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Abstract	
<p>This document reports on how the CASSIOPEIA agent-based model has been developed, through a case study, to explore the use of dynamic cost indexing on flights arriving at a major European hub airport. A scenario that simulated many flights using dynamic cost indexing to recover delay to a residual of 10 minutes resulted in a considerable average cost saving achieved per flight.</p>	

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Executive summary

This case study uses the agent-based modelling capabilities of CASSIOPEIA's platform to explore hub airport connectivity-driven variable aircraft speeds. The use of such variable speeds in delay management is also known as 'dynamic cost indexing'. This deliverable reports on the implementation of the case study, thus building on the design phases that have been described in previous deliverables.

A busy operational day in 2010, not unduly affected by flight disruption, has been carefully selected for the simulation, with multiple datasets sourced, cleaned and prepared for use with the model. Primary data have been used wherever possible, with the use of real passenger connectivity data at a large hub airport central to the case study. A full airline cost impact assessment, including airline-tailored passenger hard and soft costs, is included.

Three hierarchical dynamic cost indexing (DCI) uptake scenarios are used. These range from very few flights using DCI through to a scenario comparable in some respects to 4D trajectory management. Two fuel price scenarios are also modelled. These scenarios are nested by four levels of DCI implementation rules (relating to company policies to 'do nothing' when a flight is delayed; to recover all delay; to recover up to a residual amount of delay; and to cost-optimize delay recovery) that draw on the operational practice of airlines.

The agent-based model has produced credible cost outputs, with results that support the cost saving benefits of flying variable aircraft speeds – the cost of recovering delay through additional fuel burn can be counteracted by the reduction in passenger, crew and maintenance costs with time saved. The key findings of the simulation runs are discussed.

One scenario that simulated six airlines using DCI to recover delay to a residual of 10 minutes resulted in a considerable cost saving achieved per flight. Leaving this residual delay demonstrated superior results compared with the 'rule of thumb' policy employed by many airlines of recovering all delay above a certain threshold. A dominating effect of a high fuel price was also observed, with non-fuel cost savings unable to offset the increased fuel cost resulting in a net loss when DCI was applied.

Acknowledgements

We would like to acknowledge the kind assistance of Flughafen Zürich AG (Zürich Airport Authority) for permitting the use of Zürich Airport passenger connectivity data and Zürcher Hochschule für Angewandte Wissenschaften (Zürich University of Applied Sciences, ZHAW) for their help arranging access to the passenger data, and for compiling the database. Our thanks also go to the PRISME, DDR and CODA teams at EUROCONTROL for the provision of traffic and taxi time data.

Our gratitude goes to the airlines, ANSPs and other experts who participated in the Gatwick workshop for providing expert feedback on operational practice that helped refine the DCI rules.

1 Introduction

The objective of CASSIOPEIA's third case study was to demonstrate the usefulness of applying agent-based modelling (ABM) to understanding the impact of an increased use of dynamic cost indexing (DCI) into a major European hub. DCI involves the use of variable aircraft speeds, employed as an attempt by airlines to better manage delay costs. Increased use of DCI implies improved temporal trajectory flexibility. This flexibility provides utility to the airlines and potentially causes ANSPs disutility. Trade-offs have been examined using three scenarios of DCI uptake by airlines (with two fuel prices), nested by four levels of DCI implementation rules. The temporal scope is from current to medium-term future operations. Data availability has (in this case study) forced a choice between *either* high-fidelity passenger connectivity data *or* high-fidelity flight profile data, due to the periods for which such data are available. The former has been chosen as the more critical, since passenger connectivity drives the decision-making with regard to the aircraft and would be difficult to approximate probabilistically. The flight profile data, on the other hand, may be approximated to a reasonable extent based on available sources. Access to unique, real passenger connectivity data has been negotiated with a major European airport, although extensive cleaning thereof was required.

1.1 Purpose of the document

This document presents the description of Case Study 3, covering the data requirements, design of the simulation rules and scenarios and an outline of implementing the simulation using the agent-based software platform.

1.2 Intended readership

This report assumes the reader has a good knowledge and understanding of the European air transport system, airline operations, airports and ATM. It will be of interest to those engaged in delay cost management and/or the application of ABM in the air transport context.

1.3 Structure of the Document

The document is structured into five main sections and is mostly self-contained, so can be followed without knowledge of the previous deliverables or CASSIOPEIA's platform. After the overall introduction, Case Study 3 is defined with consideration of the required inputs, rules and scenarios. The third section outlines model implementation, offering an insight to the agents' capability. Findings and conclusions follow in Sections 4 and 5.

1.4 Inputs from other projects

N/A.

1.5 Acronyms and Terminology

Term	Definition
4DT	4D Trajectory
ABM	Agent-based model(ling)

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Term	Definition
ACMI	Aircraft, crew, maintenance and insurance
ADF	Application Development Framework
AIBT	Actual in-block time
ANSP	Air Navigation Service Provider
AO	Airline Operator
AOBT	Actual off-block time
APTI	Actual passing time over IAF (end of cruise)
ARCT	Actual reaching cruise time
ATA	Actual time of arrival (landing time)
ATFM	Air Traffic Flow Management
ATOT	Actual take-off time
BADA	Base of Aircraft Data
CHT	Charter carrier
CI	Cost Index
CO ₂	Carbon dioxide
CODA	Central Office for Delay Analysis
CRCO	Central Route Charges Office
DCI	Dynamic cost indexing
DDR	Demand Data Repository
ECAC	European Civil Aviation Conference
EFB	Electronic flight bag
EIBT	Estimated in-block time
FFP	Frequent flyer programme
FMS	Flight management system
FSC	Full-service carrier
GCD	Great circle distance

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Term	Definition
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IFR	Instrument Flight Rules
IOBT	Initial estimated off-block time
KPA	Key Performance Area
LCC	Low-cost carrier
LSZH	Zürich Airport (ICAO code)
MTOW	Maximum take-off weight
NM	Network Manager
Pax	Passengers
PaxIS	Passenger Intelligence Services (IATA)
PRISME	Pan-European Repository of Information Supporting the Management of EATM
PRU	Performance Review Unit
RDBMS	Relational Database Management System
REG	Regional carrier
s.d.	Standard deviation
s.f.	Significant figures
SIBT	Scheduled in-block time
SLF	Seat load factor (percentage of seats occupied in a flight)
SOBT	Scheduled off-block time
XML	Extensible Markup Language
ZRH	Zürich Airport (IATA code)

2 Case Study 3 definition

2.1 Definition

Previously introduced, dynamic cost indexing is employed by airlines to better manage delay costs. The cost index is a flight management system (FMS) setting in which a low value directs the aircraft to minimise fuel consumption and maximise range, and conversely a high value minimises flight time, regardless of fuel cost.

The policies for the use of variable aircraft speeds vary between airlines. The University of Westminster organised a stakeholder workshop at Gatwick Airport in October 2012 to explore operational issues with airlines, ANSPs and other industry experts – this included the use of DCI. Feedback from these stakeholders has been considered during the development of the case study (e.g. in airport selection and the degree of delay recovery possible in the real world) and incorporated in the design of the simulation rules. Key findings from the workshop include:

- Examples of when an airline would make a speed change:
 - It is company policy to attempt the recovery of **all** delay (e.g. for corporate or high-level target setting), this can be regarded as a ‘rule of thumb’;
 - The flight is into a hub airport;
 - The flight is into a less congested airport with no risk of being held on arrival and losing the recovered time;
 - The flight is likely to delay another flight operated by the same airline;
 - The number of connecting passengers on board is known by the flight crew (e.g. via the EFB), including ticket class and likely reaccommodation cost to the airline if onward connections are missed.
- Examples of when an airline would not make a speed change:
 - It is company policy never to speed up or slow down (i.e. flight crew are instructed to maintain the company’s CI setting for the flown aircraft type) except when required to meet curfews or night time bans;
 - It is company policy not to speed up into outbound hubs where the airline has less control of turnaround processes (compared with the airline’s base airport) and any en-route time saving could then be lost;
 - The effect of a delay is unknown.
- Examples of how controller workload is affected by speed change:
 - Variations in speed between aircraft is a greater challenge than a change of speed by a single aircraft (e.g. A320s flying .69 and .79, or two aircraft with the same type and operator flying .71 and .79);
 - Variation in speed is increasing as different operators respond to cost pressures with different priorities – these speed variations can be currently accommodated because traffic levels are below their peak five years ago, however variation would be a problem with a return of previous traffic levels.

2.1.1 Alignment with previous deliverables

This section analyses the alignment of this deliverable with previous deliverables of the project. Different issues raised during the implementation process, such as the type and extent of data acquired and its sensitivity, have restricted to a certain extent the initial scope presented at the beginning of the project. These changes in the scope are understood as normal in the aeronautical

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research field, and especially in CASSIOPEIA, where most of the effort has been input into developing the computer infrastructure of an agent-based model (ABM). The ABM platform developed has been tested in three case studies, each of which with its own temporal scale, scope, agents, strategies and individual decision making processes. While the main part of the computer infrastructure is the same, the reality is that in CASSIOPEIA we have generated three different research projects due to their different characteristics.

For Case Study 3, the aeronautical side of the research has explored a highly detailed and sensitive aspect of operations: the dynamic cost index application (DCI). DCI management has become in the last few years a tool that airlines have not mastered in combination with schedule recovery management. Due to the fact that cost of delay varies significantly between each aircraft based on the connections of the passengers it carries, and the variable cost of fuel, DCI has to be managed individually and in combination with schedule recovery management. The application of ABM has allowed us to select different airlines to apply different strategies in different scenarios of DCI application.

In D3.3, the objective of the case study was stated to be to explore the impact on KPIs (for ATM in general, and airlines in particular), of aircraft flying with different departure times and/or flight profiles, with different speeds and/or CI values, to optimise fuel and CO₂ costs. In particular, we wish to explore the network-level impacts of new behaviours.

The main objective of the case study has been achieved since we have managed to implement DCI application to selected airlines flying into Zürich Airport; not only exploring impact on KPIs, but identifying how different combinations of **DCI - Schedule recovery application** strategies affect passengers' delay, fuel consumption, fuel emissions, and their related costs to airline operators. While the case study has been successful in this part of the objective, the absence of passenger data for the rest of European traffic has not allowed us to explore network-level impacts of new behaviours. This restriction in the scope has obliged us to drop some of the complexity metrics presented in D2.5. However, setting up the platform of this case study has a greater value to the researchers than the results obtained, it has opened the door to a research field that will be explored from a classical and complex approach in the near future.

2.2 Inputs

Zürich Airport has been chosen as the European hub to model, with a busy weekday selected as the period to model.

The three runway airport is the hub for SWISS, a member of Star Alliance, and in 2010 was the 12th busiest ECAC airport for total passengers and 13th busiest for movements (ACI EUROPE, 2011). In 2010, 35% of passengers¹ at Zürich were transfer (connecting) passengers, a proportion comparable to SkyTeam's Paris Charles de Gaulle (30%) and Amsterdam Schiphol (41%) hubs, oneworld's London Heathrow (35%) hub and Star Alliance's second hub at Munich (37%)².

2.2.1 Day selection

A single busy weekday, not unduly disrupted by bad weather or industrial action, was selected from AUG10/SEP10. These were the two months for which the required traffic, passenger, schedule and other sources of data were available to the CASSIOPEIA team. Checks were made to identify the busiest days (almost always Fridays at a European level) and to exclude those with excessive disruption (e.g. Friday 27AUG10 was subject to serious weather ATFM delays). This process led to Friday 20AUG10 being selected as a suitable day to model. 20AUG10 was the second busiest day for

¹ 7.9m of 22.8m passengers.

² Personal communication with ACI EUROPE.

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aircraft movements at Zürich Airport during AUG10 with 829 flights arriving/departing, including general aviation and other non-passenger flights (Flughafen Zürich, 2011).

2.2.2 Traffic data

The traffic dataset for Case Study 3 has been built primarily from data sourced from EUROCONTROL, covering IFR flights for the busiest 199 ECAC airports³. Flight details such as operator, aircraft, aircraft registration number and actual times have come from PRISME, with planned route details (waypoints, coordinates and timing points) sourced from the Demand Data Repository (DDR). Fuel consumption used in the model is calculated by BADA (EUROCONTROL's Base of Aircraft Data). After considerable data cleaning, routes have been matched with actual flight details. Additional traffic data fields required by the case study have been populated with data derived from Innovata, CODA and in-house sources.

All flights were prepared to ensure network congestion was captured, however the scope of the case study was scaled back to focus on the impact of the application of DCI on Zürich-only traffic.

2.2.2.1 Traffic data cleaning and data enhancements

Aircraft:

- Inconsistencies with aircraft details, such as incorrect (or missing) registration numbers have been rectified – the movements of every aircraft operating at Zürich on 20AUG10 can now be tracked around the world (e.g. GEUOH, a British Airways A319: London Heathrow > Munich > London Heathrow > Zürich > London Heathrow > Paris Charles de Gaulle).
- Discrepancies between aircraft type and wake turbulence category have been resolved.
- Seats have been allocated to aircraft, applicable per operator. This is important so that *known* passengers per flight can be accommodated. Care has been taken to ensure allocated seats remain constant per individual aircraft, for example by allocating seats according to airline fleet records a low-cost carrier (LCC) would be expected to have a higher seat density than a full-service carrier (FSC), however aircraft can be operated (or marketed) by more than one airline so the seats should be tied to the airframe and not the operator. For example the PRISME records show that a number of A320s are jointly operated by SWISS and Edelweiss Air (e.g. HBIHY) – the number of allocated seats on this airframe (168) does not change in the model even though other A320s in their respective fleets may have more or less seats.

Airline:

- Each aircraft operator has been categorised by their primary type of operation, i.e. full-service, regional, low-cost carrier or charter. Unknown operators (coded as 'ZZZ') or with indistinguishable operations have been categorised as (medium delay cost) regional carriers. (This task also assists the identification of non-commercial passenger flights that need to be excluded.)
- Flights operated by wet lease/ACMI (aircraft, crew, maintenance and insurance) operators have been categorised by the marketing airline, for example Darwin Airline operates ACMI flights on behalf of SWISS. In cases where this has not been possible, the charter category has been applied.
- Unique pseudo flight numbers have been assigned to all flights (flight numbers are not available in the PRISME or DDR datasets) by combining the operator code with airport codes, incrementing flights through the course of the day (e.g. BAW_EGLLLSZH04 identifies the 4th British Airways flight in the day from London Heathrow to Zürich). This removes any ambiguity

³ These 199 airports were previously identified as accounting for 97% of passengers and 93% of movements in 2010.

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potentially caused by using the real flight numbers that may cover multiple legs when flights stop en-route (e.g. 'RJ153' designates Geneva > Zürich > Amman).

- Airline membership of Star Alliance, SkyTeam and oneworld (applicable for 2010) has been assigned to flights; required for passenger reaccommodation costs.
- Schedule times for 20AUG10 (supplied by Innovata) have been matched with flights. Flights that cannot be matched to a schedule time have been assigned the PRISME initial estimated off-block time (IOBT – closest time to schedule) for departure times.

