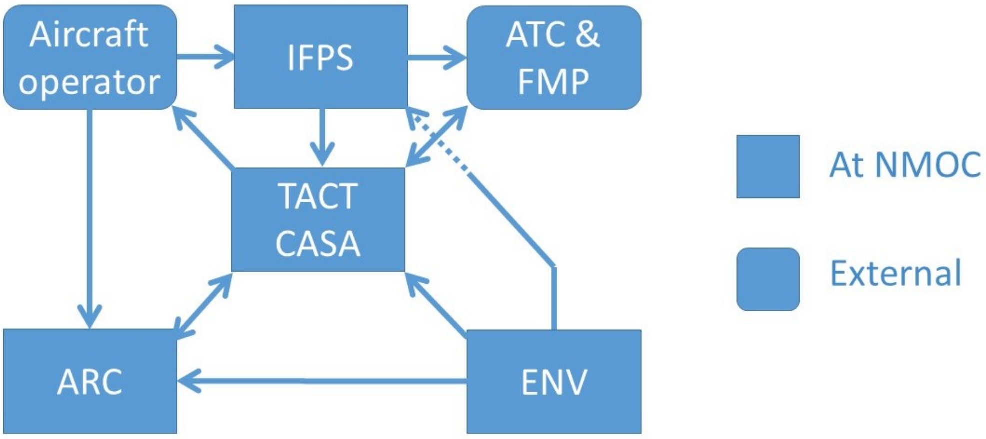


Figure 3.1: Systems in use at EUROCONTROLs Network Manager Operations Center (based on Leal de Matos et al. [11])

ATFM is performed by EUROCONTROL on all time periods [12]: strategic (up to a year ahead), pre-tactical (before the day of the flight), tactical (the day of the flight), and operational (during the flight). Further along in the process it is less about preventing general trends and more about dealing with non-predictable events such as personnel problems, or even close to the flight, weather. Post-ops analysis is also performed to evaluate network performance. In the strategic phase the peak of the previous year (summer) is analyzed and plans for the next peak season (summer) are laid out [11]. Routes, contingency measures and coordination with e.g. airspace changes are also performed. In the pre-tactical phase the ATFM plan for the day of operations is sent out. Congestion problems are identified, potential overloads are investigated and possible regulations to prevent these overloads are proposed. As a lot of the issues in the airspace are cyclical, it is usually possible to start with last week's planning. In the tactical phase all regulations for that day, that could have been predicted, are already in the TACT system. These regulations will lead to takeoff slots being issued by the CASA system. In this way, it is possible to avoid sectors going over capacity by delaying aircraft on the ground instead of holding them in-flight. This leads to a more optimized airspace and less fuel burn, leading to fewer emissions and lower operating costs for carriers. Usually, there are no changes issued by NMOC for a flight in the operational phase, as en-route delay will be issued by an ASNP. However, the presence of this flight in the airspace and its planning may have an effect on other flights planned to pass through the relevant sectors.

3.2. ATFM Delay

A result ofATFM is delay applied to flights in order to make sure that a sector stays below its (reduced) capacity [13]. These delays are collectively known as ATFM delay, as these are done for ATFM reasons. These delays are issued in the departure phase or en-route to a destination. Where possible delaying a flight before departure is preferred. This prevents emissions as a flight won't have to enter a holding or take an evasive route, which will almost certainly lead to a larger distance being flown when compared to the original flight plan.

The preferred way ATFM delay is applied is in the turnaround phase [14]. If a flight was to cross an overloaded section according to its flight plan, keeping the flight on the ground until a new overflying order is devised reduces holding. This new order is defined so that when a flight is projected to reach the sector it either has a slot or the overload is finished. In this way it is possible to keep this flight from encountering en-route delays. This new takeoff slot, that minimalizes en-route delay, is called the Calculated Takeoff Time (CTOT). As mentioned before, this way of dealing with congested airspace sectors leads to less emissions. As a result of this there is a smaller environmental impact and there are less expenses for airlines. It is important to note that a delayed departure does not always turn into a delayed arrival [15]. As it is important for airlines that passengers reach their destination on time they apply buffers in the schedule that are in-line with the projected delays, such that when these delays are taken into account a flight will still reach its destination in time. These buffers have their own disadvantages, as they may lead to early arrivals. These can have an effect on the sequencing at the destination airport and result in delays due to bunching, as this can lead to more aircraft in the TMA than projected [16].

There are many reasons for regulations [17], which are identified by codes. These codes can be applicable for departure delay, en-route delay and arrival delay. A full list can be found in Appendix A. Not all the delays are relevant for all 3 phases. For example, the ATC routeings delay (code R) is only applicable to en-route delays, and the Accident/Incident, Aerodrome Capacity, Aerodrome Services, and Industrial Action (non-ATC) delays (codes A, E, G, and N) are only applicable to departure and arrival delays. These codes do not represent equal parts of the ATFM delay distribution. Usually, at airports, weather and capacity are the biggest single cause of ATFM delay [18] [2]. En-route this is usually capacity and staffing issues [18] [2]. This is highly dependent on the year and (global) events, as for example strikes have a big effect on the network. An example event is the current conflict in Ukraine. Because of this flights are not using Russian airspace anymore, and routes from Europe toward Asia have shifted routes, leading to more traffic in some parts of the airspace [19].

The CTOTs that are issued to minimalize en-route delay are issued by EUROCONTROLs Network Manager Operations Centre (NMOC). The computations for CTOTs are performed via the CASA system, mentioned in Section 3.1, after regulations are received by the NMOC. This system creates slots according to the capacity of the regulation. After creation these slots are allocated according to a flights Estimated Time Over (ETO) the sector of airspace [20]. Generally, flights are allocated slots according to a first-come-first-serve algorithm (FC-FS), but flights that are already en-route and/or flights that cannot be regulated are treated differently, as these are allocated slots more in line with their ETO. These flights are processed before flights that have not yet departed are allocated a slot. While these flights are allocated a slot, generally they can still continue through the sector via their original flight plan. Flights that cannot be regulated i.e. are exempted from ATFCM measures are, for example, flights carrying governmental members or flights carrying out critical operations (search-and-rescue, medevac, or firefighting) [13].

EUROCONTROL is an entity that derives its power as European Network Manager from an appointment by the European Commission [21], and it regularly publishes data on its network operations. In this data it can be seen that Amsterdam Airport Schiphol has a very large amount of ATFM delay for both arrival and pre-departure delay. In the last full year of data before the COVID-19 pandemic, 2019, it experienced 2953 minutes of Arrival ATFM delay per day on average [18]. The airports with the biggest ATFM delay after Schiphol were Humberto Delgado Airport (in Lisbon) and London Heathrow with 1251 and 1211 average minutes of delay per day respectively. Thus, Schiphol has a big ATFM delay problem.

This delay trend continued during and after the pandemic, independent of the disruptions in traffic. The average amount of Airport ATFM Arrival Delay per day can be seen in the left column of Table 3.1 [22] [23] [24]. It can be observed that Schiphol regularly has the largest amount of average ATFM Arrival Delay in the operating field of the Network Manager. In fact, the only reason that Athens had more ATFM Arrival delay in 2021 was according to EUROCONTROL "ATC capacity constraints [that] generated high delays at Athens and Iraklion airports, with a peak during August 2021" [2]. These constraints are not usual, and their effect may have been amplified by the low amount of traffic during this period. In the right column of Table 3.1 [22] [23] [24] the average Airport ATFM Arrival Delay per flight can be seen. Schiphol ranks lower on this metric, still being relatively high. There appear to be 2

Table 3.1: Airport ATFM Arrival Delay rankings for both total and per-flight minutes

Average Airport ATFM Arrival Delay [minutes]			Airport ATFM Arrival Delay per flight [min./arr.]		
2020			2020		
1	Schiphol (EHAM)	455	1	Cannes-Mandelieu (LFMD)	2.97
2	Lisbon (LPPT)	210	2	Lisbon (LPPT)	1.72
3	Barajas (LEMD)	112	3	Chambéry-Aix-les-Bains (LFLB)	1.67
			5	*Schiphol (EHAM)*	*1.41*
2021			2021		
1	Athens (LGAV)	341	1	Cannes-Mandelieu (LFMD)	3.00
2	Schiphol (EHAM)	230	2	Porto (LPPR)	2.14
3	Iraklion (LGIR)	207	3	Athens (LGAV)	1.63
			9	*Schiphol (EHAM)*	*0.60*
2022*			2022*		
1	Schiphol (EHAM)	1261	1	Tours-Val de Loire (LFOT)	10.16
2	Lisbon (LPPT)	941	2	Lisbon (LPPT)	3.39
3	Athens (LGAV)	559	3	Cannes-Mandelieu (LFMD)	3.10
			5	*Schiphol (EHAM)*	*2.18*

main factors for this; on the one hand, ATFM delays at smaller airports are exacerbated by the lower amount of flights. On the other hand, the very large amount of flights at Schiphol result in a lower ranking per flight.

Data on all-causes delay at airports is also published, but specific Airport ATFM Departure Delay data is not. The reason for this is that in the case of the arrival delays there are clear reason for it: conditions at the target airport and the TMA. With departure delay the responsibility for this delay is located elsewhere (e.g. in a crossed sector of airspace or the target airport), meaning that the departure airport itself is not the cause of this delay, and it is thus hard to define it as such.

The average amount of All-Causes Delay per day can be seen in the left column of Table 3.2 [25] [26] [27]. Schiphol is not only leading in Arrival Delay, but it also suffers from extremely high amounts of pre-departure delay. As the pre-departure delay per flight, in the right column of Table 3.2 [25] [26] [27] resembles the left column (except for Milan Malpensa in 2021) it seems that the total amount of departures has a higher effect on the pre-departure delay than the amount of arrivals had on the ATFM Arrival Delay. This is worth noting, as these should be the same as the amount of departures (bar some exceptions). What could also be happening is that a singular flight has a higher impact on the general pre-departure delay, and the flights that have an effect on ATFM Arrival Delay are more specific. This could make sense as ATFM delay is more specific than all-causes delay.

As mentioned before data on Airport ATFM Departure Delay is not published separately. EUROCONTROL does however, in addition to all-causes delay, publish distributions of delay in their Central Office for Delay Analysis reports [28]. In Figure 3.2 the distribution of departure delay reasons for a sample of traffic in 2019 can be seen. Here, the Airport, En-Route and Weather delay add up to the full amount of ATFM departure delay. It can be seen that this is between 10-45% of all delays in this sample. However, this percentage must be looked at critically, as it is not specific for Schiphol and there is no traffic distribution included with this. This means that this distribution is probably not representative for the actual amount of ATFM Departure Delay.

Apart from airport data there is also a great amount of data available on sector performance and the amount of ATFM delay these sectors contribute to the network, on both a monthly and yearly basis. In the scope of this research these sector performances are less relevant, as they are a source for delays at Amsterdam Airport Schiphol, and not present in the process apart from this. However, it is good to note that The Netherlands is located in and around some of the busiest airspace in Europe, and this is why a lot of ATFM departure delay happens at Schiphol.

In the grand scope of things the main problems with these ATFM delays is not the impact on operations

Table 3.2: All causes pre-departure delay rankings for both total and per-flight minutes

Average total pre-departure delay [minutes]			Pre-departure delay per flight [min./dep.]		
2020			2020		
1	Schiphol (EHAM)	5009	1	Malpensa (LIMC)	17.81
2	Frankfurt (EDDF)	4794	2	Frankfurt (EDDF)	16.49
3	Charles-de-Gaulle (LFPG)	3893	3	Schiphol (EHAM)	15.52
2021			2021		
1	Schiphol (EHAM)	7796	1	Schiphol (EHAM)	20.40
2	Frankfurt (EDDF)	7307	2	Frankfurt (EDDF)	20.38
3	Charles-de-Gaulle (LFPG)	5991	3	Malpensa (LIMC)	20.14
2022*			2022*		
1	Schiphol (EHAM)	16603	1	Schiphol (EHAM)	28.88
2	Frankfurt (EDDF)	14438	2	Frankfurt (EDDF)	27.78
3	Charles-de-Gaulle (LFPG)	10658	3	Charles-de-Gaulle (LFPG)	21.85

but more so the impact on the image of Schiphol for the public. ATFM delays cost about €100 per minute [29] [30], but as the network manager allocated these to departing flights at Schiphol because of non-airport capacity issues, they should not be an economic problem for the airport. There is however damage to the airports image as year in year out the highest amount of all-causes delay is accrued at Schiphol, of which ATFM delay is of course a (big) part. This statistic can have effects on the psychological performance of the airport in the minds of people, which can be detrimental to the attractiveness of Schiphol to both airlines and travelers.

3.3. The Network Manager and CASA

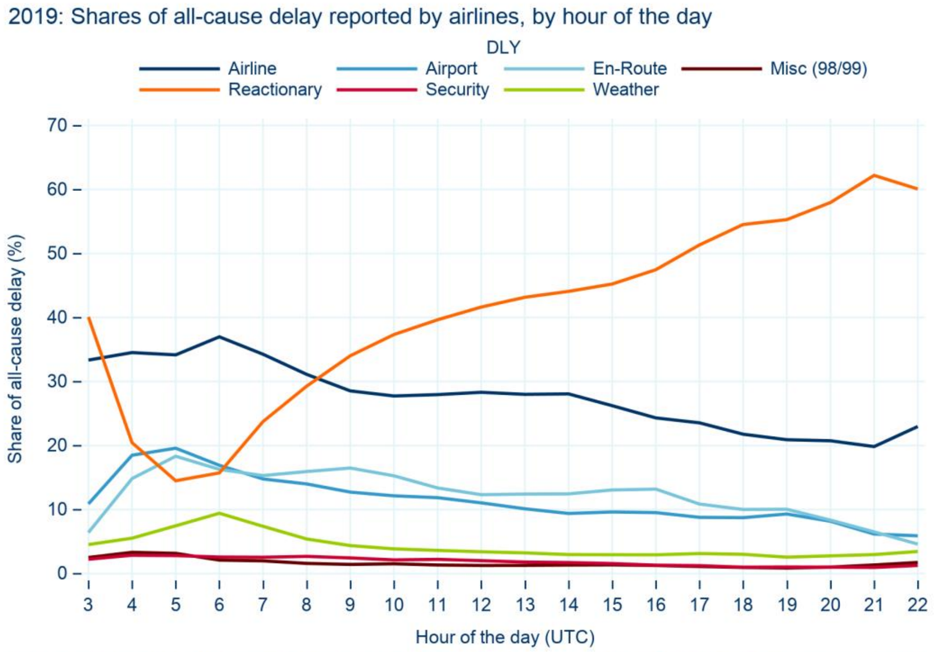
As described in Section 3.1 the European airspace manager is EUROCONTROLs NMOC. Here, the capacity regulations entered by a FMP position at ANSPs are used to generate the slots that lead to revised takeoff times in order not to overload sectors and/or airports [8]. These slots are calculated by EUROCONTROL using a system named CASA, or Computer Assisted Slot Allocation [12]. While the exact implementation of this system has never been published by EUROCONTROL, it has been extensively described on a high level to the point where its functionality can be deconstructed [20].

The Network Manager starts by creating slots for a regulation where, in case of a regulation of n flights per hour, slots are created for every $60/n$ minutes of the duration of this regulation [8]. For example, for a regulation with a capacity of 30 flights per hour with a duration of 2 hours, 60 consecutive slots are created with 2 minutes between them.

After these slots have been created it is possible to allocate flights to them. CASA generally functions as a first-come-first-serve (FC-FS) algorithm [8], based on the ETO w.r.t. a regulated sector, with some exceptions. In Figure 3.3 an example slot allocation process is depicted [12]. In this example there is a regulation with an hourly capacity of 6 flights starting up from 10:00, leading to flights 3-6 receiving a CTOT as otherwise the sector would go over capacity.

After the slots get assigned, new Calculated Takeoff Times can be derived from the Calculated Time Over (the slot time at the regulation) by calculating back from the regulation via the filed flight plan. An example can be seen in Figure 3.3, where flight 3 originally was planned to take off at 0754 (the ETOT), with an estimated time over the sector of 0954 (the ETO). Due to a regulation this ETO shifts to a new slot at 1000 (the CTO). The original duration of the flight from its planning can then be used to arrive at a new takeoff time to be at the slot by 1000, which is 0800 (the CTOT). In order to be help in turnaround planning at an airport this CTOT is further reduced, by subtracting the expected taxi time, leading to a calculated off-block time (COBT), and a related calculated start-up time (CSAT).

However, the algorithm is more complicated than creating slots and directly allocating them, as this does not take into account the state of the network and operational preferences at that point. For example,



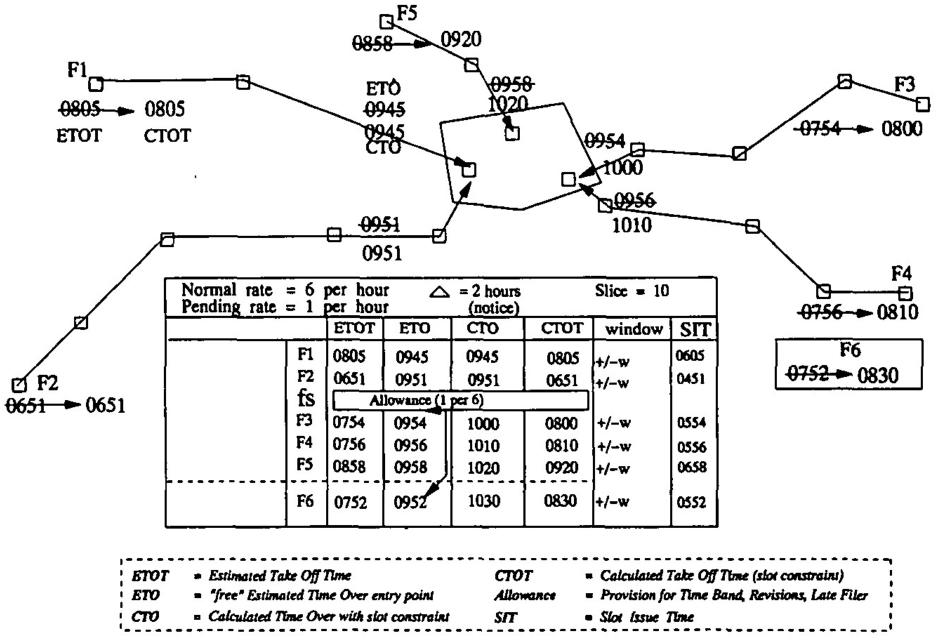
Based on CODA sample of 65.6% of commercial flights in the ECAC region in 2019 © EUROCONTROL 2020 www.eurocontrol.int/CODA

Figure 3.2: Distributions of all-cause delay reasons throughout the day [28]

flights may not be regulatable. This can be the case for flights carrying members of government or critical operations like search-and-rescue, medevac, or firefighting [13]. Another problem arises for flights that have already taken off when a regulation is set. Taking these flights into account when allocating slots with planes still on the ground may lead to the en-route flights needing to hold before they enter the sector. For this reason, they are exempted from regulations as well where possible. Note that both non-regulatable and airborne flights do count towards the capacity of a sector.

One more complication appears if a flight has multiple overloaded sectors in its flight plan. In this case separate CTOTs for each regulation are calculated, but only the most penalising CTOT (i.e. the CTOT leading to the most delay) is issued [13]. This also means that the slot of the flight in other regulations can be reissued to other flights. Slots opening up after the initial issuing can have other reasons as well, e.g. flights being rerouted, late turnarounds or issues at an airport. Therefore, CASA is constantly being re-run to search for better slots for all flights. If a better slot is found a Slot Improvement Proposal (SIP) is sent to Aircraft Operators (AOs) [13]. After receiving a SIP AOs may decide whether to accept this new slot or stick with their current planning.

The FC-FS way of allocating slots was chosen as a way to easily and fairly treat all flights in the same way, as over time all flights are assumed to equally experience advantages and disadvantages of this method. However, as quickly noted after its introduction, this may not always be the case, as it may be too strict [31]. Also of note is CAS being a heuristic and not an optimization function. CASA being a heuristic explains why EUROCONTROL is able to re-run it continously since the mid-1990s, when computational speed was lower. As an example of how much lower it was, the most powerful supercomputer in 1993 (when the CFMU came online) is about an order of magnitude less powerful than a modern smartphone (as of 2022). There has been research into other slot allocation algorithms, first by Vranas in 1996 [32] and by Van den Akker in 1997 [33], who proposed an optimization model and a column generation method respectively. Vranas also discussed computation times, which were very limiting at this point. Since then, research has continued, proposing both new methods as well as improvements to the current algorithm, for example by Ruiz et al. in 2019 [34], which proposed a slot overloading technique to reduce ATCFM delay.



Normal rate = 6 per hour △ = 2 hours (notice) Slice = 10
Pending rate = 1 per hour

	ETOT	ETO	CTO	CTOT	window	SIT
F1	0805	0945	0945	0805	+/−w	0605
F2	0651	0951	0951	0651	+/−w	0451
fs	Allowance (1 per 6)					
F3	0754	0954	1000	0800	+/−w	0554
F4	0756	0956	1010	0810	+/−w	0556
F5	0858	0958	1020	0920	+/−w	0658
F6	0752	0952	1030	0830	+/−w	0552

ETOT	= *Estimated Take Off Time*	*CTOT*	= *Calculated Take Off Time (slot constraint)*
ETO	= *"free" Estimated Time Over entry point*	*Allowance*	= *Provision for Time Band, Revisions, Late Filer*
CTO	= *Calculated Time Over with slot constraint*	*SIT*	= *Slot Issue Time*

Figure 3.3: Example of Network Manager regulations at introduction (from Duytschaever (1993) [12])

3.4. Airport CDM

Since 2018 the CDM (Collaborative Decision Management) process has been implemented at Amsterdam Airport Schiphol [35]. Via CDM the airport is connected to the European airspace network managed by EUROCONTROL. CDM is, in its basis, a collection of standards and constraints that lead to a better sharing of operational processes and data in order to better inform all the stakeholders in the processes at an airport [36]. It does this using a milestone approach [37], which means that the system takes significant events during the planning or progress of the flight and uses these to trigger the decision-making process. The most important updatable events are: the Estimated Landing Time (ELDT), the Estimated In-Block Time (EIBT), the Target Off-Block Time (TOBT), the Target Start-Up Approval Time (TSAT), and the Target Take Off Time (TTOT) [37]. The timeline of the milestones can be seen in Figure 3.4.