Other:

- Statistical taxi times for AUG10 have been sourced from CODA to replace the unreliable taxi-out and missing taxi-in times in the PRISME dataset.
- Minimum turnaround times used by the model are based on observed values. These times have been calculated after analysing the elapsed time between the estimated in-block (actual touchdown time + average taxi-in time) and subsequent actual off-block times (per aircraft). These are available per aircraft wake category (i.e. L, M, H and J) and airline type (i.e. FSC, LCC, REG and CHT) for all airlines at Zürich as a group, except for SWISS which being the dominant hub carrier has had its own minimum turnaround calculated. Corresponding times for airline type/aircraft size have been calculated to cover all other airports (grouped together) and all airlines (grouped together, including SWISS). For example, the minimum turnaround time for a medium-sized aircraft operated by a regional airline (excluding SWISS) at Zürich during AUG10 was 17 minutes.

2.2.2.2 Traffic data exclusions

Flights out of scope have been flagged for exclusion during data pre-treatment. Non-commercial passenger flights (e.g. cargo, military and corporate) have been identified for exclusion from the simulation runs based on the registration number or the airline type, the aircraft type and the aircraft type per airline. Flights showing certain characteristics have also been excluded, such as circular flights and flights with unusually fast or slow speeds.

11% of all flights in the full dataset were excluded this way. Of the 760 PRISME flights operating at Zürich Airport on 20AUG10, 84 flights (also 11%) were excluded using these cleaning rules. A further 28 flights were excluded following more in-depth analysis of the times these flights reached the start and end of the cruise phase, some of which were missing sufficient route information, with 648 flights available for the simulation. Table 1 summarises:

Table 1. Number of flights on 20AUG10

Flights	Coverage	Source
31048	CFMU Area	CFMU (for validation)
30137	Busiest 199 airports in ECAC	PRISME
829	Zürich Airport movements (includes general aviation)	Flughafen Zürich (for validation)
760	Zürich Airport movements (IFR flights only)	PRISME
648	Zürich Airport movements (flights in scope for Case Study 3)	PRISME

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2.2.3 Passenger allocations to aircraft

The calculations for the cost of delay to the airlines are driven significantly by the costs of delayed passengers. It is therefore important that a good model is built for the allocation of passengers to the flights. Case Study 3 draws on *primary* passenger connectivity data from Zürich Airport made available with the help of ZHAW⁴ (Zürich University of Applied Sciences), which are supplemented with non-connecting (terminating) passenger itineraries initially sourced from IATA's PaxIS dataset and allocated using hierarchical, in-house algorithms.

The case study utilises two categories of passenger, defined by ACI EUROPE as:

Transfer (connecting): Passengers arriving and departing on a different aircraft, or on the same aircraft bearing different flight numbers. They are counted *twice*, upon arrival and departure.

Terminating (non-connecting): Passengers who start and end their trip at the designated airport. They are counted *once*.

Having access to high-fidelity connectivity data gives the *actual* numbers of passengers connecting between individual flights, with allocated non-connecting passengers 'topping-up' the flights. Appendix B summarises the passenger allocation per airline and corresponding seat load factors for 20AUG10 (74% overall). Figure 1 illustrates 116 connecting passengers from flight LX009 (inbound SWISS widebody from Chicago O'Hare) transferring onto 29 departures at Zürich, with a further 105 passengers completing their journey.

Arriving flight	Aircraft	Connecting pax	Non-connecting pax	Total pax
LX009	A333	116	105	221

Departing flights (29)	Aircraft	Connecting pax
LX1056	A319	4
LX1104	RJ1H	3
LX1168	RJ1H	6
LX1216	A319	3
OU465	DH8D	1
:	:	:

ZRH only

Figure 1. Example of the level of passenger connectivity information per flight

Unsurprisingly given that Zürich Airport is the main hub for SWISS, 95% of all connections on 20AUG10 were between Star Alliance airlines.

Every passenger in the case study dataset can be accommodated on their intended flights and make their intended connection if flights are flown according to the schedule; no flight is overloaded. The total number of passengers in scope is 73 016, consisting of 49 876 non-connecting and 11 570 (x2 as counted twice) connecting passengers. Although there could be other passengers who are out of scope on excluded flights, this total of 73 016 compares well with Zürich Airport's published figures for the day, 72 715 – a difference of 301 (0.4%) passengers (Flughafen Zürich, 2011). Similarly the proportion of connecting passengers in scope is close to the reported monthly proportion – 32%

⁴ The large computational task of combining separate inbound and outbound connecting passenger databases into a single dataset was undertaken by ZHAW. Further data cleaning and recoding tasks were carried out by the University of Westminster to prepare the data for the simulation.

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connect in the case study dataset; 35% actually connected in AUG10 (*ibid.*). 165 connecting passengers were subsequently identified as connecting with flights departing on the next day so were reclassified as non-connecting passengers on-board their inbound flights for modelling purposes.

The PaxIS dataset provides passenger itineraries aggregated by month, captured through ticket sales. Using this source, each passenger has been allocated a directional fare, in Euros, and a 'flexibility' seat class. Passengers paying the highest fares on full-service carrier flights are deemed to have flexible tickets with all other passengers considered to possess inflexible tickets – the flexible/inflexible distinction is required by the cost scenario assignment (see Section 2.2.4.2). Overall, 9% of passengers were treated as having flexible tickets. Fares for connecting passengers were proportionally split between the inbound and outbound flights based on the flight legs' great circle distances (GCD).

A minimum connecting time (MCT) – the shortest time interval required for a passenger and baggage to connect between flights – has been assigned to each connecting passenger's itinerary using data supplied by Innovata. Although the standard MCT at Zürich is 40 minutes for all connection types, it has been possible to assign the actual MCT exceptions for 7% of connecting itineraries. For example, a longer MCT may be required for passengers connecting from arrivals from a particular origin or a shorter MCT could be available between flights operated by the same airline within the same terminal gate zone.

Tables 2 and 3 provide samples of connecting and non-connecting passenger itineraries for passengers arriving from Delhi on-board SWR_VIDPLSZH01 (note each itinerary record covers a single passenger and more information is required by the model for connecting passengers).

Table 2. Sample of connecting passengers (inbound flight number SWR_VIDPLSZH01)

Arriving flight	Departing flight	Pax	MCT	Fare Inbound fare (EUR)	Outbound fare (EUR)	Flexible/ inflexible	Itinerary
SWR_VIDPLSZH01	AAL_LSZHKJFK01	1	65	431.4	212.9	218.5 inflex	Delhi > Zürich > New York JFK
SWR_VIDPLSZH01	AAL_LSZHKJFK01	1	65	431.4	212.9	218.5 inflex	Delhi > Zürich > New York JFK
SWR_VIDPLSZH01	DLH_LSZHEDDF01	1	40	1128.2	1077.9	50.3 flex	Delhi > Zürich > Frankfurt
SWR_VIDPLSZH01	DLH_LSZHEDDF01	1	40	121.6	116.2	5.4 inflex	Delhi > Zürich > Frankfurt
SWR_VIDPLSZH01	EDW_LSZHLEPA01	1	75	216.5	186.3	30.2 inflex	Delhi > Zürich > Palma de Mallorca
SWR_VIDPLSZH01	EDW_LSZHLEPA01	1	75	263.9	227.1	36.8 inflex	Delhi > Zürich > Palma de Mallorca
SWR_VIDPLSZH01	SWR_LSZHEDDH01	1	40	160.8	144.5	16.3 inflex	Delhi > Zürich > Hamburg
SWR_VIDPLSZH01	SWR_LSZHEDDL01	1	40	210.0	195.9	14.1 inflex	Delhi > Zürich > Düsseldorf
SWR_VIDPLSZH01	SWR_LSZHEDDM01	1	40	1003.0	962.2	40.8 flex	Delhi > Zürich > Munich
SWR_VIDPLSZH01	SWR_LSZHEDDN01	1	40	167.3	159.7	7.6 inflex	Delhi > Zürich > Nuremberg

Note: passenger id data field excluded; itinerary column on the right hand side included for the benefit of the reader.

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MCT exceptions can be observed for some of the connecting passengers (65 and 75 minutes). In both tables a range of actual fares have been allocated, however for some flights there are fewer available fares to allocate (hence fare repetition) and in some cases very low fares are used – these are, however, *real* fares, perhaps subject to heavy discounting or the redemption of frequent flyer programme points.

Table 3. Sample of non-connecting passengers (inbound flight number SWR_VIDPLSZH01)

Arriving flight	Pax	Fare (EUR)	Flexible/inflexible
SWR_VIDPLSZH01	1	233.8	inflex
SWR_VIDPLSZH01	1	268.3	inflex
SWR_VIDPLSZH01	1	1313.5	flex
SWR_VIDPLSZH01	1	268.3	inflex
SWR_VIDPLSZH01	1	248.4	inflex
SWR_VIDPLSZH01	1	233.8	inflex
SWR_VIDPLSZH01	1	1358.2	flex
SWR_VIDPLSZH01	1	233.8	inflex
SWR_VIDPLSZH01	1	245.8	inflex
SWR_VIDPLSZH01	1	266.8	inflex

Note: passenger id data field excluded.

2.2.4 Cost data

The costs used in Case Study 3 refer to the tactical costs of delay to the airline (avoided or incurred). Some of the costs are based on calculations presented in ‘European airline delay cost reference values’ (Cook and Tanner, 2011), a standard cost reference used by EUROCONTROL (for example cited in EUROCONTROL’s annual Performance Review Reports and Standard Inputs for Cost Benefit Analyses documents). Here, a ‘cost scenario’ refers to the different assumptions made about the underlying costs of delay to an airline and is separate from the case study scenarios. These costs are modelled according to ‘high’, ‘base’ and ‘low’ cost scenarios (as distinct from the model scenarios of Section 2.3). The ‘base’ cost scenario values are used for crew and maintenance costs (which are less variable across airline types), and the range of cost scenarios are used for the more airline-dependent passenger costs (as described below). All costs for Case Study 3 are reported in 2010 Euros, as determined by the source used (*ibid.*).

Table 4 summarises the passenger and aircraft costs assigned by the model, and when these costs are assigned to passengers and crew (either on departure or on arrival). The calculation of these costs is described in the following sections.

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Table 4. Cost overview

Zürich inbound/outbound	Passengers & aircraft	Fuel costs	Crew & maintenance costs	Passenger hard costs (on departure delay only)	Passenger soft costs (on arrival delay at final destination only)
Inbound	Pax terminating (at Zürich)	-	-	No (hard cost has already been accounted for at origin)	Yes, at Zürich
	Pax make connection	-	-	Dynamic (will be zero if depart on-time)	Yes, at destination (not Zürich)
	Pax miss connection *	-	-	Dynamic	Yes, at destination (not Zürich)
	Aircraft	Yes	Yes (crew cost at destination)	-	-
outbound	Pax originating (at Zürich)	-	-	Dynamic	Yes, at destination (not Zürich)
	Pax connecting	-	-	Hard cost happens here with Zürich departure (i.e. hard cost is estimated between origin & Zürich, now known when depart Zürich)	Yes, at destination (not Zürich)
	Aircraft (non-rotational)	- **	Yes (crew cost at destination)	-	-
	Aircraft (rotational)	- **	Yes (crew cost at destination)	-	-

* A proportion of passengers who missed their connection are returned to their point of origin.

** If aircraft departs Zürich 10 minutes late it is assumed to arrive 10 minutes late at the destination as DCI is not applied to outbound flights.

2.2.4.1 Maintenance and crew costs

These costs include the marginal (tactical) costs of additional crew hours and maintenance burden associated with delay incurred by aircraft and are linear in time (unlike the passenger delay costs). Good fits have been obtained between the square root of the maximum take-off weight (MTOW) and costs for the 12 aircraft reference values (Cook and Tanner, 2011). MTOW values used are averages, derived from the Central Route Charges Office (EUROCONTROL) data for flights in 2008 and 2009, kindly supplied by EUROCONTROL's Performance Review Unit (PRU).

Maintenance (at-gate, taxi and en-route/arrival management) and crew cost tables with corresponding regression parameters are provided in Appendix C.

Maintenance costs are assigned with a stochastic element for delays per phase of flight, and similarly for crew costs assigned according to arrival delay. Refer to Table 5 for the method.

Table 5. Maintenance and crew cost assignment

Airline type	Method type	Summary of method
All (FSC, LCC, REG, CHT)	Stochastic (based on actual costs)	$\sim N(\text{base}, [\text{high} - \text{low}]/4)$

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2.2.4.2 Passenger costs

The cost of passenger delay to the airline may be classified as either a ‘hard’ or ‘soft’ cost, as summarised in Cook and Tanner (2012). Hard costs are due to such factors as passenger rebooking, compensation and care (partly following Regulation (EC) No. 261/2004). Although potentially difficult for airlines to ascribe on a flight-by-flight basis, due to accounting complications, these are, in theory at least, identifiable deficits in the airline’s bottom line. Soft costs manifest themselves in several ways. Due to a delay on one occasion, a passenger may defect from an unpunctual airline as a result of dissatisfaction (although quite possibly reversing this defection subsequently). Soft costs, exemplified by this type of revenue loss, are rather more difficult to quantify.

Case Study 3’s allocation of passenger cost of delay is partly statistical (drawing on Cook and Tanner, 2011) and partly explicit. We assign this a statistical cost (note that longer passenger delays have higher *per-minute* costs than shorter ones).

Passenger hard costs

Hard costs are dynamic ‘real’ costs derived from (i) the cost of rebooking, compensating and (duty of) care provided to delayed passengers and (ii) from fares. As described in Section 2.2.3, each passenger has been assigned an individual fare and corresponding ‘flexibility’ seat class (i.e. premium passengers having paid the highest fares have flexible tickets; all other passengers have inflexible tickets). For connecting passengers, the inbound flight determines ticket flexibility and the directional fare is split to cover the inbound and outbound flights.

The hard cost calculation is based on departure delay. If a flight is missed the passenger delay is the time difference between the originally scheduled *missed* flight and the actual departure time of the alternative flight. The explicit cost allocation takes advantage of the fact that passengers are allocated explicitly to each aircraft using airline-aircraft specific seating configurations and load-factors (as previously described).

Hard cost (i) the assignment of the costs of provisions

A full-service flexible passenger with a departure delay of two hours is assigned the average of the high and base cost of providing refreshment and a tax-free voucher (see Tables 6 and 7).

Table 6. Costs of provisions made by airlines, by delay duration and cost scenario

Departure delay, t (hours)	Provision (incremental)	Costs (Euro 2010, 2 s.f.) by cost scenario		
		High	Base	Low
$1.5 \leq t < 2$	Refreshment	2.0	1.7	-
$2 \leq t < 3$	+ tax-free voucher	9.4	7.7	4.7
$3 \leq t < 5$	+ meal voucher, & FFP miles	23	19	12
$t \geq 5$ (no hotel)	+ ticket discount voucher	26	21	13
Overnight	+ hotel accommodation	100	83	51

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Table 7. Cost scenario assignment by airline and ticket type

Airline (and ticket) type	Cost scenario applied
Full-service (flexible)	Average of high and base
Full-service (inflexible)	Base
Regional, LCC, charter	Average of low and base

Hard cost (ii) the assignment of the fare transfer

This applies when a delayed inbound passenger misses their connecting outbound flight (see also Section 2.2.5.1 Passenger reaccommodation rule). There is an interline settlement cost of rebooking a passenger onto an alternative flight – this is taken as the outbound fare, which would be transferred to the alternative operator. However this is cost neutral if the reaccommodated passenger is rebooked onto a flight operated by the same carrier or same alliance. As noted in Section 2.2.3, almost all connecting passengers at Zürich on 20AUG10 were between Star Alliance airlines. Note also that Case Study 3 only considers the cost to airlines and does not treat fare transfers as income to the other carrier.

Passenger soft costs

Soft costs are calculated from arrival delay at the *final destination* and are deterministic, based on passengers' fares. Full-service passenger fares are normalised from 0 (lowest) to 1 (highest), f_N in Table 9, which is used as a scalar for the appropriate soft cost value in Table 8. For connecting passengers the outbound fare is normalised. For the other airline types, each passenger's soft cost is assigned drawing on a Normal distribution using the mean of the base and low cost scenario values as the mean of the Normal distribution, with a standard deviation set at one quarter of the difference between the base and low values. This means that 95.5% of the sampled values will lie between the low and base cost scenario values.

The soft cost values in Table 8 are 10% of the full values (published in Cook and Tanner, 2011) which are more appropriate when considering costs at the network level as opposed to single-flight trade-offs. Costs are interpolated from the table to the nearest minute, however the *per-minute* values are saturated by two hours and the costs are capped after five hours. Refer to Table 9 for the method.

Table 8. Appropriately scaled passenger soft costs of delay per minute, by cost scenario

Delay (mins)	5	15	30	60	90	120	180	240	300
Low	0.001	0.002	0.007	0.019	0.025	0.027	0.027	0.027	0.027
Base	0.002	0.009	0.025	0.069	0.091	0.096	0.097	0.097	0.097
High	0.003	0.010	0.028	0.077	0.101	0.106	0.108	0.108	0.108

Table 9. Soft cost assignment

Airline type	Method type	Summary of method
Full-service	Deterministic	$f_N \times high + [1 - f_N] \times base$
Regional, LCC, charter	Stochastic (based on cost scenarios)	$\sim N ([base + low]/2, [base - low]/4)$

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2.2.4.3 Fuel burn

A detailed discussion of the use of dynamic cost indexing and associated speed changes is presented in Cook *et al.* (2009) – previously outlined in D2.6. In the context of speed optimisation (e.g. to recover delay), the optimal cost solution, expressed in terms of the cost index (CI) used, will almost always lie somewhere between CI_0 (maximum fuel conservation) and CI_{max} (minimum flight time). According to Airbus and Boeing, CI_0 and CI_{max} correspond closely to V_{MU} and V_{MO} – the minimum and maximum operating speeds of the aircraft, respectively.

Using Lufthansa Systems’ Lido flight planning software to establish a range of *operational* time savings across 23 routes, maximum speed variations were previously found to be around 8% and minimum (and mode) to be 4% (Cook *et al.*). Although higher ranges have been used in other studies, Airbus suggests working speed envelopes of 4-6% at optimum flight levels. Case Study 3 has adopted a range of *up to* $\pm 3\%$, which we consider to be neither too conservative nor too near the upper end of the range. Of further note, SKYbrary (2012) states that there is: “great variation between operators on the CI that they use for a given type or in a given situation. For example, one airline generally uses a CI of around 9 in the A320 which results in a climb speed of about 290, a cruise speed of about .76 and a descent speed of about 260. However, if the aircraft is running late, the crew may use a CI of 50 or more which would give speeds of 320, .79 and 330 for the same phases” – indicating a cruise increase of around 4%.

2.2.4.4 Summary

The timeline in Figure 2 illustrates delays relative to the schedule, attributable by phase of flight, and how they are treated by the model. (SOBT/AOBT and SIBT/AIBT are the scheduled/actual off- and in-block times.)

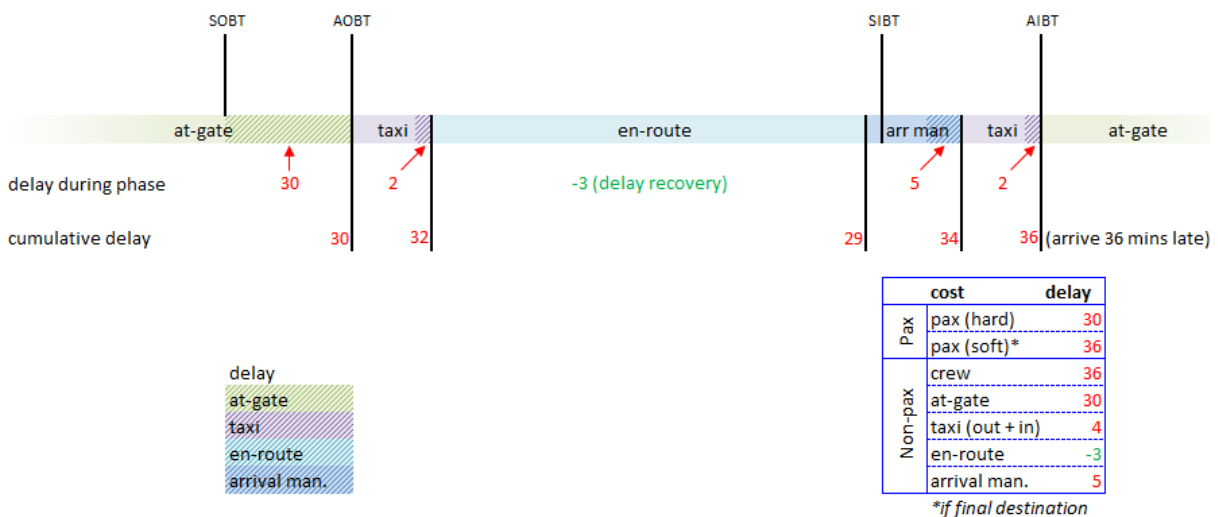


Figure 2. Delays by flight phase

2.2.5 Rules

The DCI rules have been refined using feedback from airlines that participated in the Gatwick workshop (02OCT12). Operational practice regarding the use of variable speeds en-route (dynamic cost indexing for delay recovery) range from ‘do nothing’ to attempting to recover all delay. Rule 0

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covers the ‘do nothing’ company policy whereby no en-route speed changes are made (labelled ‘none’ in later tables). Rule 1 allows for the attempted recovery of *all delay* if a flight has more than 15 minutes delay – this is a ‘rule of thumb’ policy.

Rule 2 allows for the attempted recovery of delay to a residual of 10 minutes only, since such full recovery is not cost-optimised in turns of the additional fuel burn. The more sophisticated Rule 3 allows for a cost-optimised recovery of delay, taking into account for example, passenger connections at Zürich and reduced crew costs due to recovered delay.

Note that rules 1-3 only apply to airlines in scope under the DCI uptake scenario described below.

Table 10. DCI rules

Rule number	Quantitative setting	Wait for pax setting	Comments
0	Do not use DCI ('none')	85% seat load factor (SLF)	This rule is designed to understand the base scenario. The departure delay will be the same as the arrival delay except for the uncertainty of the trajectory.
1	Recover all delay if delay >15 minutes ('rule of thumb')	Departure delay 15 minutes max.	Inbound flights to Zürich will use DCI to reduce all delay if delayed by more than 15 minutes.
2	Recover delay to a residual of 10 minutes ('residual')	Departure delay 10 minutes max.	Inbound flights to Zürich will use DCI to reduce delay to 10 minutes.
3	Cost-optimised recovery of delay ('cost')	Cost-optimised	The selection of DCI flights will be based on the optimisation of costs of the flights, taking into account the connections of passengers at Zürich, leaving the <i>cost-optimised</i> amount of residual delay (if any). (Note: <i>waitforpax calculation</i> – the model computes the optimal waiting time for connecting passengers for a flight. It is performed when a request waiting time message is received.)

2.2.5.1 Passenger reaccommodation rule

A simplified rule is used to reaccommodate passengers to alternative flights if their connection is missed:

- All passengers prefer to be rebooked onwards to their final destination (and not returned to their point of origin, although in some cases this may be necessary);
- Seats must be available on the alternative flight;
- No originally-booked passenger on the alternative flight may be ‘bumped’ (replaced) by an attempted reaccommodation;
- A reaccommodated passenger may not be subsequently ‘bumped’ by a ‘higher priority’ passenger;
- Passengers are reaccommodated onto alternative flights regardless of ticket and cabin class, in that aircraft are simply occupied according to total seat space (no account is taken of the costs associated with upgrading or downgrading);
- Only direct routings from Zürich are considered;
- For connecting passengers who are delayed at Zürich for more than five hours, 20% of them (judgemental value based on Regulation (EC) No. 261/2004) are randomly selected and returned to their point of origin with attempts made to reaccommodate the remaining 80% (and any of the 20% unable to be returned to origin) until there are no available flights – however the hard cost of provisions/care is flat after 5 hours;

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- Any passengers who cannot be reaccommodated on alternative flights are allocated the overnight hard cost (€83 from the base cost scenario in Table 6) with their soft cost capped at five hours (Table 8).

2.3 Scenarios design

The assignment of DCI usage to flights is based on a hierarchical process, firstly allowing certain airlines to use DCI, then certain flights adopting DCI based on the rules (refer to previous section). For example, if Airline X did not use DCI in its operations, a flight operated by Airline X would not implement DCI under any circumstances.

Table 11. DCI uptake scenarios

Scenario	Qualitative description	Quantitative setting	Operational comparator
SD0	Very few flights use DCI	2 airlines operating into Zürich Airport	As current
SD1	Many flights use DCI	6 airlines operating into Zürich Airport	Possible medium-term scenario
SD2	Most flights use DCI	10 airlines operating into Zürich Airport	Comparable to 4DT

Airlines using DCI are expected to continue using it in the future, i.e. airlines in scope for DCI usage in scenario SD0 are also available for DCI in SD1 and SD2 (just as SD1 airlines are also available for SD2).

Scenario SD0, with very few flights using DCI, is comparable to the current situation as opposed to scenario SD2 in which most flights are using DCI, comparable to 4D trajectory management.

Ideally, flights arriving at Zürich which were potentially already using DCI should be identified and excluded from any further application of DCI. Such flights may have been excluded already during the data cleaning/preparation phase (of the whole ECAC dataset) as flights exhibiting extremes of speed were excluded (see Section 2.2.2.2 'Traffic data exclusions'). However this specific exclusion task has been flagged for future work and would need to take into account typical flight time per aircraft type per operator per route; schedule buffer time; wind and flown route.

Two into-plane costs of fuel (Jet A1) scenarios are modelled (Table 12). The 2010 fuel price, EUR 0.6 / kg, as cited in 'European airline delay cost reference values' (Cook and Tanner, 2011) and a higher more recent fuel price, EUR 0.9 / kg, established as the highest price between 2010 and September 2013.

Table 12. Fuel price scenarios

Scenario	Qualitative description	Quantitative setting	Operational comparator
SF0	2010 fuel price	EUR 0.6 / kg	Comparable to 2010
SF1	Highest fuel price between 2010 and mid-2013	EUR 0.9 / kg	As current / medium-term scenario

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2.3.1 Selection of airlines for DCI uptake scenarios

Having excluded non-passenger flights from the traffic dataset, 56 airlines operating at Zürich on 20AUG10 are in scope for Case Study 3. Of these airlines, two, six and ten carriers have been selected for the DCI uptake scenarios listed in Table 11.

SWISS is the dominant carrier at Zürich, accounting for over half of all flights and 91% of connecting passengers on 20AUG10 (refer to Appendix B for details) precluding selection for SD0. Tables 13-15 list the airlines selected for the DCI uptake scenarios and a brief explanation behind the rationale. In each DCI uptake scenario table, arriving flights (only) have been considered, i.e. 329 of the 648 total flights are in scope.

Table 13. Airlines selected for DCI uptake scenario SD0

Airline	AO type	Arriving flights	Arriving connecting pax	Comments
Lufthansa	FSC	14	101	Most arriving flights with over 100 connecting pax (after SWISS)
Edelweiss Air	CHT	8	125	Charter operator based at Zürich with connecting pax onto SWISS departures (both members of the Lufthansa Group)

Qualitative description: very few flights use DCI.

Quantitative setting: maximum of 22 flights available for DCI (7% of arrivals).

Table 14. Airlines selected for DCI uptake scenario SD1 (including SD0 airlines)

Airline	AO type	Arriving flights	Arriving connecting pax	Comments
Lufthansa	FSC	14	101	Refer to SD0 (Table 13)
Edelweiss Air	CHT	8	125	Refer to SD0 (Table 13)
SWISS (narrowbodies)	FSC	160	8076	DCI usage to connect with departing widebodies at hub airport
Austrian	FSC	4	56	Connecting pax onto various departures (and a member of the Lufthansa Group)
Singapore Airlines	FSC	1	63	Long haul flight with high number of connecting pax (large early average arrivals ⁵)
United Airlines	FSC	1	62	Long haul flight with high number of connecting pax

Qualitative description: many flights use DCI.

Quantitative setting: maximum of 188 flights available for DCI (56% of arrivals) – impact of including SWISS narrowbodies.

⁵ Analysis of Zürich flights OCT09-OCT10 revealed large early average arrival times on the westbound long-hauls of Singapore and Thai Airways International (17.2 minutes and 17.7 minutes early respectively).

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Table 15. Airlines selected for DCI uptake scenario SD2 (including SD0 and SD1 airlines)

Airline	AO type	Arriving flights	Arriving connecting pax	Comments
Lufthansa	FSC	14	101	Refer to SD0 (Table 13)
Edelweiss Air	CHT	8	125	Refer to SD0 (Table 13)
Austrian	FSC	4	56	Refer to SD1 (Table 14)
Singapore Airlines	FSC	1	63	Refer to SD1 (Table 14)
United Airlines	FSC	1	62	Refer to SD1 (Table 14)
SWISS	FSC	181	10787	All aircraft now in scope (narrowbodies and widebodies)
Cirrus Airlines	REG	6	29	Regional airline with the most connecting pax
Croatia Airlines	FSC	4	108	Connecting pax onto various departures
Thai Airways International	FSC	1	64	Long haul flight with high number of connecting pax (large early average arrivals)
Blue1	LCC	1	11	Low-cost airline with the most connecting pax

Qualitative description: most flights use DCI.

Quantitative setting: maximum of 221 flights available for DCI (65% of arrivals).

2.3.2 Summary of the available simulation combinations

20 valid simulation scenarios are available using the combinations of DCI rules, DCI uptake and fuel price – the scenario identifier reflects this relationship e.g. S013 = SD0 (very few flights use DCI) + SF1 (high fuel price) + Rule 3 (cost-optimised recovery of delay).

Table 16 summarises the combinations. The scenario identification codes are used throughout Section 4.