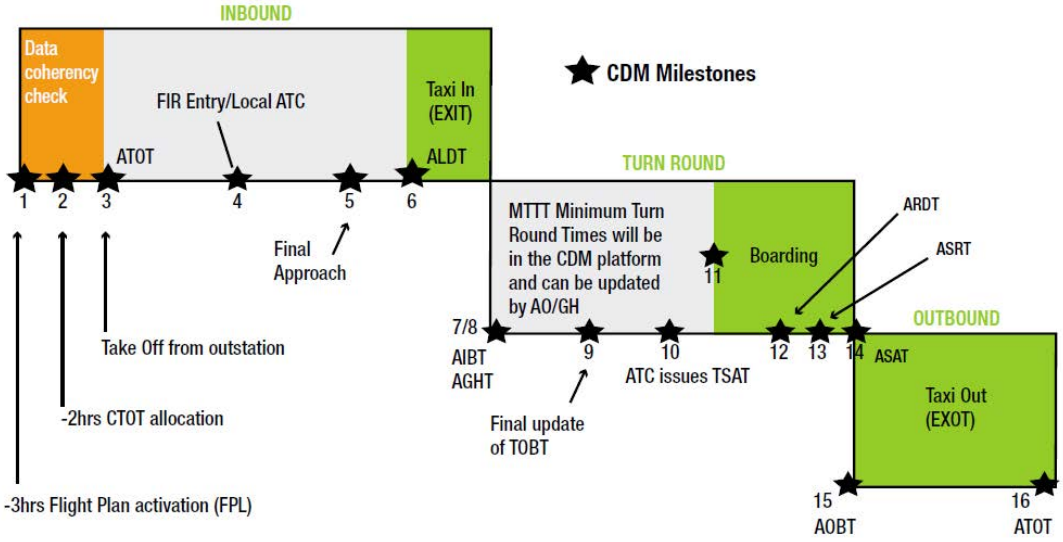


Figure 3.4: CDM Milestones (from EUROCONTROL CDM Implementation Manual [37])

The CDM process is mainly aimed at shortening turnaround times by making more information available to operational partners. The main partners at Schiphol are Luchtverkeersleiding Nederland (LVNL), Royal Schiphol Group (RSG), KLM, the Royal Netherlands Meteorological Institute KNMI, other airlines represented by the Schiphol Airline Operators Committee (SAOC), handling agents, and EUROCONTROLs Network Manager Operations Centre [38]. Before the CDM process was implemented sharing operational data between these stakeholders could be very difficult. With the implementation completed all parties in the turnaround have access to a central platform containing all data, alleviating this issue. The main point of contact for the Network Manager is LVNL [39], which receives the CTOTs from NMOC and uses them in their pre-departure systems. Updates and implementation of the CDM were led by RSG [40]. While EUROCONTROL has published standards for implementing the CDM process [37], it is up to an airport (and all stakeholders) to perform the specific implementation.

In Figure 3.4 it can be seen that a CTOT will be issued at TOBT -2 hours in the case of a regulated flight, but this CTOT may continue to be improved in order to reduce the delay experienced by a flight. This is also the reason why CASA is running continuously at NMOC; as new status updates enter the system more information becomes available and improvements may become viable [32]. So, for most regulated flights, there will be a CTOT scheduled before entering the last phase of the turnaround process.

These updates are processed via Departure Planning Information (DPI) messages between the Network Manager and the CDM process [41], which are depicted in Figure 3.5. It can be seen that at two hours before the Expected Off-Block Time (EOBT) the messages switch from Early-DPI to Target-DPI messages. There are two types of T-DPI messages: Target-DPI-target (T-DPI-t) and Target-DPI-sequenced (T-DPI-s). At EOBT-2h a Target-DPI-target message is sent out containing the Target Off-Block Time and informing the Network Manager on when the flight could depart. If a flight is not regulated, at TOBT-40m the T-DPI-t is switched to a Target-DPI-sequenced message, which provides NM with a Target Startup Time (TSAT) and planned departure time. For a regulated flight, the T-DPI-t message is kept until 10 minutes before the TSAT in order to keep the slot improvement open as long as possible. After this, the T-DPI-s is sent out to confirm the planning as of that moment, and slot improvement is no longer possible. The pilot has to achieve the startup within +- 5 minutes of the TSAT window, otherwise the flight has to re-enter the departure planning [35]. If a flight is regulated, it also has to achieve the CTOT window within -5 and +10 minutes, otherwise it will also enter the recalculation process [35] [42].

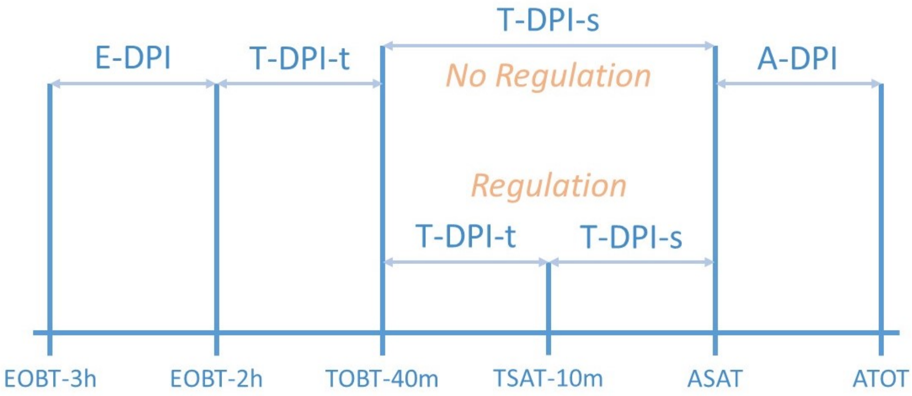


Figure 3.5: DPI updates (based on Schiphol CDM Manual [35])

The CDM process and NMOC are connected via the paths shown in Figure 3.6. In short, all the partners at the airport feed data to NM and in return get an CTOT and related parameters [35]. In more detail: NMOC receives TTOTs, TOBTs, TSATs, EOBTs, and taxitimes for planned runways. In turn, NMOC provides airlines and the ANSP with CTOTs. The airlines instruct pilots with these CTOTs, and the ANSP passes on the CTOTs with the TTOTs, TSATs, and EOBTs to the airport, which provides TOBTs back to ATC. These TOBTs are received from ground handlers. The airport is in contact with the pilots, providing them TOBTs and TSATs, which can be used in communicating a startup time with the ground handlers. Once the pilots are ready, they request clearance from ATC; and once cleared they proceed to their departure runway. Meanwhile, the NM is continually updated with the relevant TTOTs, TOBTs, TSATs, EOBTs, and taxitimes and the loop through the system continually updates.

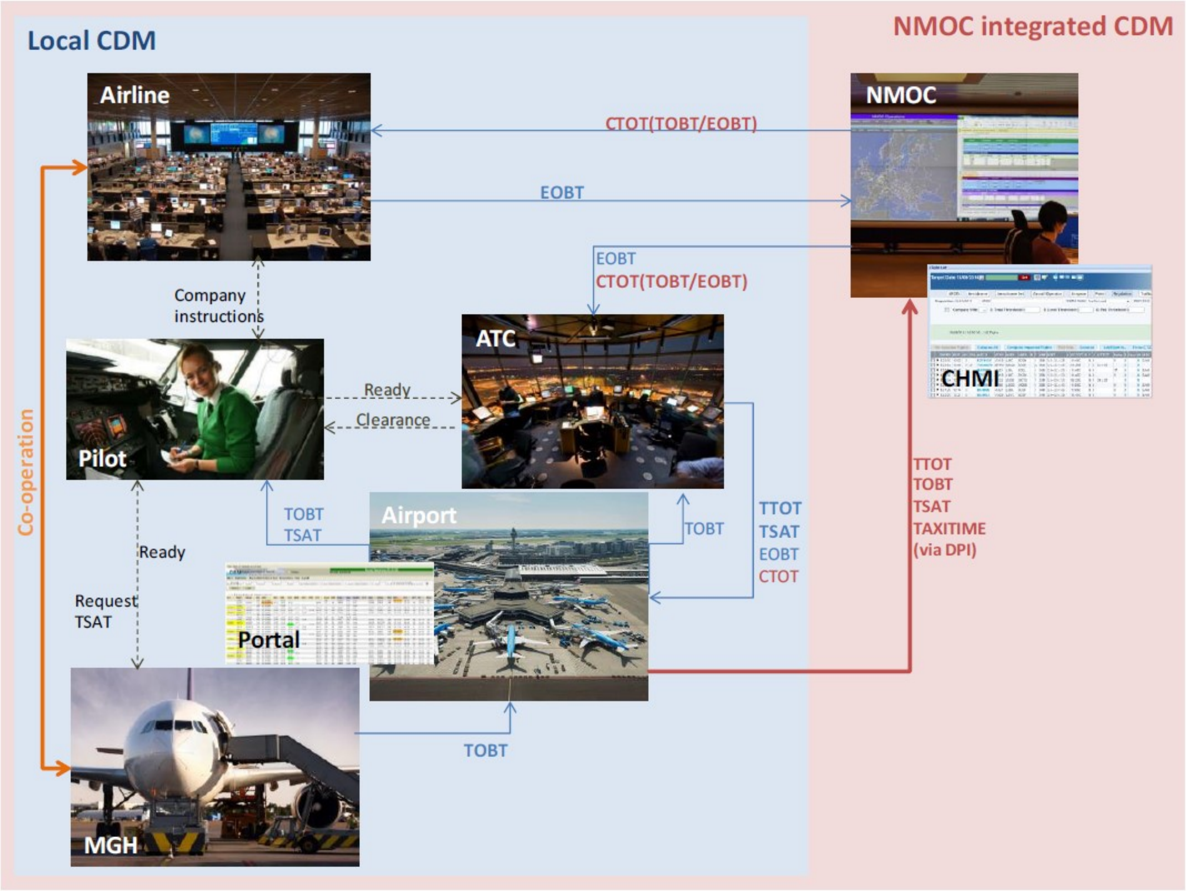


Figure 3.6: Interaction between A-CDM and NMOC (from Schiphol CDM Manual [35])

The main changes that will happen with CTOTs are flights that may also get assigned a better slot by CASA before takeoff if possible and within implementation parameters. Flights may also miss their scheduled turnaround times which may lead to a snowball effect further delaying their take-off, as a new slot may not be available in CASA. The times chosen in base of these interactions are currently selected by EUROCONTROL in their CDM implementation guide [37]. These times are provided for implementation without background on what the effect will be of varying them. The results of this thesis will contribute to the understanding of the different interactions between the CDM process and the network manager and will research the effect of varying temporal horizons on the total ATFM delay at Schiphol.

4

Model Description

In this chapter the model set-ups required to investigate the interactions between the Airport Collaborative Decision-Making process and the Network Manager are laid out. As these systems are very complex it is not feasible to investigate these effects by using a theoretical approach. Instead, they need to be modeled up to a high degree of fidelity in order to catch all the nuances present in the actual system.

As there is a lot of historic data available (which will be discussed in Chapter 5) the model will function as a post-operational analysis. Here it will be able to move throughout the day and take the same steps the original process did (with varied parameters) while taking advantage of quickly moving through low-activity periods, which would still take up time in a real-time variant.

The model containing the CASA system is laid out in Section 4.1. The model representing the CDM process is discussed in Section 4.2. The way these models will interact in the model runs is presented in Section 4.3.

4.1. Network Manager model

As explained in Section 3.3, the Network Manager Operation Centre uses data from the CDM system, filed flight plans, and data on regulations [20]. From this it provides CTOTs back to the CDM system, which in turns provides it to the different stakeholders. The general workings of the proposed TACT-CASA model can be seen in Figure 4.1. The workings start with airlines providing flight plans to NMOC before operation. These flight plans contain the route the flight will take and the Expected Off Block Time (EOBT). During operation the CDM system (or the relevant partner in case CDM has not been installed at an airport) will provide NM with the TTOT, TOBT, TSAT and current taxitimes.