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Table 16. Simulation scenarios

ID	DCI uptake scenario	Fuel price scenario	DCI rules	Comments
S000			Rule0: Do not use DCI	Baseline values (2010)
S001	SD0: Very few flights use DCI	SF0: 2010 fuel price	Rule1: Recover all delay if delay >15 minutes	2 airlines use DCI
S002			Rule2: Recover delay to a residual of 10 minutes	2 airlines use DCI
S003			Rule3: Cost-optimised recovery of delay	2 airlines use DCI
S010			Rule0: Do not use DCI	Baseline values (2010) with high fuel price (2013)
S011	SD0: Very few flights use DCI	SF1: High fuel price (2013)	Rule1: Recover all delay if delay >15 minutes	2 airlines use DCI
S012			Rule2: Recover delay to a residual of 10 minutes	2 airlines use DCI
S013			Rule3: Cost-optimised recovery of delay	2 airlines use DCI
S100			Rule0: Do not use DCI	Ignore (same as S000)
S101	SD1: Many flights use DCI	SF0: 2010 fuel price	Rule1: Recover all delay if delay >15 minutes	6 airlines use DCI
S102			Rule2: Recover delay to a residual of 10 minutes	6 airlines use DCI
S103			Rule3: Cost-optimised recovery of delay	6 airlines use DCI
S110			Rule0: Do not use DCI	Ignore (same as S010)
S111	SD1: Many flights use DCI	SF1: High fuel price (2013)	Rule1: Recover all delay if delay >15 minutes	6 airlines use DCI
S112			Rule2: Recover delay to a residual of 10 minutes	6 airlines use DCI
S113			Rule3: Cost-optimised recovery of delay	6 airlines use DCI
S200			Rule0: Do not use DCI	Ignore (same as S000)
S201	SD2: Most flights use DCI	SF0: 2010 fuel price	Rule1: Recover all delay if delay >15 minutes	10 airlines use DCI
S202			Rule2: Recover delay to a residual of 10 minutes	10 airlines use DCI
S203			Rule3: Cost-optimised recovery of delay	10 airlines use DCI
S210			Rule0: Do not use DCI	Ignore (same as S010)
S211	SD2: Most flights use DCI	SF1: High fuel price (2013)	Rule1: Recover all delay if delay >15 minutes	10 airlines use DCI
S212			Rule2: Recover delay to a residual of 10 minutes	10 airlines use DCI
S213			Rule3: Cost-optimised recovery of delay	10 airlines use DCI

Duplicate scenarios are excluded (e.g. S100 = S000).

3 Implementation synopsis

Case Study 3 has been implemented using the agent-based software platform developed in the CASSIOPEIA project (see D3.4). The specific implementation details of Case Study 3 are described in Appendix D, with corresponding XML code extracts available in Appendix E.

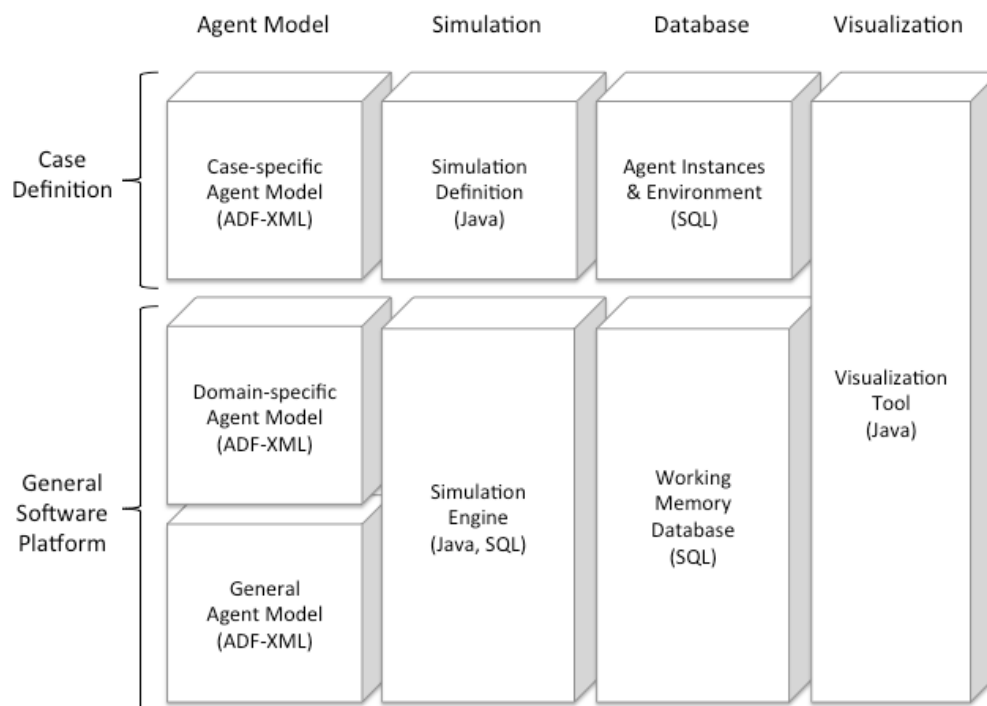


Figure 3. Main components of the software architecture

3.1 Case-specific agent model

According to the agent-based model supported by the software platform (Figure 3), the implementation of Case Study 3 includes the design of case specific behaviour for agents.

This case study uses all the types of agents designed for the platform, such as airlines, aircraft and airports. It also uses a pseudo-agent ('manager') to control the simulation.

Each agent needs to define its own capability to simulate the behaviour of the case. So, there are five different ADF-XML files, three of them to define a capability, one more for managing behaviour and another one to define simulation attributes.

Please refer to Appendix D for a description of these files.

4 Simulation findings

Key results of the case study are discussed in this section. Multiple output tables are available in Appendix A, whilst the scenario combinations that resulted in the most interesting findings are considered here in detail.

4.1 Generation of results

A total of 20 scenarios have been simulated using the simulation platform. Each simulation run generates two XML files: one file contains full outputs per flight, and another file for indicator metrics. The average simulation time for each scenario is approximately two minutes. Notwithstanding the uncertainty components described in Appendix D.2, the simulations were run once each in consideration of the fact that the modelling was largely deterministic and the statistical testing presented in Appendix D.2 was typically based on 648 modelled flights in each case.

The scenarios have been simulated using a desktop computer with the following characteristics:

Hardware:

Processor: Intel Core i5-2500

Memory: 8GB DDR3

Storage: HDD 500G 7200 rpm SATA3

Software:

OS: Microsoft Windows 7 Professional 64-bit SP1

RDBMS: MySQL Community Server 5.6.1

Java Virtual Machine 1.7.0u40

Jadex 2.2.1

A total of 648 passenger flights were available for simulation; of the 329 inbound flights a maximum of 221, 65% of arrivals, were in scope for DCI usage (scenario SD2 only, when most flights use DCI).

4.2 Significance testing

The results have been assessed through standard Key Performance Areas (KPA), listed in Table 17. The differences between the mean values per flight of the baseline and other scenarios have been tested for significance using standard z-tests. A threshold value of 2% of the baseline has been applied (right hand column of Table 17), so that (artefactual) differences below the threshold have been disregarded and not reported upon. All indicator results are available in Appendix A.

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Table 17. Key Performance Areas and indicators

KPA	Indicator	Units	Definition	Threshold
Predictability	P1 departure time	% ≤ <i>n</i> mins	Delay from gate cf. schedule (<i>n</i> = 3, 10, 15)	N/A
	P1 departure delay	mins	Delay from gate cf. schedule (total)	N/A
	P1 departure delay	mins/flight	Delay from gate cf. schedule (per flight; s.d.)	0.2
	P2 arrival time	% ≤ <i>n</i> mins	Delay at gate cf. schedule (<i>n</i> = 3, 10, 15) ⁶	N/A
	P2 arrival delay	mins	Delay at gate cf. to schedule (total)	N/A
	P2 arrival delay	mins/flight	Delay at gate cf. schedule (per flight; s.d.)	0.2
Cost-efficiency	C1 non-fuel cost	Euros (000s)	Cost of pax, crew & maintenance (total)	N/A
	C1 non-fuel cost	Euros/flight	Cost of pax, crew & maintenance (per flight; s.d.)	100
	C2 fuel cost	Euros (000s)	Cost of fuel (total)	N/A
	C2 fuel cost	Euros/flight	Cost of fuel (per flight; s.d.)	50
	C3 net cost	Euros (000s)	Cost of pax, crew, maintenance & fuel (total)	N/A
	C3 net cost	Euros/flight	Cost of pax, crew, maint. & fuel (per flight; s.d.)	150
Environmental impact	E1 CO ₂	kilotonnes	CO ₂ emitted (total)	N/A
	E1 CO ₂	tonnes/flight	CO ₂ emitted (per flight; s.d.)	300

Note: although the non-fuel cost (C1) consists of the cost of passengers, crew and maintenance, is largely driven by the passenger cost.

Although uncertainty metrics have been designed to assess potential workload disbenefits imposed on controllers by the increased use of DCI (based on feedback from ANSPs at the Gatwick workshop and later correspondence) it has not been possible to implement these rules within the case study timeframe. Dropping uncertainty metrics also negatively impacted the flexibility metrics which relied on the former as an input.

4.3 Scenario comparisons

High level, no-scenario (baseline) checks show that the simulation produced credible results. For example, flights that had *not* applied DCI and arrived late (23 minutes late on average) had an average delay cost of approximately €80 per minute (2 s.f.) – very close to the European network average cost of ATFM delay, €81 per minute (Cook and Tanner, 2011).

All indicators have been calculated with respect to the baseline conditions (i.e. DCI is not applied; very few flights use DCI; 2010 fuel price) and under modelled changes, for example delay changes generated under DCI rules 1, 2 and 3 (recover all delay if delay is >15 minutes; recover to a residual delay of 10 minutes; cost-optimised delay recovery) with scenarios SD1 and SD2 (many and most

⁶ SES performance targets for 2020: arrival delay with > 95% of flights within 3 minutes of schedule (other 5% with an average delay < 10 minutes), and block-to-block standard deviation < 1.5% of route mean for repeatedly flown routes using aircraft with comparable performance (SESAR Consortium, 2006).

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flights use DCI). All indicator results are available in Appendix A, of which the significant and/or pertinent findings include:

- i. A narrow range of (departure and) arrival average delay minutes per flight result under conditions when en-route delay recovery is applied (-4 to 1 minute(s) of delay per flight across all scenarios);
- ii. The dominating effect of the high fuel price scenario (SF1), more than counteracting the effect of non-fuel cost savings, resulting in a net loss when DCI is applied;
- iii. The recovery of delay to a residual of 10 minutes (Rule 2) gave the highest average net saving overall of €960 per flight;
- iv. Scenario S102 (incorporating Rule 2 for six airlines) gave the best average passenger, crew and maintenance (i.e. non-fuel) cost saving and average net saving per flight.

Expanding point (i), the average reduction in arrival delay minutes per flight ranged from -4 or -3 minutes for scenarios incorporating DCI rules 1 and 2 (S101, S102, S111, S112, S201, S202, S211 and S212) up to an increase in delay of 1 additional minute for some of the other scenarios. As expected, the cost-optimisation scenarios (incorporating DCI Rule 3), showed a lower average reduction in arrival delay minutes per flight, of between -1 and 1 minute – the slight worsening of delay reflecting speed reduction due to cost optimisation.

The high fuel price scenario (point (ii) above) had a major influence on costs, increasing the net cost for *all* scenarios, including those with a cost-optimised recovery of delay – for instance the lowest total net cost for any of the SF1 scenarios (S211, €5.4m) was higher than the most expensive 2010 fuel price scenario (S003, €5.2m). The S010 baseline scenario with the high fuel price has the highest total net costs overall, €6.3m.

Moving to point (iii), grouping all scenarios by their DCI rule, revealed that Rule 2 (the recovery of delay to a residual of 10 minutes – S002, S012, S102, S112, S202 and S212) gave the highest average net saving (and lowest net cost) overall. Of the scenarios implementing Rule 2, scenario S102, which simulated the medium-term timeframe with six airlines using DCI, gave the best average net saving – this key finding (point (iv) above) is discussed in more detail later.

An average net saving of €1 100 was observed for the ‘rule of thumb’ scenarios, S101 and S201 (recover all delay if the delay is >15 minutes, for six and ten airlines), returning better net savings than the cost-optimisation scenarios (S103 and S203). It thus appears that there was some misalignment between the passenger wait rules and the en-route recovery algorithms in the cost-optimisation scenario, which should be resolved in future work, building on the already demonstrated benefits of the S102 scenario in particular, whereby it makes best financial sense to leave residual delay (Section 4.3.1 further examines the cost-optimisation scenarios).

The environmental impact indicator did not add great additional value, showing a similar total tonnage of CO₂ across all scenarios. As there is little more to report for the C2 fuel cost and E1 CO₂ tonnes indicators, our attention is focused instead on the remaining cost and predictability indicators.

Table 18 presents the baseline (S000) values with nine selected scenarios and four indicators. Differences between the baseline and the nine scenarios are shown – negative differences reveal scenarios making an improvement (i.e. a reduction in the average delay or cost per flight) with positive differences showing a relative worsening.

Of nine selected scenarios, S101, S102, S111, S112, S201, S202, S211 and S212 all resulted in similar average delay savings per flight with regards to departure and arrival delay (point (i) above). Although each of these scenarios also produced a lower average non-fuel cost (though not a net cost reduction when high fuel price is included) only S102 shows a *significant* cost saving per flight ($p < 0.05$), highlighted in a white font and grey background in Table 18. S102 also had the highest proportion of flights arriving within ≤10 and ≤15 minutes (P2) and is now examined more closely.

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Table 18. Simulation key findings – scenario differences compared with baseline values (three parts)

Indicator	Units	S000	S010	S101	S102
		Baseline;	Baseline;	Many flights use DCI;	Many flights use DCI;
		2010 fuel;	high fuel;	2010 fuel;	2010 fuel;
		DCI: 'none'	DCI: 'none'	DCI: 'thumb'	DCI: 'residual'
P1 dep delay	mins/flight	(8)	1	-4	-4
P2 arrival delay	mins/flight	(12)	1	-4	-4
C1 non-fuel cost	Euros/flight	(5000)	340	-1100	-1200
C3 net cost	Euros/flight	(7900)	1800	-1100	-1200

Indicator	Units	S000	S111	S112	S201
		Baseline;	Many flights use DCI;	Many flights use DCI;	Most flights use DCI;
		2010 fuel;	high fuel;	high fuel;	2010 fuel;
		DCI: 'none'	DCI: 'thumb'	DCI: 'residual'	DCI: 'thumb'
P1 dep delay	mins/flight	(8)	-4	-3	-3
P2 arrival delay	mins/flight	(12)	-4	-3	-3
C1 non-fuel cost	Euros/flight	(5000)	-870	-920	-1100
C3 net cost	Euros/flight	(7900)	620	580	-1100

Indicator	Units	S000	S202	S211	S212
		Baseline;	Most flights use DCI;	Most flights use DCI;	Most flights use DCI;
		2010 fuel;	2010 fuel;	high fuel;	high fuel;
		DCI: 'none'	DCI: 'residual'	DCI: 'thumb'	DCI: 'residual'
P1 dep delay	mins/flight	(8)	-4	-3	-4
P2 arrival delay	mins/flight	(12)	-3	-3	-3
C1 non-fuel cost	Euros/flight	(5000)	-940	-1000	-800
C3 net cost	Euros/flight	(7900)	-940	450	690

Baseline values in brackets; difference in minutes or Euros per flight shown for the other nine scenarios; 2 s.f. used; the value highlighted in a white font on a grey background is a significant difference ($p < 0.05$). Other significant differences relating to the high fuel price, departure and arrival delay are highlighted in Appendix A.

Values for all indicators and all scenarios are available in Appendix A.

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S102 is one of the medium-term timeframe scenarios, with six airlines using DCI (2010 fuel price) to recover delay to a residual of 10 minutes. The effect of scenario S102 is apparent when the average arrival delay of baseline flights, 10 minutes, is compared with the average arrival delay of 8 minutes for all S102 flights (9% of which used DCI). Furthermore, when only considering the flights with arrival delays >10 minutes, these accounted for 27% of the baseline scenario but 17% of S102.

The significant non-fuel (i.e. passenger, crew and maintenance) cost saving shown with S102 is attributable to the leftwards shift in the delay distribution, as illustrated in Figure 4.

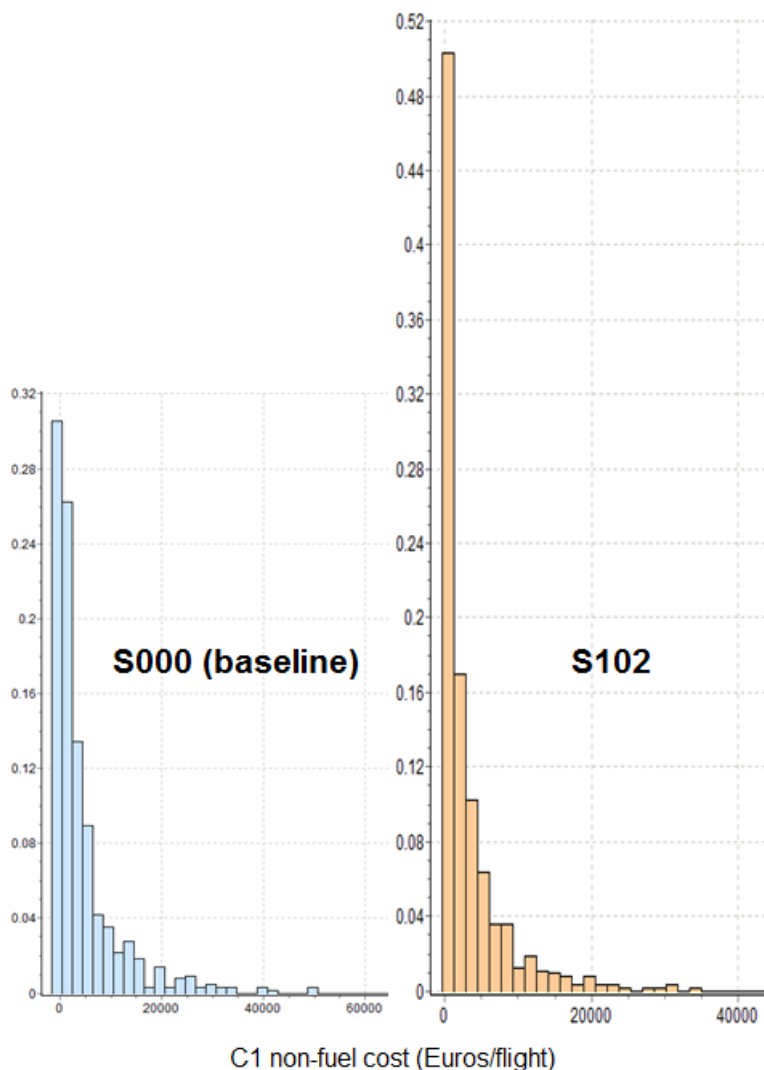


Figure 4. Distribution S000 and S102 non-fuel cost (C1)

This movement of the delay distribution had a significant effect on the non-fuel (i.e. passenger, crew and maintenance) costs. The total non-fuel cost of S102 is €800k lower than S000 (see Appendix A).

4.3.1 Cost-optimisation scenario examination

Further investigation into the effect of the passenger wait rules on the cost-optimised scenarios for Zürich outbound flights shows these flights received additional departure delay. The cost-optimised

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delay recovery flights within each group of DCI uptake scenarios (SD0 very few flights, SD1 many flights and SD2 most flights use DCI) had the highest total number of departure delay minutes (underlined) compared with the non-cost-optimised flights, summarised in Table 19.

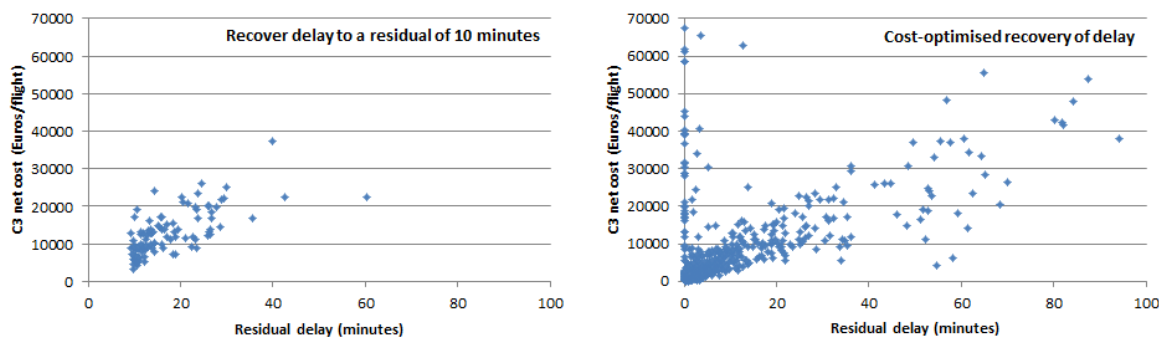
Table 19. Comparison of total departure delay per scenario

Fuel scenarios	SD0 scenarios	Departure delay (total)	SD1 scenarios	Departure delay (total)	SD2 scenarios	Departure delay (total)
2010 fuel price	S003	<u>5600</u>	S103	<u>5100</u>	S203	<u>5200</u>
	S002	4900	S101	3100	S201	3100
	S001	4800	S102	3000	S202	3100
High fuel price	S013	<u>5400</u>	S113	<u>5600</u>	S213	<u>5200</u>
	S011	5400 *	S112	3100	S211	3100
	S012	4900	S111	3100	S212	3100

* S011 also had a high total number of departure delay minutes, though not as high as S013.

Scenario codes that end with a '3' use the cost-optimised recovery of delay rule (Rule 3); total departure delay minutes shown to 2 s.f. Each scenario group is sorted by total departure delay.

Focusing on an individual flight (DLH_LSZHEDDF05, Zürich to Frankfurt), by waiting for passengers at Zürich under the cost-optimised scenario (S103), this flight took-off with a 27 minute delay compared with the on-time departure for the equivalent baseline scenario (S000) flight – in this case the flight delayed waiting for passengers received a net cost 14 times that of the baseline scenario flight, predominantly due to passenger delay costs.



Residual delay at the end of cruise before any additional delay, e.g. taxi-in.

Five outliers have been excluded from both graphs.

Figure 5. Residual delay of Rule 2 (recover to 10 minutes) and Rule 3 (cost-optimised) scenarios

Figure 5 illustrates the residual delay per flight at the end of the cruise phase, after the application of DCI to inbound Zürich flights (i.e. DCI has been used to reduce the delay recorded at take-off). The graph to the left shows how DCI has reduced delay to 10 minutes (or more) due to Rule 2 (S002, S012, S102, S112, S202 and S212). The graph to the right shows the residual delay due to DCI applied with the cost-optimised Rule 3 (S003, S013, S103, S113, S203 and S213) – flights that were early at the end of the cruise phase have zero delay. 67% of cost-optimised flights (on the right) have

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had take-off delay recovered to less than 10 minutes in contrast with the flights on the left. There is, however, a considerable residual delay that remains in the right hand graph.

A final example of how the additional cost driven by non-optimal departure delay affected the cost-optimised scenario is the contrast between flights using DCI to recover one minute (or less) of delay. Whereas 51% of Rule 2 (recover to residual delay of 10 minutes) flights only recovered up to one minute of delay, 79% of Rule 3 (cost-optimised scenario) flights did so. This indicates that a greater number of Rule 3 flights were limited by the increased cost of speeding up when attempting to recover the additional departure delay.

In summary, the cost-optimised scenarios require realignment between the passenger wait rules and the en-route recovery algorithms. Currently, excessive departure delay accumulates as flights wait for passengers at Zürich, resulting in high onward costs.

5 Conclusions

Case Study 3 has explored the use of dynamic cost indexing by flights into a major European hub airport through a new implementation of CASSIOPEIA's agent-based model platform. The model's decision-making process for applying increased aircraft speeds to recover delays for inbound flights has been driven by *real* connecting passenger itineraries at Zürich Airport. The case study has attempted to closely simulate the operational practice of airlines through the use of primary data (e.g. passenger itineraries and MCTs) combined with DCI usage rules based on feedback from carriers (e.g. the 'rule of thumb' policy), with costs calculated using the European standard tactical cost data source.

Output from multiple scenarios, covering three timeframes, have been compared with the baseline situation using predictability, cost-efficiency and environmental impact indicators. The overall results are broadly consistent with expected outcomes, such as arrival delay reduction when DCI is applied and credible cost outputs. DCI usage leads to a change in the cost dynamics: the cost of fuel increases with the additional fuel burn in contrast with passenger, crew and maintenance costs, which decrease as a function of time saved (S101, S102, S111, S112, S201, S202, S211 and S212). A dominating effect of the high fuel price scenario (SF1) was observed, more than counteracting the effect of non-fuel cost savings, resulting in a net loss when DCI was applied. This has important implications under changing fuel price regimes in future.

An informative outcome was the significant average passenger, crew and maintenance (i.e. non-fuel) cost savings per flight under scenario S102. This scenario simulated the medium-term future with six airlines using DCI at Zürich Airport, with a company policy applied of only recovering delay to a residual of 10 minutes. Leaving this residual demonstrated superior results compared with the 'rule of thumb' employed by many airlines of recovering all delay above a certain threshold. This scenario may be set in further context by future work, whereby the cost-optimisation algorithms may be improved to demonstrate further rubrics regarding the *optimal* amounts of residual delay.

Regarding other future research, extended data cleaning should seek to positively identify flights that are already using DCI, to prevent additional delay recovery from being applied in the simulation. Furthermore, it would be interesting to run the model for a different hub airport, one with a lower proportion of connections and a single airline alliance present – this would increase the hard cost fare transfer when passengers who missed connecting flights required reaccommodating onto competitors' flights, further raising the financial importance of making flight connections. Both of these factors could change the cost trade-off dynamics, if such data were available in future.

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Appendix A Simulation results

Significant improvements whereby the scenario mean is lower than the S000 baseline (2010 fuel) value are highlighted in a white font and grey background. Significant deteriorations are shown underlined. Significant figures are used.

Indicator	Units	S000	S001	S002
		Baseline; 2010 fuel; DCI: 'none'	V. few flights use DCI; 2010 fuel; DCI: 'thumb'	V. few flights use DCI; 2010 fuel; DCI: 'residual'
P1 departure time, per cent	<=3 mins	71%	74%	73%
P1 departure time, per cent	<=10 mins	79%	80%	79%
P1 departure time, per cent	<=15 mins	82%	84%	83%
P1 departure delay, total	mins	5400	4800	4900
P1 departure delay, mean (sd)	mins/flight	8 (20)	7 (19)	8 (19)
P2 arrival time, per cent	<=3 mins	60%	60%	59%
P2 arrival time, per cent	<=10 mins	73%	75%	75%
P2 arrival time, per cent	<=15 mins	77%	80%	79%
P2 arrival delay, total [1]	mins	7800	7300	7300
P2 arrival delay, mean (sd) [2]	mins/flight	12 (32)	11 (32)	11 (31)
C1 non-fuel cost, total [3]	Euros (000s)	3210	3050	2930
C1 non-fuel cost, mean (sd) [3]	Euros/flight	5000 (11800)	4700 (10800)	4500 (10600)
C2 fuel cost, total	Euros (000s)	1930	1930	1930
C2 fuel cost, mean (sd)	Euros/flight	3000 (7220)	3000 (7220)	3000 (7220)
C3 net cost, total	Euros (000s)	5140	4980	4860
C3 net cost, mean (sd)	Euros/flight	7900 (14300)	7700 (13600)	7500 (13500)
E1 CO ₂ , total	kilotonnes	10170	10170	10170
E1 CO ₂ , mean (sd)	tonnes/flight	15700 (38000)	15700 (38000)	15700 (38000)

[1] P2 arrival delay, total – total delay formerly P4

[2] P2 arrival delay, mean (sd) – standard deviation formerly P3

[3] C1 non-fuel cost – formerly C1 delay cost (non-fuel costs)

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continued

Significant improvements whereby the scenario mean is lower than the S000 baseline (2010 fuel) value are highlighted in a white font and grey background. Significant deteriorations are shown underlined. Significant figures are used.

Indicator	Units	S000	S003	S010
		Baseline; 2010 fuel; DCI: 'none'	V. few flights use DCI; 2010 fuel; DCI: 'cost'	Baseline; high fuel; DCI: 'none'
P1 departure time, per cent	<=3 mins	71%	69%	70%
P1 departure time, per cent	<=10 mins	79%	76%	76%
P1 departure time, per cent	<=15 mins	82%	80%	80%
P1 departure delay, total	mins	5400	5600	6000
P1 departure delay, mean (sd)	mins/flight	8 (20)	9 (20)	9 (21)
P2 arrival time, per cent	<=3 mins	60%	57%	58%
P2 arrival time, per cent	<=10 mins	73%	70%	72%
P2 arrival time, per cent	<=15 mins	77%	77%	77%
P2 arrival delay, total [1]	mins	7800	8100	8400
P2 arrival delay, mean (sd) [2]	mins/flight	12 (32)	13 (32)	13 (32)
C1 non-fuel cost, total [3]	Euros (000s)	3210	3240	3430
C1 non-fuel cost, mean (sd) [3]	Euros/flight	5000 (11800)	5000 (10200)	5300 (12700)
C2 fuel cost, total	Euros (000s)	1930	1930	2900
C2 fuel cost, mean (sd)	Euros/flight	3000 (7220)	3000 (7210)	4500 (10800)
C3 net cost, total	Euros (000s)	5140	5170	6330
C3 net cost, mean (sd)	Euros/flight	7900 (14300)	8000 (13200)	9800 (17700)
E1 CO ₂ , total	kilotonnes	10170	10170	10180
E1 CO ₂ , mean (sd)	tonnes/flight	15700 (38000)	15700 (38000)	15700 (38100)

[1] P2 arrival delay, total – total delay formerly P4

[2] P2 arrival delay, mean (sd) – standard deviation formerly P3

[3] C1 non-fuel cost – formerly C1 delay cost (non-fuel costs)

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continued

Significant improvements whereby the scenario mean is lower than the S000 baseline (2010 fuel) value are highlighted in a white font and grey background. Significant deteriorations are shown underlined. Significant figures are used.