The regulation process starts three hours before the start of the regulation, when the first slot allocation is performed by the CASA system at NMOC [32]. As discussed in Section 3.3 this system uses a rule-based First Come First Serve (FC-FS) algorithm to allocate a slot and the relevant delay to the regulated flights. To achieve this, it uses the ETO and the flight status (whether an aircraft is still on ground or en-route, and whether it is a special flight). First, non-regulatable flights are allocated. These are flights performing critical missions or flight carrying heads of state or government officials. While these flights are allocated a slot closest to their ETO, they can follow their original flight plan, a slot is only allocated to make sure the sector is not further overloaded. Next the en-route flights are allocated a slot. Like the non-regulatable flights, they are allocated a slot but can follow their original flight plan. One exception to this is if the total of en-route flights exceeds the capacity, in which case they are delayed en-route by holding or rerouted (strictly speaking the same holds for non-regulatable flights as well, but their volume is low enough to assume this will not happen). Finally, the rest of the flights are allocated a free slot closest to their ETO times. Slots can only be allocated after a flights ETO, since they will not be available before this time according to the planning. Of course, flights can arrive sooner than originally planned after discussion with an AO and if a quicker turnaround can be completed, but this

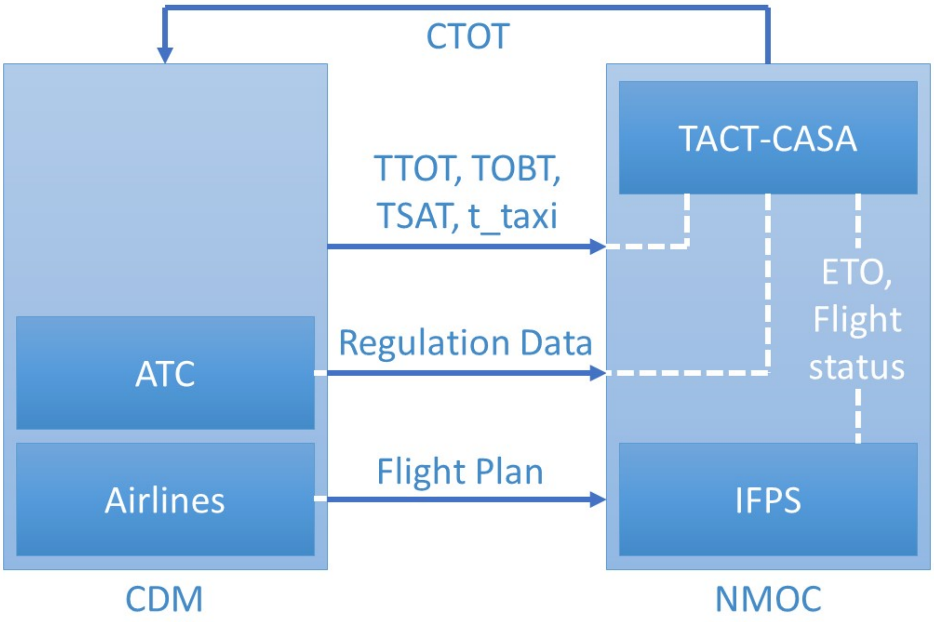


Figure 4.1: Data going in and coming out of CASA

is outside the scope of this project. Once the slot times are known the difference between their original ETO and their slot time (now called the Calculated Time Over) can be calculated. This change is the same change to be applied to their takeoff time, leading to a Calculated Takeoff Time issued by NMOC.

This workflow is best illustrated with an example. In Figure 4.2 a regulation is shown in Sector Y. This regulation starts at 9:00 and ends at 9:15, with a reduced hourly capacity of 30 flights. Next to the regulation information the relevant list of flights for this period flying through Sector Y is shown. In this example, apart from the ETO, the ETOTs are also shown. This is to illustrate that at this time, 6:00, flights F3 and F7 are already underway and cannot be held at the airport.

With this information the slots for this regulation can be created. With an hourly capacity of 30 flights/hour for a regulation from 9:00 until 9:15 8 slots will be created from 9:00 onward 2 minutes apart. Before any other flights are allocated, first the non-regulatable (not applicable here) and en-route flights need to be allocated a slot. F3 has an ETO of 9:03, so it is allocated the 9:02 slot. F7, with an ETO of 9:11, is allocated the 9:10 slot. The slots and these allocations can be seen in Figure 4.3.

With F3 and F7 allocated it is possible to mo0ve on to the flights that are still on the ground at the start of the regulation. As the flights are allocated in a FC-FS manner the way of allocating them is sorting them by ETO and moving down this list. F1 has an ETO of 9:00, a slot which it keeps after allocation. F2 could have gone to slot 2 at 9:02, but as that slot is already populated by F3 it moves to slot 3 at 9:04 with a delay of 3 minutes. F4 can be allocated at its original time. F5 can be allocated at 9:08, with one minute of delay when compared to its original ETO. F6 could have been allocated at slot 6, but that is already taken, so it moves to slot 7 at 9:12 with 2 minutes of delay. Finally, F8 can be allocated to slot 8 with a minute of delay. These allocations can be seen in Figure 4.4.

With all flights allocated it is possible to use the applied delays to calculate the CTOTs for these flights. Only F2, F5, F6 and F8 have delays and thus changed take-off times. CTOTs for F1, F3, F4 and F7 are however still issued as they need to conform to them, even if they are already en-route as is the case for F3 and F7. For the delayed flights finding their CTOT is simply a matter of adding the delay to their ETOTs, as the travel times should not differ. The final CTOTs can be seen in Figure 4.5.

For this example, the following assumptions are applied: first, only 1 regulation is taken into account. It may be that a flight encounters multiple regulations. In this case, the most penalizing regulation is leading and the ETOs for the other regulations need to be updated to reflect this. Secondly, this

Flight	ETOT	ETO
F1	06:10	09:00
F2	06:20	09:01
F3	04:30	09:03
F4	07:00	09:06
F5	06:30	09:07
F6	07:30	09:10
F7	05:45	09:11
F8	06:45	09:13

Current time: 06:00
Regulation start: 09:00
Regulation end: 09:15
Regulation capacity: 30

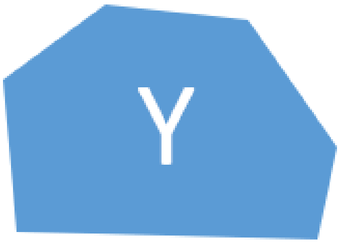


Figure 4.2: Original flight list and regulation for CASA example

Slot	Slot time	ID	Delay
1	09:00		
2	09:02	F3	-
3	09:04		
4	09:06		
5	09:08		
6	09:10	F7	-
7	09:12		
8	09:14		

Figure 4.3: Slots created by CASA and non-regulatable flights

Slot	Slot time	ID	Delay
1	09:00	F1	-
2	09:02	F3	-
3	09:04	F2	+3
4	09:06	F4	-
5	09:08	F5	+1
6	09:10	F7	-
7	09:12	F6	+2
8	09:14	F8	+1

Figure 4.4: Rest of slots populated and delays calculated

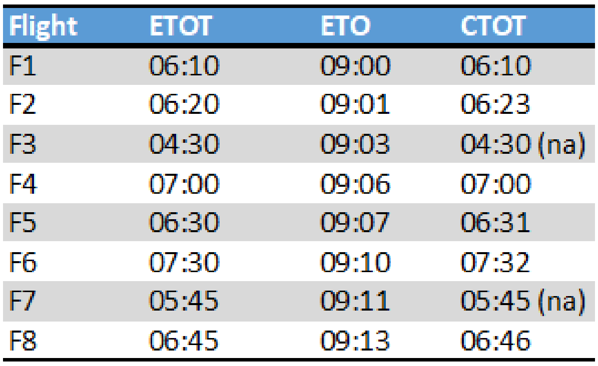
example was designed to illustrate the principles used and is synthetic. In real life empty slots may happen, flights may get rerouted to avoid regulations, problems in turnaround can cause delays leading to flights missing slots, needing reallocation, and many other things may happen.

In the scope of this project, as only departures out of Schiphol and flights in applicable regulations are relevant, and a global snowball effect can be held to a minimum, it can be assumed that the CASA implementation will not need an optimization function. However, if this algorithm was ever expanded for an implementation where multiple points of departure are set against another it will likely need an extra layer of optimization after the heuristic has run in order to deal with most penalizing regulations and slot improvements. While outside the scope of this project, it can be expected that these extra optimizations can be done via a heuristic method as well, but a few internal iterations might be needed to converge on the solution.

4.2. Airport CDM model

In Section 3.4 background was provided on the CDM process, including Figure 3.4 which showed the milestones in EUROCONTROLs example implementation. However, at Schiphol, not all of these milestones were implemented, and thus these do not need to be modeled. To add to this, in the scope of this thesis only the turnaround and outbound phases are relevant, so milestones 3-8 can be excluded (with milestones 1 and 2 treated differently). Milestones 14-16 take place once a flight has pushed back and is on its way to takeoff, at this point ATFM delay at the airport can no longer be applied to the flight anymore.

In Section 3.4 it was also explained that the relevant CDM partner issues updates that are then processed and used in updating projected milestones. For example, if a baggage handler had a turnaround take 10



Flight	ETOT	ETO	CTOT
F1	06:10	09:00	06:10
F2	06:20	09:01	06:23
F3	04:30	09:03	04:30 (na)
F4	07:00	09:06	07:00
F5	06:30	09:07	06:31
F6	07:30	09:10	07:32
F7	05:45	09:11	05:45 (na)
F8	06:45	09:13	06:46

Figure 4.5: Flight list with issued CTOTs

minutes longer than planned this 10 minutes will propagate throughout the milestones, with margins to both sides in case equipment or clearance is available earlier or later than planned. Assumptions in modelling this will have a big impact in how a flight moves through the process, as this means that delays at a milestone can be caught or will only delay a flight more via a snowball effect.

In modelling this system the entire operational process up to the turnaround can be omitted, as this project is about the delay on the departures from Schiphol. This means that all parts of the turnaround until the in-block time are not relevant here. This in-block time triggers an auto update of the TOBT after which the turnaround process starts. A more in-depth look at the milestones will be provided before converging on a model proposition.

CDM milestone 9, as seen in Figure 3.4, is the final TOBT update (as long as nothing unplanned happens). Here, the TOBT, as calculated in the CDM system, is sent to the airline and the ground handler to confirm that this target will be met. After confirming, this TOBT is set and will not be changed. At milestone 10, a TSAT is issued by ATC. While this is not strictly issued to the pilot until TOBT-40m, it is visible in the CDM for relevant partners from EOBT-3h onward.

Milestone 11 indicates the start of boarding. At this point information from the gate agent is received in the Airport CDM system and the flight status is set to BRD (for Boarding) [37]. Milestones 12 and 14 are not implemented at Schiphol [35]. At milestone 13 the Start-up Request Time is indicated. It is set by ATC if an aircraft is ready and within the TSAT window, after which the flight status is changed to RDY (for ready) [37]. Milestone 15 is the flight pushing back, with its status changing to TAX (for taxi), and finally milestone 16 is the flight taking off, with its status changing from TAX to AIR and the aircraft leaving the CDM ecosystem [37]. Of course, if a flight encounters a problem and has to turn around it will automatically be entered back in the CDM upon landing, but this is considered to be outside of the scope of this research as this is an irregular occurrence.

As discussed the model will be a post-operational analysis. This allows for a model that will be able to pre-process data in a way to index key events and use them in the CDM process as decision factors (for example the planned EOBT and when the flight was actually ready). In the simulation, the flight will enter the system at the same time as the original flight but its updates and sequencing will be dependent on the model parameters active at that time.

A part of special interest is de-icing. De-icing is not a defined milestone, but it is a key driver in the turnaround process; if a fight is not deiced according to the planning, this will have a big impact on the planned times. This is because de-icing is often limited at an airport, and slots will be handed out for this just like in an airspace regulation: if a slot is missed, a new slot needs to be allocated. An added factor of complexity is that there are multiple ways deicing might happen: at the gate of the aircraft, at another gate where the aircraft will have to be moved to, or at a remote deicing position [35].

The main data links of the CDM process can be seen in Figure 4.6. Note that these are not one-to-one with the internal datastreams and predictions, but these present a good global overview of the CDM data flow. The entire process starts with the Schedule Info and the Inbound Info, leading to a TOBT at the initialization of the process. This TOBT is combined with the taxi times (via the gate planning) and possible de-icing to form a TTOT. From this TTOT the TSAT can be calculated, taking into account the

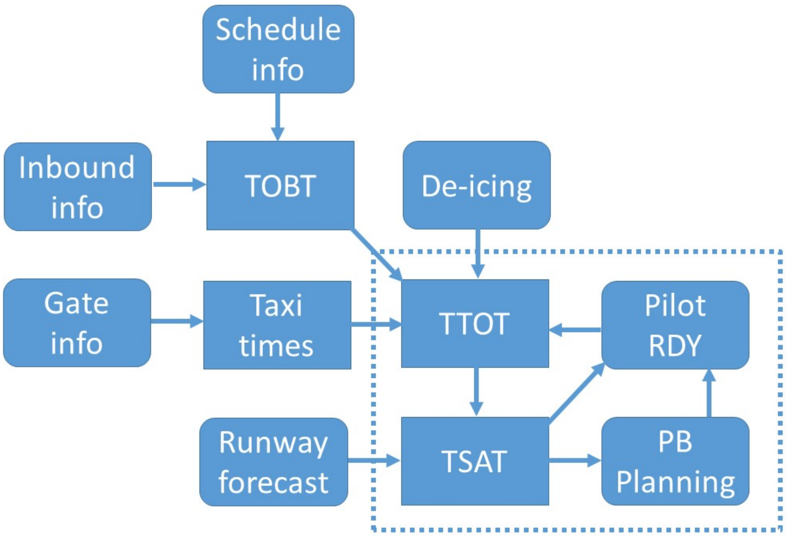


Figure 4.6: Main data links of the CDM system [AAS CDM]

active runways and the taxi times. It then returns to the TTOT via the PB (Push Back) planning and the pilot indicating readiness. This loop is continually run until takeoff.

To summarize the model setup: flights are initialized in the CDM system at the same time they were initialized in real life. From this historical data, times are extracted where milestone and non-milestone events happened. From here on the CDM system will be simulated using the rules described in the implementation manual and the time horizons set as a parameter.

4.3. Interaction between models

In Section 4.1 and Section 4.2 the separate models of the systems were discussed. However, these models need to interact in order to be able to investigate their interactions. This implemented combined model can be seen in Figure 4.7 and will function as follows:

- Once a flight is active in the CDM its route will be compared to a list of current and planned regulations to find out whether the flight will be affected by a regulation.
- If there are no regulations, the flight is issued no CTOT and is returned to the CDM system.
- In case there is a regulation the relevant regulation data is queried from the database, as are all relevant flights and their ETO. This data is used in the slot allocation process described in Section 4.1.
- From this slot allocation a CTOT is returned which is utilised in the CDM process. In case of multiple regulations the most penalising CTOT is returned.
- Flights are returned to the CDM process.

If something changes in the turnaround, then the slot allocation process is performed again. This may lead to a different CTOT, which can then again be taken into account in the CDM process. The main parameter to be investigated is the time between the flight being locked into a CTOT and the Actual Startup Time (ASAT) (or the time when a T-DPI-t switches to a T-DPI-s for a regulated flight). It will be varied in order to investigate the change in delay following changes to it. If a flight is not regulated, then it will pass through the CDM process as usual.

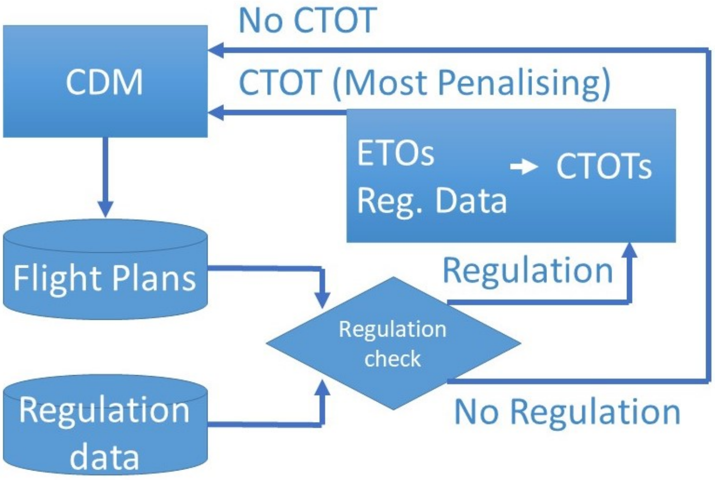


Figure 4.7: CDM and NM interaction data streams

5

Data Exploration & Analysis

As discussed in Chapter 4, several data sources are needed to run the fast-time simulation. These are data on regulations (when, where, what capacity, what flights, their status, and their ETOs), and data from the departures at Schiphol which include flight plans and historical data from the CDM system (for example when they were ready for startup in actual operation). The regulation data is discussed in Section 5.2, flight plan data is discussed in Section 5.3 and CDM data is discussed in Section 5.4. However, a lot of data from EUROCONTROL is only available for the public via their Network Strategic Tool, NEST. Because of this, a small introduction on NEST is presented first in Section 5.1.

5.1. Network Strategic Tool

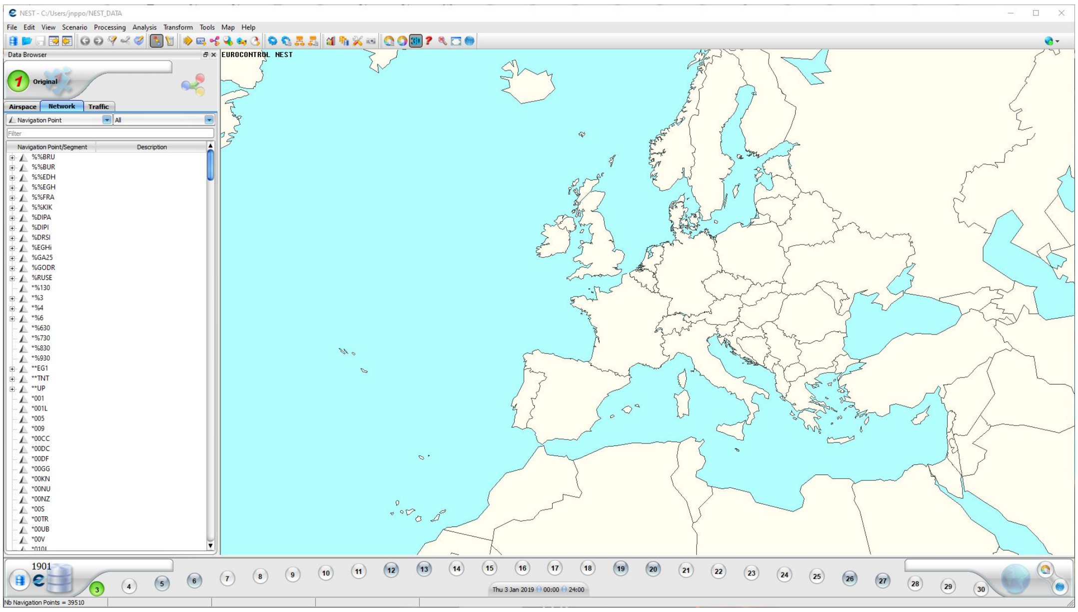


Figure 5.1: Overview of EUROCONTROL Network strategic tool (NEST)

The Network Strategic Tool, NEST, is a piece of software developed by EUROCONTROL aimed at scenario based network capacity planning and airspace design. The GUI is depicted in Figure 5.1. It is used internally at EUROCONTROL and by ANSPs to [43]:

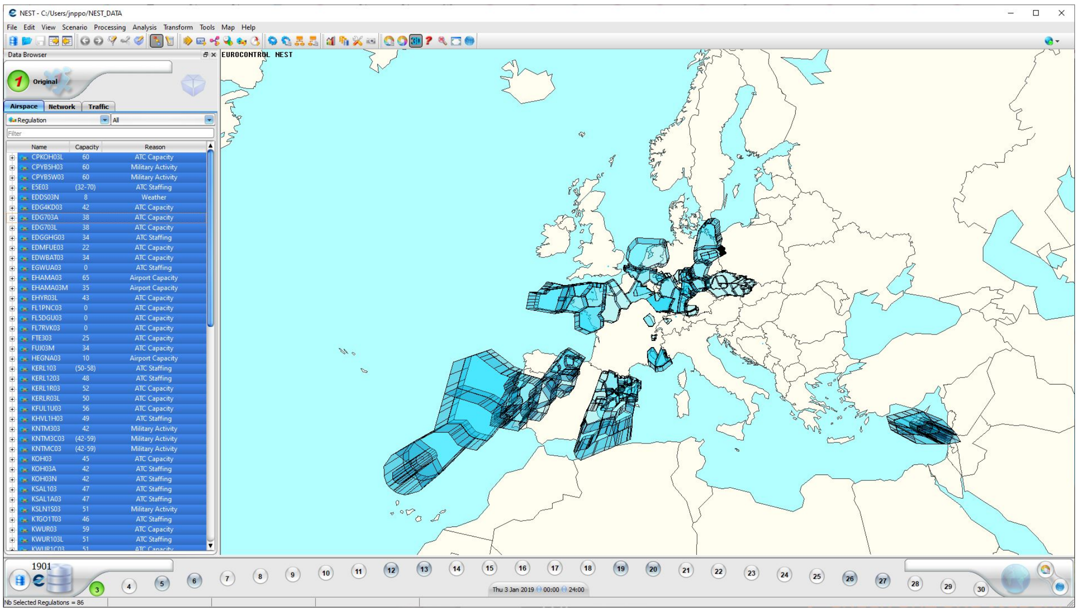
- optimise the available resources and improve performance at network level
- design and develop the airspace structure

- plan the capacity and performing related post operations analyses
- organise the traffic flows in the air traffic flow and capacity management (ATFCM) strategic phase
- prepare scenarios to support fast and real-time simulations
- conduct ad-hoc studies at local and network level

As NEST is scenario based small changes that are made can be easily evaluated. In order to support evaluating these changes, EUROCONTROL issues datasets for NEST at the end of each AIRAC cycle (AIRAC is shorthand for Aeronautical Information Regulation And Control, a definition of common dates where information is scheduled). These datasets contain the European airspace and route network, traffic information and distribution, and traffic forecasts made by EUROCONTROL [44]. This data can be used to perform one of the tasks above, for example, simulating changes in regulations and providing data and visualizations of the effect on delay.

It appears that NEST contains everything needed for this study, but this is not the case. As NEST is developed to evaluate changes made to the existing network setup it lacks a CDM component, which means the changes in time cannot be evaluated. Accessing NEST dynamically is also not possible, as it lacks an API, so the functions in it cannot be accessed via another program. This is also the case for the data in the AIRAC sets. While this data can be seen and evaluated in NEST, it is not possible to query it automatically externally, which means that all data must be exported manually. Doing this would severely scope the project, as this is very labor-intensive.

5.2. Regulation data



Name	Capacity	Reason
CPKOH03L	60	ATC Capacity
CPYB5H03	60	Military Activity
CPYB5W03	60	Military Activity
E5E03	(32-70)	ATC Staffing
EDDS03N	8	Weather
EDG4KD03	42	ATC Capacity
EDG703A	38	ATC Capacity
EDG703L	38	ATC Capacity
EDGGHG03	34	ATC Staffing
EDMFUE03	22	ATC Capacity
EDWBAT03	34	ATC Capacity
EGWUA03	0	ATC Staffing
EHAMA03	65	Airport Capacity
EHAMA03M	35	Airport Capacity
EHYR03L	43	ATC Capacity
FL1PNC03	0	ATC Capacity
FL5DGU03	0	ATC Capacity
FL7RVK03	0	ATC Capacity
FTE303	25	ATC Capacity
FUJ03M	34	ATC Capacity
HEGNA03	10	Airport Capacity
KERL103	(50-58)	ATC Staffing
KERL1203	48	ATC Staffing
KERL1R03	52	ATC Capacity
KERLR03L	50	ATC Capacity
KFUL1U03	56	ATC Capacity
KHVL1H03	49	ATC Staffing
KNTM303	42	Military Activity
KNTM3C03	(42-59)	Military Activity
KNTMC03	(42-59)	Military Activity
KOH03	45	ATC Capacity
KOH03A	42	ATC Staffing
KOH03N	42	ATC Staffing
KSAL103	47	ATC Staffing
KSAL1A03	47	ATC Staffing
KSLN1S03	51	Military Activity
KTGO1T03	46	ATC Staffing
KWUR03	59	ATC Capacity
KWUR103L	51	ATC Staffing
KWUR1C03	51	ATC Capacity