Indicator	Units	S000	S011	S012
		Baseline; 2010 fuel; DCI: 'none'	V. few flights use DCI; high fuel; DCI: 'thumb'	V. few flights use DCI; high fuel; DCI: 'residual'
P1 departure time, per cent	<=3 mins	71%	73%	75%
P1 departure time, per cent	<=10 mins	79%	79%	80%
P1 departure time, per cent	<=15 mins	82%	83%	84%
P1 departure delay, total	mins	5400	5400	4900
P1 departure delay, mean (sd)	mins/flight	8 (20)	8 (20)	8 (20)
P2 arrival time, per cent	<=3 mins	60%	60%	63%
P2 arrival time, per cent	<=10 mins	73%	73%	75%
P2 arrival time, per cent	<=15 mins	77%	78%	80%
P2 arrival delay, total [1]	mins	7800	8000	7200
P2 arrival delay, mean (sd) [2]	mins/flight	12 (32)	12 (33)	11 (32)
C1 non-fuel cost, total [3]	Euros (000s)	3210	3320	2960
C1 non-fuel cost, mean (sd) [3]	Euros/flight	5000 (11800)	5100 (12500)	4600 (10100)
C2 fuel cost, total	Euros (000s)	1930	2900	2900
C2 fuel cost, mean (sd)	Euros/flight	3000 (7220)	4500 (10800)	4500 (10800)
C3 net cost, total	Euros (000s)	5140	6220	5860
C3 net cost, mean (sd)	Euros/flight	7900 (14300)	9600 (17200)	9000 (15600)
E1 CO ₂ , total	kilotonnes	10170	10170	10160
E1 CO ₂ , mean (sd)	tonnes/flight	15700 (38000)	15700 (38000)	15700 (38000)

[1] P2 arrival delay, total – total delay formerly P4

[2] P2 arrival delay, mean (sd) – standard deviation formerly P3

[3] C1 non-fuel cost – formerly C1 delay cost (non-fuel costs)

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continued

Significant improvements whereby the scenario mean is lower than the S000 baseline (2010 fuel) value are highlighted in a white font and grey background. Significant deteriorations are shown underlined. Significant figures are used.

Indicator	Units	S000	S013	S101
		Baseline; 2010 fuel; DCI: 'none'	V. few flights use DCI; high fuel; DCI: 'cost'	Many flights use DCI; 2010 fuel; DCI: 'thumb'
P1 departure time, per cent	<=3 mins	71%	72%	85%
P1 departure time, per cent	<=10 mins	79%	77%	88%
P1 departure time, per cent	<=15 mins	82%	81%	91%
P1 departure delay, total	mins	5400	5400	3100
P1 departure delay, mean (sd)	mins/flight	8 (20)	8 (20)	5 (18)
P2 arrival time, per cent	<=3 mins	60%	59%	69%
P2 arrival time, per cent	<=10 mins	73%	72%	81%
P2 arrival time, per cent	<=15 mins	77%	77%	86%
P2 arrival delay, total [1]	mins	7800	7700	5400
P2 arrival delay, mean (sd) [2]	mins/flight	12 (32)	12 (31)	8 (30)
C1 non-fuel cost, total [3]	Euros (000s)	3210	3060	2520
C1 non-fuel cost, mean (sd) [3]	Euros/flight	5000 (11800)	4700 (10600)	3900 (11600)
C2 fuel cost, total	Euros (000s)	1930	2900	1930
C2 fuel cost, mean (sd)	Euros/flight	3000 (7220)	4500 (10800)	3000 (7220)
C3 net cost, total	Euros (000s)	5140	5960	4450
C3 net cost, mean (sd)	Euros/flight	7900 (14300)	9200 (16200)	6900 (14300)
E1 CO ₂ , total	kilotonnes	10170	10170	10170
E1 CO ₂ , mean (sd)	tonnes/flight	15700 (38000)	15700 (38000)	15700 (38000)

[1] P2 arrival delay, total – total delay formerly P4

[2] P2 arrival delay, mean (sd) – standard deviation formerly P3

[3] C1 non-fuel cost – formerly C1 delay cost (non-fuel costs)

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continued

Significant improvements whereby the scenario mean is lower than the S000 baseline (2010 fuel) value are highlighted in a white font and grey background. Significant deteriorations are shown underlined. Significant figures are used.

Indicator	Units	S000	S102	S103
		Baseline; 2010 fuel; DCI: 'none'	Many flights use DCI; 2010 fuel; DCI: 'residual'	Many flights use DCI; 2010 fuel; DCI: 'cost'
P1 departure time, per cent	<=3 mins	71%	86%	72%
P1 departure time, per cent	<=10 mins	79%	89%	79%
P1 departure time, per cent	<=15 mins	82%	91%	82%
P1 departure delay, total	mins	5400	3000	5100
P1 departure delay, mean (sd)	mins/flight	8 (20)	5 (18)	8 (19)
P2 arrival time, per cent	<=3 mins	60%	67%	61%
P2 arrival time, per cent	<=10 mins	73%	83%	74%
P2 arrival time, per cent	<=15 mins	77%	87%	79%
P2 arrival delay, total [1]	mins	7800	5500	7200
P2 arrival delay, mean (sd) [2]	mins/flight	12 (32)	8 (30)	11 (31)
C1 non-fuel cost, total [3]	Euros (000s)	3210	2410	2840
C1 non-fuel cost, mean (sd) [3]	Euros/flight	5000 (11800)	3700 (9860)	4400 (9140)
C2 fuel cost, total	Euros (000s)	1930	1930	1930
C2 fuel cost, mean (sd)	Euros/flight	3000 (7220)	3000 (7230)	3000 (7230)
C3 net cost, total	Euros (000s)	5140	4340	4770
C3 net cost, mean (sd)	Euros/flight	7900 (14300)	6700 (12800)	7400 (12300)
E1 CO ₂ , total	kilotonnes	10170	10180	10180
E1 CO ₂ , mean (sd)	tonnes/flight	15700 (38000)	15700 (38100)	15700 (38100)

[1] P2 arrival delay, total – total delay formerly P4

[2] P2 arrival delay, mean (sd) – standard deviation formerly P3

[3] C1 non-fuel cost – formerly C1 delay cost (non-fuel costs)

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continued

Significant improvements whereby the scenario mean is lower than the S000 baseline (2010 fuel) value are highlighted in a white font and grey background. Significant deteriorations are shown underlined. Significant figures are used.

Indicator	Units	S000	S111	S112
		Baseline; 2010 fuel; DCI: 'none'	Many flights use DCI; high fuel; DCI: 'thumb'	Many flights use DCI; high fuel; DCI: 'residual'
P1 departure time, per cent	<=3 mins	71%	85%	85%
P1 departure time, per cent	<=10 mins	79%	89%	88%
P1 departure time, per cent	<=15 mins	82%	91%	91%
P1 departure delay, total	mins	5400	3100	3100
P1 departure delay, mean (sd)	mins/flight	8 (20)	5 (18)	5 (18)
P2 arrival time, per cent	<=3 mins	60%	68%	69%
P2 arrival time, per cent	<=10 mins	73%	82%	82%
P2 arrival time, per cent	<=15 mins	77%	86%	86%
P2 arrival delay, total [1]	mins	7800	5500	5500
P2 arrival delay, mean (sd) [2]	mins/flight	12 (32)	8 (30)	8 (30)
C1 non-fuel cost, total [3]	Euros (000s)	3210	2650	2620
C1 non-fuel cost, mean (sd) [3]	Euros/flight	5000 (11800)	4100 (10200)	4000 (10800)
C2 fuel cost, total	Euros (000s)	1930	2900	2900
C2 fuel cost, mean (sd)	Euros/flight	3000 (7220)	4500 (10800)	4500 (10800)
C3 net cost, total	Euros (000s)	5140	5550	5520
C3 net cost, mean (sd)	Euros/flight	7900 (14300)	8600 (15600)	8500 (16400)
E1 CO ₂ , total	kilotonnes	10170	10180	10180
E1 CO ₂ , mean (sd)	tonnes/flight	15700 (38000)	15700 (38000)	15700 (38000)

[1] P2 arrival delay, total – total delay formerly P4

[2] P2 arrival delay, mean (sd) – standard deviation formerly P3

[3] C1 non-fuel cost – formerly C1 delay cost (non-fuel costs)

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continued

Significant improvements whereby the scenario mean is lower than the S000 baseline (2010 fuel) value are highlighted in a white font and grey background. Significant deteriorations are shown underlined. Significant figures are used.

Indicator	Units	S000	S113	S201
		Baseline; 2010 fuel; DCI: 'none'	Many flights use DCI; high fuel; DCI: 'cost'	Most flights use DCI; 2010 fuel; DCI: 'thumb'
P1 departure time, per cent	<=3 mins	71%	73%	85%
P1 departure time, per cent	<=10 mins	79%	78%	89%
P1 departure time, per cent	<=15 mins	82%	81%	91%
P1 departure delay, total	mins	5400	5600	3100
P1 departure delay, mean (sd)	mins/flight	8 (20)	9 (20)	5 (18)
P2 arrival time, per cent	<=3 mins	60%	61%	70%
P2 arrival time, per cent	<=10 mins	73%	74%	81%
P2 arrival time, per cent	<=15 mins	77%	77%	86%
P2 arrival delay, total [1]	mins	7800	8100	5600
P2 arrival delay, mean (sd) [2]	mins/flight	12 (32)	12 (33)	9 (30)
C1 non-fuel cost, total [3]	Euros (000s)	3210	3270	2500
C1 non-fuel cost, mean (sd) [3]	Euros/flight	5000 (11800)	5000 (12600)	3900 (9010)
C2 fuel cost, total	Euros (000s)	1930	2890	1930
C2 fuel cost, mean (sd)	Euros/flight	3000 (7220)	4500 (10800)	3000 (7220)
C3 net cost, total	Euros (000s)	5140	6160	4430
C3 net cost, mean (sd)	Euros/flight	7900 (14300)	9500 (17100)	6800 (12200)
E1 CO ₂ , total	kilotonnes	10170	10160	10180
E1 CO ₂ , mean (sd)	tonnes/flight	15700 (38000)	15700 (38000)	15700 (38000)

[1] P2 arrival delay, total – total delay formerly P4

[2] P2 arrival delay, mean (sd) – standard deviation formerly P3

[3] C1 non-fuel cost – formerly C1 delay cost (non-fuel costs)

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continued

Significant improvements whereby the scenario mean is lower than the S000 baseline (2010 fuel) value are highlighted in a white font and grey background. Significant deteriorations are shown underlined. Significant figures are used.

Indicator	Units	S000	S202	S203
		Baseline; 2010 fuel; DCI: 'none'	Most flights use DCI; 2010 fuel; DCI: 'residual'	Most flights use DCI; 2010 fuel; DCI: 'cost'
P1 departure time, per cent	<=3 mins	71%	85%	72%
P1 departure time, per cent	<=10 mins	79%	88%	77%
P1 departure time, per cent	<=15 mins	82%	91%	82%
P1 departure delay, total	mins	5400	3100	5200
P1 departure delay, mean (sd)	mins/flight	8 (20)	5 (18)	8 (19)
P2 arrival time, per cent	<=3 mins	60%	66%	60%
P2 arrival time, per cent	<=10 mins	73%	82%	72%
P2 arrival time, per cent	<=15 mins	77%	86%	77%
P2 arrival delay, total [1]	mins	7800	5600	7400
P2 arrival delay, mean (sd) [2]	mins/flight	12 (32)	9 (30)	11 (31)
C1 non-fuel cost, total [3]	Euros (000s)	3210	2600	3190
C1 non-fuel cost, mean (sd) [3]	Euros/flight	5000 (11800)	4000 (11600)	4900 (12800)
C2 fuel cost, total	Euros (000s)	1930	1930	1930
C2 fuel cost, mean (sd)	Euros/flight	3000 (7220)	3000 (7210)	3000 (7210)
C3 net cost, total	Euros (000s)	5140	4530	5120
C3 net cost, mean (sd)	Euros/flight	7900 (14300)	7000 (14400)	7900 (15300)
E1 CO ₂ , total	kilotonnes	10170	10160	10170
E1 CO ₂ , mean (sd)	tonnes/flight	15700 (38000)	15700 (38000)	15700 (38000)

[1] P2 arrival delay, total – total delay formerly P4

[2] P2 arrival delay, mean (sd) – standard deviation formerly P3

[3] C1 non-fuel cost – formerly C1 delay cost (non-fuel costs)

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continued

Significant improvements whereby the scenario mean is lower than the S000 baseline (2010 fuel) value are highlighted in a white font and grey background. Significant deteriorations are shown underlined. Significant figures are used.

Indicator	Units	S000	S211	S212
		Baseline; 2010 fuel; DCI: 'none'	Most flights use DCI; high fuel; DCI: 'thumb'	Most flights use DCI; high fuel; DCI: 'residual'
P1 departure time, per cent	<=3 mins	71%	85%	84%
P1 departure time, per cent	<=10 mins	79%	89%	88%
P1 departure time, per cent	<=15 mins	82%	91%	91%
P1 departure delay, total	mins	5400	3100	3100
P1 departure delay, mean (sd)	mins/flight	8 (20)	5 (18)	5 (18)
P2 arrival time, per cent	<=3 mins	60%	69%	67%
P2 arrival time, per cent	<=10 mins	73%	81%	80%
P2 arrival time, per cent	<=15 mins	77%	86%	86%
P2 arrival delay, total [1]	mins	7800	5600	5700
P2 arrival delay, mean (sd) [2]	mins/flight	12 (32)	9 (30)	9 (30)
C1 non-fuel cost, total [3]	Euros (000s)	3210	2530	2690
C1 non-fuel cost, mean (sd) [3]	Euros/flight	5000 (11800)	3900 (9230)	4100 (11600)
C2 fuel cost, total	Euros (000s)	1930	2900	2900
C2 fuel cost, mean (sd)	Euros/flight	3000 (7220)	4500 (10800)	4500 (10800)
C3 net cost, total	Euros (000s)	5140	5430	5590
C3 net cost, mean (sd)	Euros/flight	7900 (14300)	8400 (15300)	8600 (16600)
E1 CO ₂ , total	kilotonnes	10170	10170	10170
E1 CO ₂ , mean (sd)	tonnes/flight	15700 (38000)	15700 (38000)	15700 (38000)

[1] P2 arrival delay, total – total delay formerly P4

[2] P2 arrival delay, mean (sd) – standard deviation formerly P3

[3] C1 non-fuel cost – formerly C1 delay cost (non-fuel costs)

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continued

Significant improvements whereby the scenario mean is lower than the S000 baseline (2010 fuel) value are highlighted in a white font and grey background. Significant deteriorations are shown underlined. Significant figures are used.

Indicator	Units	S000	S213
		Baseline; 2010 fuel; DCI: 'none'	Most flights use DCI; high fuel; DCI: 'cost'
P1 departure time, per cent	<=3 mins	71%	72%
P1 departure time, per cent	<=10 mins	79%	79%
P1 departure time, per cent	<=15 mins	82%	82%
P1 departure delay, total	mins	5400	5200
P1 departure delay, mean (sd)	mins/flight	8 (20)	8 (20)
P2 arrival time, per cent	<=3 mins	60%	61%
P2 arrival time, per cent	<=10 mins	73%	75%
P2 arrival time, per cent	<=15 mins	77%	80%
P2 arrival delay, total [1]	mins	7800	7600
P2 arrival delay, mean (sd) [2]	mins/flight	12 (32)	12 (32)
C1 non-fuel cost, total [3]	Euros (000s)	3210	3220
C1 non-fuel cost, mean (sd) [3]	Euros/flight	5000 (11800)	5000 (11900)
C2 fuel cost, total	Euros (000s)	1930	2900
C2 fuel cost, mean (sd)	Euros/flight	3000 (7220)	<u>4500</u> (10800)
C3 net cost, total	Euros (000s)	5140	6120
C3 net cost, mean (sd)	Euros/flight	7900 (14300)	9400 (17100)
E1 CO ₂ , total	kilotonnes	10170	10170
E1 CO ₂ , mean (sd)	tonnes/flight	15700 (38000)	15700 (38000)

[1] P2 arrival delay, total – total delay formerly P4

[2] P2 arrival delay, mean (sd) – standard deviation formerly P3

[3] C1 non-fuel cost – formerly C1 delay cost (non-fuel costs)

Appendix B Airline and passenger summary

This table summarises the total number of flights and passengers (both arriving and departing) at Zürich Airport on 20AUG10. The number of connecting passengers is precise; the remainder of non-connecting passengers have been estimated using in-house algorithms.