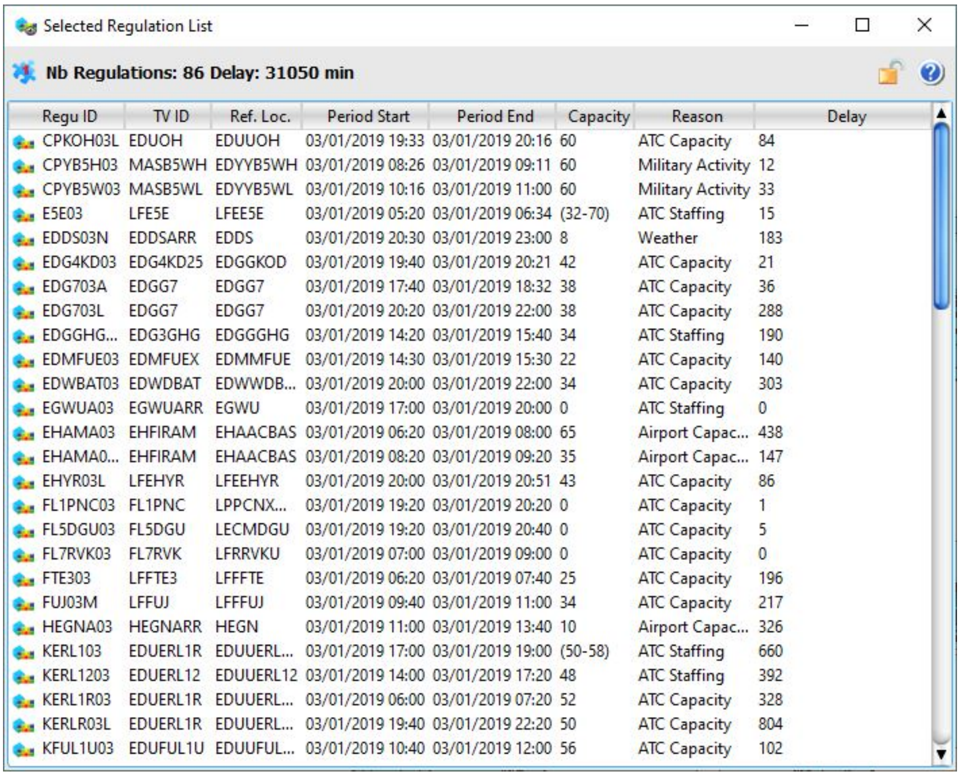
Nb Selected Regulations = 86

Figure 5.2: Regulations as shown in NEST

As discussed in Chapter 4 and in the introduction the following data is needed on regulations for the simulation:

- Regulation Identifier (location)
- Regulation Start Time
- Regulation End Time
- Regulation Capacity

Data on flights is also needed, but this is discussed in Section 5.3. NEST data sets contain data on historic regulations. An overview of all regulations on January 3rd 2019 is depicted in Figure 5.2. These



Nb Regulations: 86 Delay: 31050 min

Regu ID	TV ID	Ref. Loc.	Period Start	Period End	Capacity	Reason	Delay
CPKOH03L	EDUOH	EDUUOH	03/01/2019 19:33	03/01/2019 20:16	60	ATC Capacity	84
CPYB5H03	MASB5WH	EDYYB5WH	03/01/2019 08:26	03/01/2019 09:11	60	Military Activity	12
CPYB5W03	MASB5WL	EDYYB5WL	03/01/2019 10:16	03/01/2019 11:00	60	Military Activity	33
E5E03	LFE5E	LFEE5E	03/01/2019 05:20	03/01/2019 06:34	(32-70)	ATC Staffing	15
EDDS03N	EDDSARR	EDDS	03/01/2019 20:30	03/01/2019 23:00	8	Weather	183
EDG4KD03	EDG4KD25	EDGGKOD	03/01/2019 19:40	03/01/2019 20:21	42	ATC Capacity	21
EDG703A	EDGG7	EDGG7	03/01/2019 17:40	03/01/2019 18:32	38	ATC Capacity	36
EDG703L	EDGG7	EDGG7	03/01/2019 20:20	03/01/2019 22:00	38	ATC Capacity	288
EDGGHG...	EDG3GHG	EDGGGHG	03/01/2019 14:20	03/01/2019 15:40	34	ATC Staffing	190
EDMFUE03	EDMFUEX	EDMMFUE	03/01/2019 14:30	03/01/2019 15:30	22	ATC Capacity	140
EDWBAT03	EDWDBAT	EDWWDB...	03/01/2019 20:00	03/01/2019 22:00	34	ATC Capacity	303
EGWUA03	EGWUARR	EGWU	03/01/2019 17:00	03/01/2019 20:00	0	ATC Staffing	0
EHAMA03	EHFIRAM	EHAACBAS	03/01/2019 06:20	03/01/2019 08:00	65	Airport Capac...	438
EHAMA0...	EHFIRAM	EHAACBAS	03/01/2019 08:20	03/01/2019 09:20	35	Airport Capac...	147
EHYR03L	LFEHYR	LFEEHYR	03/01/2019 20:00	03/01/2019 20:51	43	ATC Capacity	86
FL1PNC03	FL1PNC	LPPCNX...	03/01/2019 19:20	03/01/2019 20:20	0	ATC Capacity	1
FL5DGU03	FL5DGU	LECMDGU	03/01/2019 19:20	03/01/2019 20:40	0	ATC Capacity	5
FL7RVK03	FL7RVK	LFRRVKU	03/01/2019 07:00	03/01/2019 09:00	0	ATC Capacity	0
FTE303	LFFTE3	LFFFTE	03/01/2019 06:20	03/01/2019 07:40	25	ATC Capacity	196
FUJ03M	LFFUJ	LFFFUJ	03/01/2019 09:40	03/01/2019 11:00	34	ATC Capacity	217
HEGNA03	HEGNARR	HEGN	03/01/2019 11:00	03/01/2019 13:40	10	Airport Capac...	326
KERL103	EDUERL1R	EDUUERL...	03/01/2019 17:00	03/01/2019 19:00	(50-58)	ATC Staffing	660
KERL1203	EDUERL12	EDUUERL12	03/01/2019 14:00	03/01/2019 17:20	48	ATC Staffing	392
KERL1R03	EDUERL1R	EDUUERL...	03/01/2019 06:00	03/01/2019 07:20	52	ATC Capacity	328
KERLR03L	EDUERL1R	EDUUERL...	03/01/2019 19:40	03/01/2019 22:20	50	ATC Capacity	804
KFUL1U03	EDUFUL1U	EDUUFUL...	03/01/2019 10:40	03/01/2019 12:00	56	ATC Capacity	102

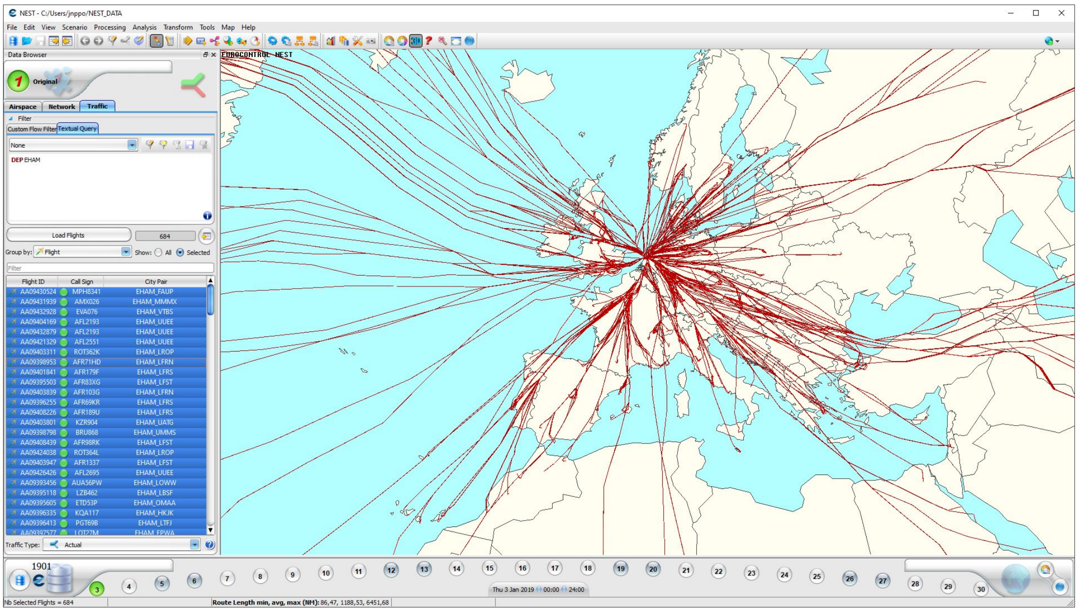
Figure 5.3: Regulations data as shown in NEST

regulations can be selected in NEST, leading to the list shown in Figure 5.3. It can be seen that the data contains the needed Regulation ID, Sector ID, the Reference Location ID, the Regulation Start and End and the capacity. The data on these regulations can be also be exported in bulk to a plain text file. Here it will have the following data headers:

- Parent ID
- Parent Type
- Regulation ID
- Sector / TV ID
- AS / TV
- Ref. Loc. ID
- Ref. Loc. Type
- Reason
- Window width
- Slice Width
- Date
- Label
- Day Before
- Start
- End
- Capacity
- Delay

It can be seen that this contains more data that could be useful. For example, this denotes if the regulation is active on more than 1 day, which could make processing multiple days easier.

5.3. Flight plans



None

DEP EHAM

684

Group by: Flight Show: ○ All ● Selected

Flight ID	Call Sign	City Pair
AA09430524	MPH8341	EHAM_FAUP
AA09431939	AMX026	EHAM_MMMX
AA09432928	EVA076	EHAM_VTBS
AA09404169	AFL2193	EHAM_UUEE
AA09432879	AFL2193	EHAM_UUEE
AA09421329	AFL2551	EHAM_UUEE
AA09403311	ROT362K	EHAM_LROP
AA09398953	AFR71HD	EHAM_LFRN
AA09401841	AFR179F	EHAM_LFRS
AA09395503	AFR83XG	EHAM_LFST
AA09403839	AFR103G	EHAM_LFRN
AA09396255	AFR69KR	EHAM_LFRS
AA09408226	AFR189U	EHAM_LFRS
AA09403801	KZR904	EHAM_UATG
AA09398798	BRU868	EHAM_UMMS
AA09408439	AFR98RK	EHAM_LFST
AA09424038	ROT364L	EHAM_LROP
AA09403947	AFR1337	EHAM_LFST
AA09426426	AFL2695	EHAM_UUEE
AA09393456	AUA56PW	EHAM_LOWW
AA09395118	LZB462	EHAM_LBSF
AA09395605	ETD53P	EHAM_OMAA
AA09396335	KQA117	EHAM_HKJK
AA09396413	PGT69B	EHAM_LTFJ
AA09397577	LOT27M	EHAM_EPWA

Traffic Type: Actual

Thu 3 Jan 2019 00:00 24:00

Nb Selected Flights = 684

Route Length min, avg, max (NM): 86,47, 1188,53, 6451,68

Figure 5.4: Flights from NEST

The following data is needed from the flight plans to work together with the regulations:

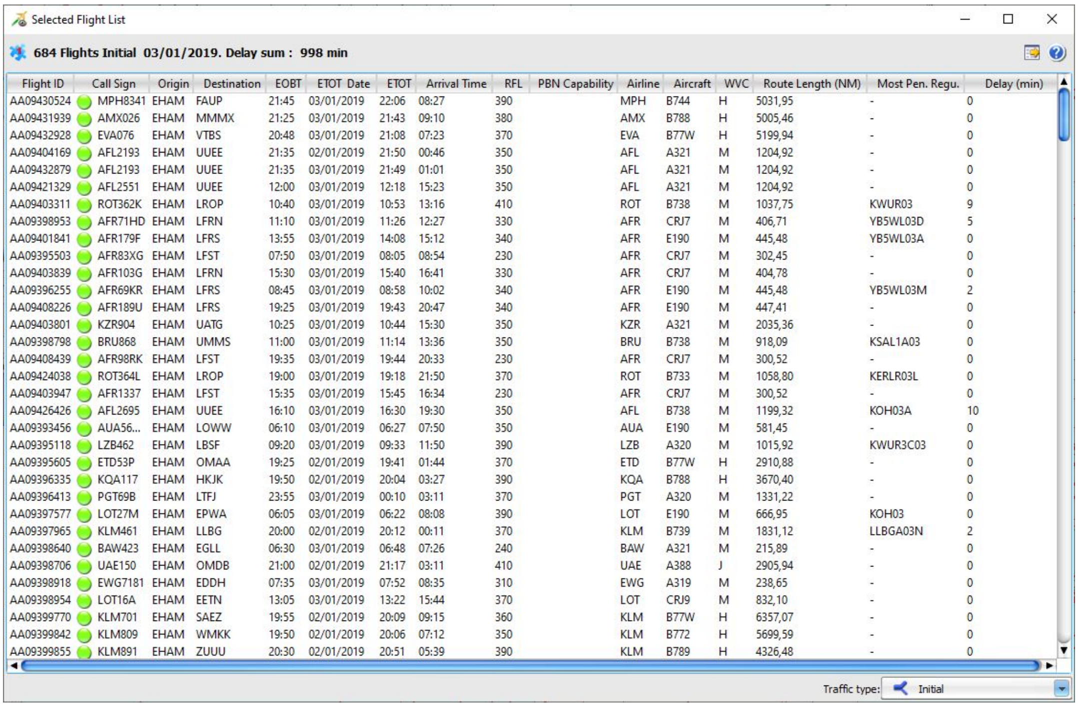
- Flight ID
- Route
- Flight Status (i.e. non-regulatable)

The way this data is envisioned is as follows; for flights departing from Schiphol the route points from the flight plan can be used to ascertain whether there are regulations that will be encountered en-route. If there are none, nothing happens. However, if there are regulations that will be encountered the flight plans of all flights affected by this regulation will be queried. The flights plans for other flights will contain an ETO, which can be used together with a projected ETO of the departure from Schiphol. NEST contains data from all flights and thus also contains data on all departures from Schiphol, which can be observed in Figure 5.4.

Unlike the regulation data, this flight plan data is not as easily exported from NEST. For each regulation, there is a regulated flight list. Such a list can be seen in Figure 5.5. This list contains all flights that are affected by a selected regulation. Data on these flights contains whether they were regulatable and for example their origin, destination, off-block, take off and arrival times. Crucially, this list does not contain the routing for a flight, which must be exported separately. This means that for each day it may be needed to export over 1000 flight plans by hand, which can be done but would severely limit the scope of this thesis.

The flights plans for Schiphol departures are readily accessible, as these are still present in the systems of LVNL. These files are split into hours of the day, containing all routing information. Before use, these must be appended in order to contain all information on a day. Compare routes to (regulation) sectors can be performed using a database of routing points and the relevant sector, or using a coordinate database for both routing points and sectors. Both methods might be feasible, and a method will be selected during implementation.

A final note on the relevant flights plans for regulations (excluding Schiphol departures): it is recognized that their flight plans are not strictly needed in order to perform the allocation by CASA. After all, only their ETO and their exemption status needs to be known. However, currently no source for these ETOs is known, and they must thus be calculated from accessible data. At a later stage of this project access to data containing only these ETOs could still be granted. In any case, flights plans can also be made into ETOs with a small amount of processing, creating a list of ETOs per regulation which is more computationally efficient in the model run compared to processing flight plans on the go.


Selected Flight List

684 Flights Initial 03/01/2019. Delay sum : 998 min

Flight ID	Call Sign	Origin	Destination	EOBT	ETOT Date	ETOT	Arrival Time	RFL	PBN Capability	Airline	Aircraft	WVC	Route Length (NM)	Most Pen. Regu.	Delay (min)
AA09430524	● MPH8341	EHAM	FAUP	21:45	03/01/2019	22:06	08:27	390		MPH	B744	H	5031,95	-	0
AA09431939	● AMX026	EHAM	MMMX	21:25	03/01/2019	21:43	09:10	380		AMX	B788	H	5005,46	-	0
AA09432928	● EVA076	EHAM	VTBS	20:48	03/01/2019	21:08	07:23	370		EVA	B77W	H	5199,94	-	0
AA09404169	● AFL2193	EHAM	UUEE	21:35	02/01/2019	21:50	00:46	350		AFL	A321	M	1204,92	-	0
AA09432879	● AFL2193	EHAM	UUEE	21:35	03/01/2019	21:49	01:01	350		AFL	A321	M	1204,92	-	0
AA09421329	● AFL2551	EHAM	UUEE	12:00	03/01/2019	12:18	15:23	350		AFL	A321	M	1204,92	-	0
AA09403311	● ROT362K	EHAM	LROP	10:40	03/01/2019	10:53	13:16	410		ROT	B738	M	1037,75	KWUR03	9
AA09398953	● AFR71HD	EHAM	LFRN	11:10	03/01/2019	11:26	12:27	330		AFR	CRJ7	M	406,71	YB5WL03D	5
AA09401841	● AFR179F	EHAM	LFRS	13:55	03/01/2019	14:08	15:12	340		AFR	E190	M	445,48	YB5WL03A	0
AA09395503	● AFR83XG	EHAM	LFST	07:50	03/01/2019	08:05	08:54	230		AFR	CRJ7	M	302,45	-	0
AA09403839	● AFR103G	EHAM	LFRN	15:30	03/01/2019	15:40	16:41	330		AFR	CRJ7	M	404,78	-	0
AA09396255	● AFR69KR	EHAM	LFRS	08:45	03/01/2019	08:58	10:02	340		AFR	E190	M	445,48	YB5WL03M	2
AA09408226	● AFR189U	EHAM	LFRS	19:25	03/01/2019	19:43	20:47	340		AFR	E190	M	447,41	-	0
AA09403801	● KZR904	EHAM	UATG	10:25	03/01/2019	10:44	15:30	350		KZR	A321	M	2035,36	-	0
AA09398798	● BRU868	EHAM	UMMS	11:00	03/01/2019	11:14	13:36	350		BRU	B738	M	918,09	KSAL1A03	0
AA09408439	● AFR98RK	EHAM	LFST	19:35	03/01/2019	19:44	20:33	230		AFR	CRJ7	M	300,52	-	0
AA09424038	● ROT364L	EHAM	LROP	19:00	03/01/2019	19:18	21:50	370		ROT	B733	M	1058,80	KERLR03L	0
AA09403947	● AFR1337	EHAM	LFST	15:35	03/01/2019	15:45	16:34	230		AFR	CRJ7	M	300,52	-	0
AA09426426	● AFL2695	EHAM	UUEE	16:10	03/01/2019	16:30	19:30	350		AFL	B738	M	1199,32	KOH03A	10
AA09393456	● AUA56...	EHAM	LOWW	06:10	03/01/2019	06:27	07:50	350		AUA	E190	M	581,45	-	0
AA09395118	● LZB462	EHAM	LBSF	09:20	03/01/2019	09:33	11:50	390		LZB	A320	M	1015,92	KWUR3C03	0
AA09395605	● ETD53P	EHAM	OMAA	19:25	02/01/2019	19:41	01:44	370		ETD	B77W	H	2910,88	-	0
AA09396335	● KQA117	EHAM	HKJK	19:50	02/01/2019	20:04	03:27	390		KQA	B788	H	3670,40	-	0
AA09396413	● PGT69B	EHAM	LTFJ	23:55	03/01/2019	00:10	03:11	370		PGT	A320	M	1331,22	-	0
AA09397577	● LOT27M	EHAM	EPWA	06:05	03/01/2019	06:22	08:08	390		LOT	E190	M	666,95	KOH03	0
AA09397965	● KLM461	EHAM	LLBG	20:00	02/01/2019	20:12	00:11	370		KLM	B739	M	1831,12	LLBGA03N	2
AA09398640	● BAW423	EHAM	EGLL	06:30	03/01/2019	06:48	07:26	240		BAW	A321	M	215,89	-	0
AA09398706	● UAE150	EHAM	OMDB	21:00	02/01/2019	21:17	03:11	410		UAE	A388	J	2905,94	-	0
AA09398918	● EWG7181	EHAM	EDDH	07:35	03/01/2019	07:52	08:35	310		EWG	A319	M	238,65	-	0
AA09398954	● LOT16A	EHAM	EETN	13:05	03/01/2019	13:22	15:44	370		LOT	CRJ9	M	832,10	-	0
AA09399770	● KLM701	EHAM	SAEZ	19:55	02/01/2019	20:09	09:15	360		KLM	B77W	H	6357,07	-	0
AA09399842	● KLM809	EHAM	WMKK	19:50	02/01/2019	20:06	07:12	350		KLM	B772	H	5699,59	-	0
AA09399855	● KLM891	EHAM	ZUUU	20:30	02/01/2019	20:51	05:39	390		KLM	B789	H	4326,48	-	0

Traffic type: Initial

Figure 5.5: Flight data from NEST

5.4. CDM data

The data needed for the CDM process has been provided by LVNL. It is provided in blocks of a month instead of by AIRAC. The headers of the data and their meaning can be seen in Appendix B. This dataset contains every update sent to the CDM server as it actually happened throughout all of 2019. Only a part of it is relevant, as there are also arrival data updates being sent; and there is also info in the dataset that is not applicable here.

Of note is the way time is used in the CDM data. Instead of a date time format (for example YYYY-MM-DD HH:mm:ss) time the CDM data is in the Unix time format. This format is widely used in computing, and denotes time by the amount of seconds passed since January 1st 1970 at 00:00:00 UTC. Unix time is useful in computers since the date and time can be saved as a single variable, and with the 32-bit standard this format will work until 19 January 2038. However, the way date and time are saved by NEST are not in Unix time, and to use these dates with the CDM data they will need to be converted to it. The same holds for selecting specific days in the data, as it is split by month. Conversion is trivial, but it can be time-consuming and should be avoided where possible.

Some pre-processing needs to be performed on this data in order to use it in the fast-time simulation. As this data contains all updates issued to the flight it is possible to revert it back to a database of when what was updated. This is needed as the simulation would not otherwise know these updates, as no live data is being fed into it. Turnaround times could also be simulated, but this may not lead to a good representation of the updates on that day, and these turnaround phases would need to be modeled first, which would be a big research project on its own.

To summarize: per flight the initial states need to be saved, together with when the flight was initialized. After this, every update and when it happened, as well as what category it belongs in, needs to be extracted as well. This needs to be done to make it clear to the later simulation when all milestones happened.

6

Research Proposal

Before any analyses, modelling, or simulations can be performed, it is essential to scope the project. This allows for research that is focused, structured, plannable, and executable in the set time boundaries. In this project the key lies in understanding and mapping out the relevant parts of the CDM process and CASA, together with all the relevant inputs. In this chapter the outline and continuation of this thesis projected is presented. It can be seen as an extension of Chapter 2. There, the reasons for this project were discussed. Here, with the rest of this report as background, the way of realizing this project is discussed. Therefore, an extensive literature study is required as there are no off-the-shelf solutions or systems recreations (publicly) available. Once there is a clear path towards custom CDM and CASA implementations the first step of the framework will be complete. This chapter contains a small high-level summary of the performed research, a discussion on the experimental setup, and the expected results and how they will add value.

6.1. Research Performed

The context of the project is presented in Chapter 3. In this, the background on the delay at Schiphol was shown. Compared to other airports in the European network, it appears that Schiphol has a disproportionate amount of delay for its departing flights. In the long-term, this could lead to travelers avoiding Schiphol. ATFM delay is a substantial part of these delays. Furthermore, the systems that are part of the network wide communication and the creation of ATFM delays, the Airport CDM system and CASA, were also described here.