Airline	Airline type	Total flights	Total pax	Seat load factor	Proportion of Zürich Pax	Arriving connecting pax	Departing connecting pax
SWISS	FSC	364	39749	0.73	54.3%	10787	10756
Air Berlin	LCC	42	5928	0.81	8.1%	7	13
Lufthansa	FSC	28	2259	0.70	3.1%	101	106
Edelweiss Air	CHT	18	2619	0.82	3.6%	125	215
British Airways	FSC	12	1229	0.75	1.7%	3	0
CityJet	REG	12	710	0.59	1.0%	0	0
Cirrus Airlines	REG	12	223	0.58	0.3%	29	30
easyJet	LCC	10	1336	0.84	1.8%	0	1
Scandinavian Airlines (SAS)	FSC	10	1081	0.80	1.5%	39	69
KLM Royal Dutch Airlines	FSC	10	991	0.81	1.4%	0	5
TAP Portugal	FSC	10	985	0.72	1.3%	25	51
Belair	LCC	8	1044	0.75	1.4%	0	0
Austrian	FSC	8	728	0.62	1.0%	56	39
Croatia Airlines	FSC	8	443	0.73	0.6%	108	49
Niki	LCC	6	833	0.73	1.1%	5	2
germanwings	LCC	6	707	0.79	1.0%	0	0
Iberia	FSC	6	668	0.79	0.9%	0	0
Turkish Airlines (THY)	FSC	6	582	0.78	0.8%	10	13
BA CityFlyer	REG	6	300	0.60	0.4%	0	0
Helvetic Airways	LCC	5	375	0.75	0.5%	0	0
Emirates	FSC	4	995	0.69	1.4%	8	17
Delta Air Lines	FSC	4	726	0.81	1.0%	10	8
Finnair	FSC	4	435	0.77	0.6%	1	0
Jat Airways	FSC	4	411	0.82	0.6%	4	2
CSA Czech Airlines	FSC	4	300	0.81	0.4%	5	10
Montenegro Airlines	FSC	4	294	0.72	0.4%	10	3
Adria Airways	FSC	4	240	0.70	0.3%	22	24
LOT Polish Airlines	FSC	4	136	0.49	0.2%	13	8
City Airline	REG	4	85	0.49	0.1%	1	0
OLT Ostfriesische Lufttransport	REG	4	58	0.44	0.1%	2	1
El Al Israel Airlines	FSC	3	502	0.96	0.7%	44	10
Singapore Airlines	FSC	2	745	0.79	1.0%	63	33
Air Canada	FSC	2	408	0.96	0.6%	31	61
Continental Airlines	FSC	2	408	0.87	0.6%	29	24

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Airline	Airline type	Total flights	Total pax	Seat load factor	Proportion of Zürich Pax	Arriving connecting pax	Departing connecting pax
Thai Airways International	FSC	2	406	0.76	0.6%	64	15
American Airlines	FSC	2	391	0.87	0.5%	0	51
US Airways	FSC	2	371	0.91	0.5%	11	48
United Airlines	FSC	2	328	0.67	0.4%	62	85
Aer Lingus	FSC	2	327	0.77	0.4%	0	0
SunExpress	CHT	2	302	0.80	0.4%	0	0
Belle Air	LCC	2	246	0.75	0.3%	0	0
Air Malta	FSC	2	241	0.85	0.3%	21	13
Airlift Service	CHT	2	236	0.80	0.3%	0	0
Cyprus Airways	FSC	2	206	0.82	0.3%	4	1
airBaltic	LCC	2	196	0.82	0.3%	0	0
Aeroflot-Russian Airlines	FSC	2	182	0.78	0.2%	0	0
Malev	FSC	2	165	0.68	0.2%	0	0
TAROM	FSC	2	165	0.71	0.2%	0	0
Bulgaria Air	FSC	2	162	0.72	0.2%	9	0
Ukraine International Airlines	FSC	2	152	0.73	0.2%	41	11
Royal Jordanian Airlines	FSC	2	142	0.65	0.2%	0	0
Blue1	LCC	2	123	0.65	0.2%	11	10
bmi regional	REG	2	73	0.74	0.1%	0	0
Blue Islands	REG	2	71	0.77	0.1%	0	0
B&H Airlines	FSC	2	55	0.42	0.1%	23	2
Air Caraibes	REG	1	174	0.51	0.2%	0	0

Appendix C Maintenance and crew cost tables

The maintenance cost tables and regression parameters are listed for the at-gate, taxi and en-route flight phases. For arrival management, use the en-route cost table/parameters and fuel burn factor. All MTOW values are expressed in tonnes; costs are in 2010 Euros per minute.

Crew cost table/parameters follow maintenance and are applied to arrival delay.

At-gate maintenance costs of delay per minute (no fuel burn assumed)

Aircraft	MTOW	Low cost scenario	Base cost scenario	High cost scenario
B733	60.4	0.2	0.4	0.6
B734	65.6	0.2	0.5	0.6
B735	55.2	0.2	0.4	0.5
B738	72.6	0.2	0.4	0.6
B752	107.1	0.3	0.6	0.7
B763	180.7	0.4	0.7	1.1
B744	392.5	0.8	1.0	1.1
A319	66.6	0.2	0.5	0.6
A320	73.6	0.2	0.4	0.6
A321	86.4	0.3	0.5	0.7
AT43	16.8	0.1	0.2	0.3
AT72	22.1	0.1	0.3	0.3

At-gate regression parameters apply to all aircraft

Parameter	Low cost scenario	Base cost scenario	High cost scenario
r^2	0.96	0.96	0.88
m	0.04	0.05	0.06
c	-0.14	0.04	0.12

Cost per minute:

$$y = (m \cdot \sqrt{\text{MTOW}}) + c$$

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Taxi maintenance costs of delay per minute (baseline fuel burn assumed)

Aircraft	MTOW	Low cost scenario	Base cost scenario	High cost scenario
B733	60.4	6.7	10.9	14.3
B734	65.6	7.4	11.8	15.4
B735	55.2	7.2	11.4	15.0
B738	72.6	6.5	10.4	14.1
B752	107.1	10.3	16.3	21.4
B763	180.7	12.5	19.5	26.6
B744	392.5	23.7	34.5	44.8
A319	66.6	5.9	9.8	12.8
A320	73.6	7.5	11.9	16.1
A321	86.4	7.1	11.4	14.9
AT43	16.8	2.8	4.5	5.9
AT72	22.1	3.3	5.4	6.9

Taxi regression parameters apply to all aircraft

Parameter	Low cost scenario	Base cost scenario	High cost scenario
r^2	0.96	0.97	0.98
m	1.31	1.88	2.46
c	-3.61	-4.12	-5.24

Cost per minute:

$$y = (m \cdot \sqrt{\text{MTOW}}) + c$$

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En-route *and* arrival management maintenance costs of delay per minute (fuel burn excluded)

Aircraft	MTOW	Low cost scenario	Base cost scenario	High cost scenario
B733	60.4	1.6	3.5	4.4
B734	65.6	1.9	3.7	4.6
B735	55.2	1.6	3.2	3.9
B738	72.6	1.4	2.9	4.2
B752	107.1	2.1	4.2	5.2
B763	180.7	2.9	5.4	7.9
B744	392.5	6.0	7.6	8.5
A319	66.6	1.7	3.7	4.7
A320	73.6	1.7	3.4	4.9
A321	86.4	2.1	4.1	5.1
AT43	16.8	0.8	1.6	2.0
AT72	22.1	1.0	2.0	2.5

En-route *and* arrival management regression parameters apply to all aircraft

Parameter	Low cost scenario	Base cost scenario	High cost scenario
r^2	0.94	0.97	0.91
m	0.32	0.37	0.43
c	-0.86	0.35	0.87

Cost per minute: $y = (m \cdot \sqrt{\text{MTOW}}) + c$

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Arrival management maintenance costs of delay per minute (fuel burn excluded)

Use en-route costs and regression parameters with a fuel burn factor (0.88 for all aircraft).

Crew costs of delay per minute

Aircraft	MTOW	Low cost scenario	Base cost scenario	High cost scenario
B733	60.4	0	8.5	17.7
B734	65.6	0	8.2	17.8
B735	55.2	0	8.0	17.3
B738	72.6	0	9.0	19.5
B752	107.1	0	9.0	18.1
B763	180.7	0	12.9	34.6
B744	392.5	0	16.7	45.0
A319	66.6	0	7.3	15.2
A320	73.6	0	7.8	16.1
A321	86.4	0	7.8	16.1
AT43	16.8	0	5.6	11.5
AT72	22.1	0	6.1	13.0

Crew regression parameters apply to all aircraft

Parameter	Low cost scenario	Base cost scenario	High cost scenario
r^2	0	0.95	0.91
m	0	0.72	2.24
c	0	2.29	-0.42

Cost per minute: $y = (m \cdot \sqrt{MTOW}) + c$

Appendix D Implementation details

This appendix details the implementation of Case Study 3. Corresponding XML code extracts are listed in Appendix E.

D.1.1 Airport capability

The airport capability manages take-off and landing activities, using slot reservation. Each flight asks the airport for permission before these activities, and the airport calculates delay according to runway occupancy. There is an example of the file *costIndexing.capability.xml* (Appendix E, XML extract 1), located in the *simulator.airline* package.

The description includes several beliefs (see XML extract 2). Some of them are inherited from the airline definition, such as the ICAO airport code, time zone, flights and simulation. The specific beliefs have the following meaning:

- *dep. slot*: slot time for taking-off;
- *arr. slot*: slot time for landing;
- *departures*: list of slots reserved for taking-off;
- *arrivals*: list of slots reserved for landing.

This definition includes a plan for each reasoning step (see XML extract 3):

- *initialize*: Creates an airport and initialises its beliefs. It is performed at agent initialisation automatically;
- *generate delay zrh*: Delay calculation in Zurich is simulated with a high level of detail. It removes expired slot reservations and inserts a new one for the requesting flight. The delay at the airport is calculated according to slot occupancy and slot time. This plan is performed when a *request delay zrh* message is received;
- *generate delay other*: Delay calculation in other airports is calculated with a lower level of detail. It calculates airport delay comparing schedule times with actual times. This plan is performed when a *request delay other* message is received.

There are several message events to perform the desired behaviour (see XML extract 4):

- *confirm initialized*: outgoing message that notifies the manager that the airport has been initialised and it is ready to start the execution (internal control);
- *request delay zrh*: incoming message which contains a flight id and its receiver is LSZH;
- *request delay other*: incoming message which contains a flight id and its receiver is any other airport but LSZH;
- *inform delay*: outgoing message which notifies the aircraft of the runway delay.

There is also an expression to find out a flight in the belief set *flights* with a specific identifier (see XML extract 5).

These are the required libraries for the capability (see XML extract 6):

D.1.2 Airline capability

The airline capability calculates the optimal flight speed and waiting time for connecting passengers, according to delay costs and fuel costs. It also calculates the actual cost of our flights in scope. Appendix E XML extract 7 shows the header and the footer of the file *costIndexing.capability.xml*, located in the *simulator.airline* package.

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The description includes several beliefs (see XML extract 8). There are no additional beliefs for capability behaviour, all of them are inherited from the airline definition.

The description contains several goals (see XML extract 9) to describe agent behaviour:

- *gen missing conn costs*: Calculates the delay costs of missing a connection with another flight. Missed *connections* are replaced with new *connections* after *EIBT* time, and generate *soft* and *hard costs*;
- *gen hard costs*: Calculates the cost of delay due to compensations to the passengers, such as food provision and accommodation. Providing the *delay* of the flight and the set of passenger fares, it generates the *hard costs*;
- *gen soft costs*: Calculates the cost of delay due to lack of confidence in the airline. As in hard cost generation, providing the delay of the flight and the set of passenger fares, it generates the soft costs;
- *connecting pax dest costs*: Calculates the delay costs of passengers with connections at destination. Providing the *EIBT* and *connections* with other flights, selects missed connections and calculates the *hard* and *soft cost* of missing these connections;
- *non connecting pax costs*: Calculates the delay costs of passengers without further connections. Providing the *delay* and a set of *passenger* fares, it generates the *soft costs*;
- *non pax delay costs*: Calculates the delay costs of crew and fuel consumption. Providing the *duration* of cruise, the *speed* and the details of the *flight*, it generates the *fuel costs* and the *crew costs*.

This definition includes a plan for each reasoning step (see XML extract 10):

- *initialize*. Creates an airline and initialises its beliefs. It is performed at agent initialisation automatically;
- *waitforpax calculation*. Calculates the optimal waiting time for connecting passengers for a flight. It is performed when a *request waiting time* message is received;
- *ci calculation*. Calculates the optimal speed for a flight. It is performed when a *request ci* message is received;
- *missing conn costs*. Calculates the delay costs of passengers with connections at destination. It is performed when a *missing conn cost* goal is dispatched;
- *connecting pax dest costs*. Calculates the delay costs of passengers with connections at destination. It is performed when a *connecting pax dest costs* goal is dispatched;
- *non connecting pax costs*. Calculates the delay costs of passengers without further connections. It is performed when a *non connecting pax costs* goal is dispatched;
- *non pax delay costs*. Calculates the delay costs of crew and fuel consumption. It is performed when a *non pax delay costs* goal is dispatched;
- *soft costs*. Calculates the cost of delay due to lack of confidence in the airline;
- *hard costs*. Calculates the cost of delay due to compensations to the passengers, such as food provision and accommodation.

There are several message events to perform the desired behaviour (see XML extract 11):

- *confirm initialized*: outgoing message that notifies the manager that the airline has been initialised and it is ready to start the execution (internal control);
- *request waiting time*: incoming message that contains the flight identifier to calculate waiting time for connecting passengers;
- *inform waiting time*: outgoing message that informs the aircraft the amount of time it has to wait for connecting passengers;
- *request ci*: incoming message that contains the flight identifier to calculate the optimal speed;
- *inform ci*: outgoing message that informs the aircraft the optimal speed;

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- *request alloc costs*: incoming message with no contents to perform cost allocation;
- *inform allocated*: outgoing message that informs the manager that the costs are allocated.

There are also some expressions to obtain data from belief sets, such as the expressions *get_flight*, *prev_flight* and *next_flight*.

For instance, *get_flight* obtain the flight comparing the flight id. *prev_flight* obtain the previous flight with the same aircraft, and *next_flight* do the same but for the next flight (see XML extract 12).