In order to investigate the departure ATFM delays these systems and their interactions need to be modeled, as their workings and interactions are too complex to easily draw conclusions from. For example, a change in the planning of one flight may not only lead to that flight being delayed and re-entering slot allocation calculations at the Network Manager, but this may also lead to a snowball effect that can be observed throughout the network. In order to support this a fast-time model implementation was proposed in Chapter 4.

In order to accurately model the actual situation the models need to be fed with representative data. The data sources used in this project were described in Chapter 5. As there is an abundance of historic data this can be adapted to feed the model. The changes that need to be made in order to use this data in the simulation are also described in Chapter 5.

6.2. Experimental setup

This section describes the set-up of the experiment, taking into account the relevant context and the stated research goals. The model set-up is described in Chapter 4, here the focus is on the experiment and its limitations.

6.2.1. Model

The proposed model will be written in Python. Python is a high-level general-purpose programming language that is widely taught and used throughout the BSc. and MSc. program of Aerospace Engineering at Delft University of Technology. The code will be extensively documented in order to provide guidance on decisions in the case of future continuation of relevant research where these programs need to be applied. While Python is not computationally efficient when compared to e.g. C(++) or Java, it is a simple to modify language with many available resources that handles large datasets well, such as the CDM data described in Section 5.4. Computational time is also not the main driver of this research as long as it is within reasonable bounds, as the main analysis is a post-operational analysis based on historical data and not a real-time application. For further analysis of the results of this research Python will also be used. In this way, the experiment will be easily reproducible for someone with access to the same date, as access to Python is ubiquitous, and the model will be open-source if approved by the stakeholders in the process.

6.2.2. Independent variables and output

As mentioned in Chapter 4 the proposed models are a modified fast-time simulation of the CDM process with a Network Manager component added to it for the ATFM delays. The independent variable used in testing is the time horizon between the Actual Start-Up Time and the time where the T-DPI-t message switches to a T-DPI-s message, signifying finalization of the planning for a specific flight. This variable can be made visible in Figure 3.5, leading to Figure 6.1.

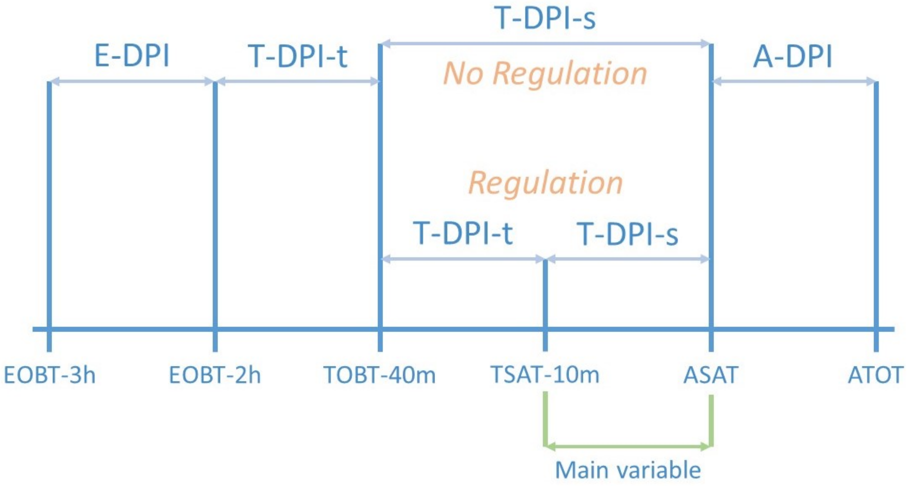


Figure 6.1: Main variable in project (based on Schiphol CDM Manual [35])

The changes in these times will be in the order of (multiple) minutes. The main focus of this project will be lengthening this time to see if the interaction stabilizes and the total amount of delay decreases because of it. It must also be noted that increasing this time does come with detrimental effects, as the flexibility of the operation is reduced, leading to a trade-off between informing the Network Manager and the flexibility of the operation. Shortening this timespan will also be investigated. If drastically reducing the time does not lead to a significantly higher amount of delay, this may also be helpful in operation, as this leaves more time for slot improvement by the Network Manager.

Runs with different times will result in different amounts of delay issued on that day. By comparing these outcomes it will be possible to see the impact of changing this time. The algorithm is set to have a set outcome for each run, but a sensitivity analysis is needed to see if a run has a local maximum/minimum or whether the change is a true change in the amount of delay.

6.2.3. Data

While synthetic data could be used there seems to be no real advantages to taking this approach as the focus is on the actual workings of Schiphol, and getting synthetic data to the point where the nuances of the actual operation aren't lost could be a research topic on its own. This does mean that the actual data needs to be collected and processed. Data can be collected from relevant partners like LVNL, RSG and EUROCONTROL that are product owners of the systems. Partners is unwilling to share data, for example if certain performance characteristics can be derived from it. For now, it is assumed that getting data from partners is not an issue, and the relevant data sources have already been identified as discussed in Chapter 5. Once the systems are implemented it might be possible to adapt them to shadow the actual systems at Schiphol in real-time use (if the correct datastreams are entered into it), but this is outside the scope of the project.

6.2.4. Verification and Validation

An important part in proving these findings are representative for the actual situation at Amsterdam Airport Schiphol is verification and validation. Verification can be performed on both systems via code review and unit testing. Verification after coupling the two systems will also be performed, but might be complex, especially if complicated synthetic data will need to be generated to perform this test.

For validation, the system can be run with the data from a day with the original interaction between the two systems. The outcome of this will then be able to be compared to the actual events of that day in NEST and the LVNL data. While this needs to be as accurate as possible, it is replicating a complex system and results within an order of magnitude in total ATFM delay minutes can already be seen as relatively representative.

6.2.5. Limitations

While the data from LVNL and EUROCONTROL will not be able to be made available for the general public the outcomes of the system will be, as these do not contain any sensitive data. The systems themselves will also be able to be made public after a scrub of any comments containing sensitive data. This will also facilitate future research into this subject, possibly performed on the basis of the recommendations that will follow the outcome of this study.

A big limitation in this study will be the assumption that the flights will be able to follow a (modified) CDM process. As the phases of the turnaround are not modeled (either with distribution or via a rule based approach) exceptions may happen in the real situation that are not present in the model representation. Nevertheless, the outcomes of this study should still be valid, with more research into these effects possible at a later moment.

6.3. Results

This study will lead to more insight in the CDM/NM interactions at Amsterdam Airport Schiphol. These new insights will hopefully be used to move towards lowering the amount of delay at the airport and improving the operation, but this implementation is not the aim of this research. Insights found in this project may also be implemented at other airports to lead to the desirable effects that may come out of this study. However, research into these measures at another airport is needed to show if the effects hold, since there are many factors coming together in this, leading to these interactions instead of having clear linear relationships.

This study will broaden understandings of Air Traffic Flow Management in Europe, as no studies have previously been performed in this subject that are available publicly. For most partners in and around airports the workings of the Airport Collaborative Decision Making system and the workings of the Network Manager are just assumed to work in the way they work because that is how they work. This report aims to begin a change in perspective on this subject.

7

Conclusion

This report presents the first steps in the research project clarifying the interaction between the Network Manager and Amsterdam Airport Schiphol in the area of ATFM delay. In order to take these steps this report contains a literature study into Air Traffic Flow Management (specifically in Europe), ATFM delay (in general and at Schiphol), the systems in use at the EUROCONTROL Network Manager Operations Centre, and the CDM process at Schiphol. In this literature study it was found that Schiphol has both a relative and high position in both arrival and departure delays, of which ATFM delay is a big part. In the case of the departures, there is an interaction between the Network Manager and the CDM process which has not been investigated before. Changing the time horizon where this interaction takes place may reduce departure ATFM delay. However, as these systems are highly complex, they need to be accurately modeled to a sufficient degree in order to investigate these interactions.

A modelling approach to appease these concerns was proposed in this report. The proposed approach uses fast-time models of the CASA and CDM systems in order to quickly and accurately reflect the effect of changes to the time horizon in the CDM process. Historic data for these models will be gathered from LVNL and EUROCONTROL. The use of historic data instead of synthetic data will hopefully allow the model to capture the nuances of these systems more easily.

The results from study will lead to more insight in the CDM/NM interactions at Amsterdam Airport Schiphol. This will hopefully lead towards lowering the amount of delay at the airport and improving the operation. Insights found in this project may also be implemented at other airports if desirable effects come out of this study. No matter the outcome of the research, this study will broaden understandings of Air Traffic Flow Management in Europe and its interaction with airport systems.

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A

ATFM Delay Codes

Regulation cause	Code	Guidelines
Accident/incident	A	Reduction of expected ATC capacity due to an aircraft accident / incident
ATC capacity	C	Demand exceeds or complexity reduces declared or expected ATC capacity
Aerodrome services	E	Reduced capacity due to the degradation or non-availability of support equipment at an airport e.g. Fire Service, De-icing / snow removal equipment or other ground handling equipment.
Aerodrome capacity	G	Reduction in declared or expected capacity due to the degradation or non-availability of infrastructure at an airport e.g. Work in Progress, shortage of aircraft stands etc. Or when demand exceeds expected aerodrome capacity.
Industrial action (ATC)	I	Reduction in any capacity due to industrial action by ATC staff
Airspace management	M	Reduction in declared or expected capacity following changes in airspace / route availability due to small scale military activity
Industrial action (non-ATC)	N	A reduction in expected / planned capacity due to industrial action by non ATC personnel.
Special event	P	Reduction in planned, declared or expected capacity or when demand exceeds the above capacities as a result of a major sporting, governmental or social event. It may also be used for ATM system upgrades and transitions. Large multinational military exercises may also use this reason. This category should only be used with prior approval during the planning process.
ATC routeings	R	Network solutions / scenarios used to balance demand and capacity
ATC staffing	S	Unplanned staff shortage reducing expected capacity
ATC equipment	T	Reduction of expected or declared capacity due to the non-availability or degradation of equipment used to provide an ATC service
Environmental issue	V	Reduction in any capacity or when demand exceeds any capacity due to agreed local noise, runway usage or similar procedures. This category should only be used with prior agreement in the planning process.
Weather	W	Reduction in expected capacity due to any weather phenomena. This includes where weather impacts airport infrastructure capacity, but where aerodrome services are operating as planned / expected.
Other	O	This should only be used in exceptional circumstances when no other category is sufficient. An explanatory ANM remark MUST be given to allow post ops analysis.

B

CDM information headers

Header	Meaning
timesec	Unix timestamp (epoch)
sfplid	Internal ID
acid	Aircraft id (flight name)
adep	Departure airport
dest	Destination
eobt	Expected Off-Block Time
actype	Aircraft type indicator
wtc	Weight class
flightState	Tower flight state
etd	Estimated time of departure
retd	Revised estimated time of departure
atd	Actual time of departure
atd	Actual time of departure
eta	Estimated time of arrival
ata	Actual time of arrival
aibt	Actual in block time
aobt	Actual off block time
eibt	Estimated in block time (eta + taxi)
etot	Estimated takeoff time
tasat	Target start up time
ttot	Target take off time
asrt	Actual startup request time
sobt	Scheduled off block time
tobt	Target off block time
slot	Slot (landing slot arrivals from asap)
firDelay	Difference slot and eta
trwy	Takeoff runway
lrwy	Landing runway
depGnr	Departure gate
arrGnr	Arrival gate
sid	Standard instrument departure
ssr	SSR code
text	Comments (between tower and AAA)
as_corr_state	Astra correllation state
as_airport_area	Astra airport area
as_presentation_area	Astra presentation area
fpos_state	Flight position state (status flight position data) .P = ... position
ctot	Calculated takeoff time
heli_ind	Heli indicator
engine_type	Engine type
nr_of_engine	Number of engines
bat	Best arrival time
stack	Arrival stack
reg	Registration
mtw	NOT maximum takeoff weight, unknown
edit	Unknown
mlut	Unknown
cdmfs	CDM flight state
rpark	Remote parking
deicing_state	Deicing state
center_crossing	Whiskey 5 36C/18C crossing to 36L/18R
vlc	Unknown