These are the required libraries for the capability (see XML extract 13).

D.1.3 Aircraft capability

Aircraft in Case Study 3 have the capability of adapting the speed in response to delays in the environment in two points: at ready time and at cruise time. Appendix E XML extract 14 shows the header and the footer of the file *costIndexing.capability.xml*, located in the *simulator.aircraft* package.

The description includes several beliefs (see XML extract 15). Some of them are inherited from the airline definition, such as the ICAO airport code, model, flights and simulation. The specific beliefs have the following meaning:

- *taxi in time*: duration of taxi in;
- *taxi out time*: duration of taxi out.

The description contains several goals (see XML extract 16) to simulate each phase of the flight:

- *startup*: sets startup time according to *previous* and *current* flight data and returns waiting time;
- *request AOC*: requests optimal speed or waiting for connecting passenger time to the airline to initialise flight trajectory, using *current* flight details;
- *ready*: sets ready time if the aircraft is ready to depart using *current* and *previous* flight details;
- *taxi out*: initialises trajectory at taxi out, using *current* flight details;
- *take off*: updates trajectory at take-off, using *current* flight details;
- *cruise*: updates trajectory at cruise time, using *current* flight details;
- *approximation*: updates trajectory at approximation, using *current* flight details;
- *landing*: updates trajectory at landing, using *current* flight details.

This definition includes a plan for each reasoning step (see XML extract 17):

- *initialize*: Creates an aircraft agent and initialises its beliefs. It is performed automatically at agent creation;
- *flight simulation*: Simulates several flight phases using goal dispatching. It is performed when a *perform_simulation* message is received;
- *startup*: Initialisation phase. It is performed when a *startup* goal is dispatched;
- *request aoc*: Request data to the AOC such as the waiting time for connecting passengers or the aircraft flight speed. It is performed when a *request_aoc* goal is dispatched;
- *ready*: Check if the aircraft was ready to depart. It is performed when a *startup* goal is dispatched;
- *taxi out*: Creates initial trajectory at taxi out (AOBT). It is performed when a *taxi_out* goal is dispatched;
- *take off*: Updates trajectory at take-off (ATOT). It is performed when a *take_off* goal is dispatched;
- *cruise*: Updates trajectory at cruise time (ARCT). It is performed when a *cruise* goal is dispatched;

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- *approximation*: Updates trajectory at approximation (APTI). It is performed when an *approximation* goal is dispatched;
- *landing*: Updates trajectory at landing (ATA). It is performed when a *landing* goal is dispatched.

There are several message events to perform the desired behaviour (see XML extract 18):

- *perform simulation*: incoming message that notifies the aircraft to perform flight simulation;
- *confirm simulation*: outgoing message that informs the manager the end of flight simulation in an aircraft;
- *request waiting time*: outgoing message to request the waiting time for connecting passengers for a flight;
- *inform waiting time*: incoming message which notifies the Network Manager (NM) of the list of proposals of slots exchanges;
- *request ci*: outgoing message to request the flight speed for a flight;
- *inform ci*: incoming message to inform the optimal flight speed;
- *request delay*: outgoing message which request the airport delay at the runway;
- *inform delay*: incoming message which rejects the delay in the runway of the airport;
- *confirm initialized*: outgoing message that notifies the manager the end of initialisation plan.

These are the required libraries for the capability (see XML extract 19):

D.1.4 Manager

The manager is a pseudo agent designed to provide some functionalities to control the simulation. It creates the agents in the platform, starts the simulation and analyses its results. This case study extends the general definition of the manager agent (see the general definition in D3.4). Appendix E XML extract 20 shows the header and the footer of the file *Manager.agent.xml*, located in the *simulator.manager* package.

This agent uses one capability (see XML extract 21), *cmscap*, for starting airline agents.

The agent has several beliefs (see XML extract 22). Some of these have a constant initial value as it is common to all simulations. Other beliefs are initialised by the Java plan because their initial values are dynamic.

- *simulation*: simulation data for the current simulation (identifier, regulation...);
- *flights*: list of all loaded flights (from the database) in the current simulation;
- *aircrafts*: list of all aircraft loaded;
- *airlines*: list of all airlines loaded;
- *airports*: list of all airports loaded.

The agent has six goals (see XML extract 23):

- *cms create component*: create components through the CMS component in the simulator (part of the predefined capability);
- *create agents*: creates agents using data from agent instances;
- *create indicators*: calculates some indicators according to simulation results.

There are six plans to achieve these goals, one plan for each goal, and another one to initialise the environment (see XML extract 24):

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- *protocol*: controls the simulation;
- *create agents*: creates simulated agents;
- *create indicators*: analyses the simulation results.

There are several events that interact with the airline agents (exchange of messages – see XML extract 25):

- *confirm initialized*: incoming message sent by an agent to inform that it has been initialised and it is ready to start the execution;
- *perform simulation*: outgoing message that request the aircraft to perform flight simulation;
- *confirm simulation*: incoming message which informs the manager that the flight simulation was performed;
- *request allocation costs*: outgoing message which notifies the airline to calculate actual costs of flights;
- *inform allocated*: incoming message which informs the manager that the actual cost calculation was performed.

There are also some expressions to obtain specific data from belief sets (see XML extract 26):

- *query airport flights*: gets all flights for an airport;
- *query airline flights*: gets all flights for an airline;
- *query flights*: gets all flights of the simulation;
- *query flight*: gets a flight comparing the provided flight identifier with each flight.

Refer to XML extract 27 for the required libraries for this agent.

D.1.5 Application

The application file for Case Study 3 (contained in the package *simulator*) defines four component types: airlines, airports, aircraft and the manager. The last one, i.e. the manager, is created at simulation start, and there is a list of different simulation scenarios (see XML extract 28).

For example, scenario S010 has some predefined values for fuel price and regulation id, other parameters are using the default values.

D.2 Simulation definition

There are 25 plans in Java language to implement agent behaviour algorithms. Each plan has been defined in the agent-based model.

Time points corresponding to the different phases of a flight (i.e. take-off, landing, taxi-in, taxi-out) are simulated with an element of uncertainty, for example to take some account of wind and operational non-determinism. For each time point there is an initial value T_0 considered as input data for the system. This initial value is modified with some variation dT generated automatically sampling from a Normal distribution $\sim N(0, T_0 * 1.5/100)$, i.e. a mean of 0 a variance of $T_0 * 1.5/100$. The final value T for a time point is obtained as $T = T_0 + dT$.

The following classes are created to provide new functionalities in the platform to describe case behaviour.

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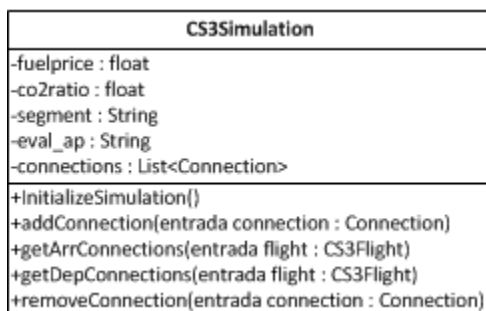


Figure 6. Class CS3Simulation

The simulated scenarios in Case Study 3 are characterised with the following attributes:

- *fuel price*: fuel price scenario;
- *co2 ratio*: CO₂ emitted per kg of fuel ratio;
- *segment*: segment analysed in flight trajectory;
- *eval ap*: airport where the flight data are collected.

The class CS3Simulation contains the following methods:

- *initializeSimulation*: obtain all elements of the environment;
- *addConnection*: add a new connection;
- *getArrConnections*: get arrival connections for a flight;
- *getDepConnections*: get departure connections for a flight;
- *removeConnections*: remove a missed connection.

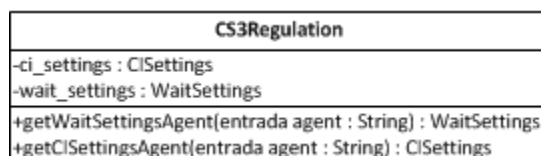


Figure 7. Class CS3Regulation

CS3 Regulations are characterised with the following attributes:

- *ci settings*: configuration to select the optimal CI;
- *wait settings*: configuration to select the optimal waiting time for connecting passengers.

It contains the following methods:

- *getWaitSettingsAgent*: return wait settings for regulated agents, else returns default wait setting (SLF85);
- *getCISettingsAgent*: return CI settings for regulated agents, else returns default CI setting (FIXED CI).

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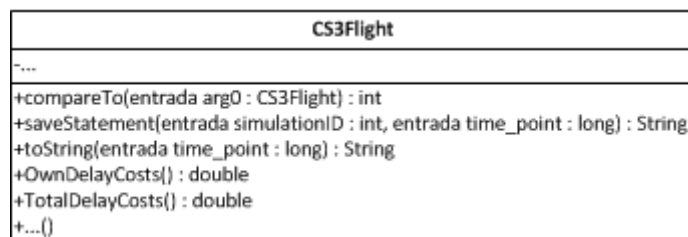


Figure 8. Class CS3Flight

Flights in CS3 have additional information about the following topics:

- Estimated time points for each phase;
- Actual time points for each phase;
- Passenger data;
- Delay costs;
- Fuel costs;
- Flight speeds;
- Fuel consumption.

Furthermore, they also have defined some methods to provide new functionalities to calculate delays, durations and accumulate flight costs.

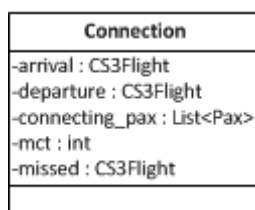


Figure 9. Class Connection

A connection is characterised with an arrival flight, a departure flight, the minimum connecting time between flights and a missed flight if it is a new connection from a missed connection.

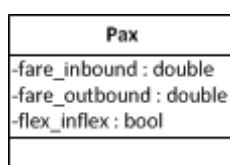


Figure 10. Class Pax

Each passenger has a flight fare. There are two types of fares, inbound and outbound, if the flight has connections. Fares can be flexible or inflexible.

D.3 Agent instances and environment

There are six more tables of data in the database to adapt the base platform to the specific design of Case Study 3 (see Figure 11).

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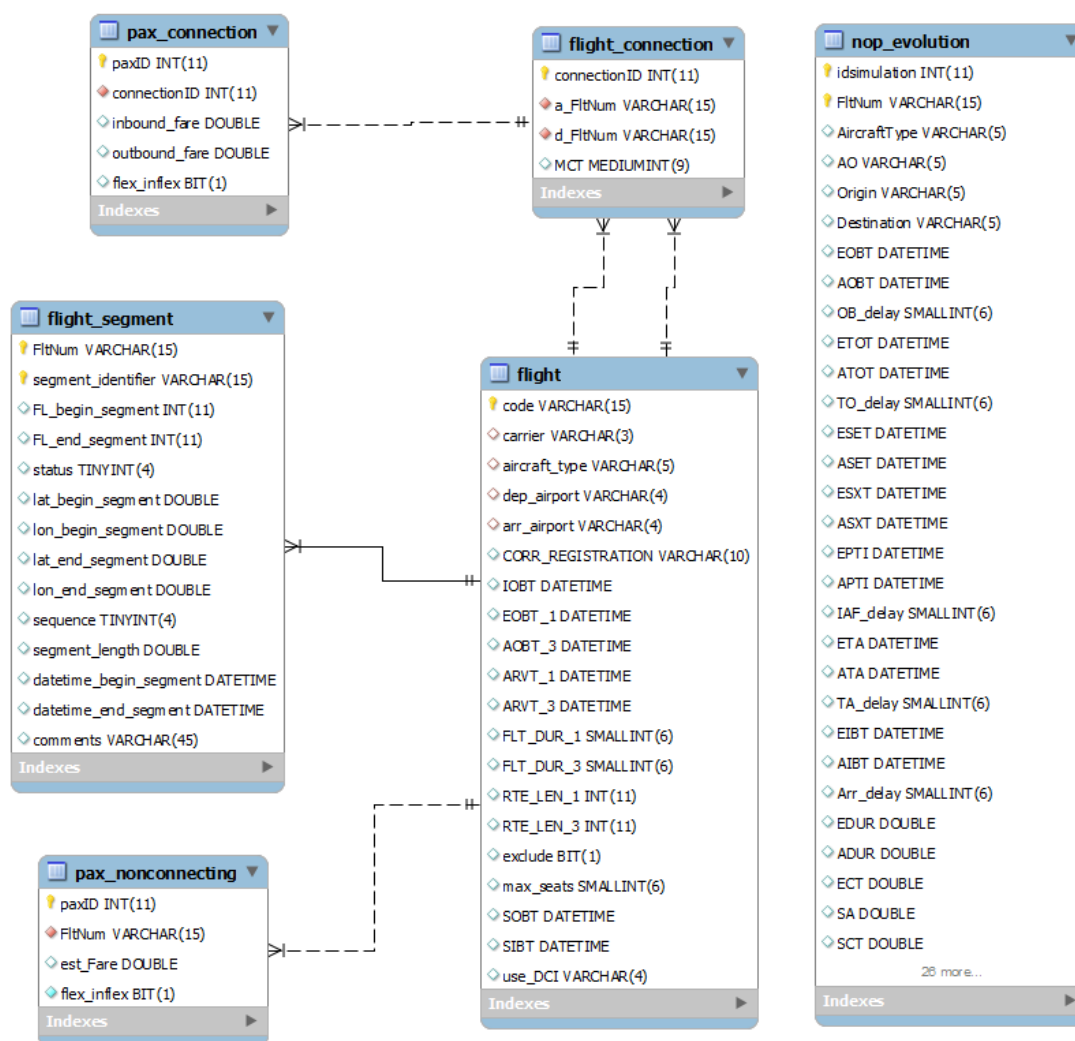


Figure 11. Database tables

In summary, the database includes the following details:

- **Flight** table is extended to contain the initial attributes of a flight for Case Study 3, such as the scheduled times, the number of seats and the DCI availability;
- **Flight_segment** table contains segment data about flights, such as the start and end time for a flight in a segment;
- **Flight_connection** table contains the connections established between flights. Each row contains the identifier for the departure flight, the arrival flight and the MCT;
- **Pax_connection** table contains fare data about connecting passengers;
- **Pax_nonconnecting** table contains fare data about passengers for a flight;
- **Nop_evolution** table contains all the output values for each flight in the simulation, such as the times, costs, delays and durations for each phase.

Appendix E Simulation code

The following XML code extracts accompany Appendix D Implementation details (Appendix D sub-headings are included to assist the reader).

Extracts refer to Appendix D.1.1 Airport capability

XML extract 1

```
<?xml version="1.0" encoding="UTF-8"?>
<!--
  <H3Case 3: Airport capability.</H3>
  Generate delays in a dynamic CI environment
-->
<capability xmlns="http://jadex.sourceforge.net/jadex"
  xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
  xsi:schemaLocation="http://jadex.sourceforge.net/jadex
    http://jadex.sourceforge.net/jadex-bdi-2.3.xsd"
  name="CostIndexing"
  package="simulator.airport">
  <!-- Behavior elements -->
</capability>
```

XML extract 2

```
<beliefs>
  <beliefref name="simulation" >
    <abstract/>
  </beliefref>

  <beliefref name="icao" >
    <abstract/>
  </beliefref>

  <beliefsetref name="flights" >
    <abstract/>
  </beliefsetref>

  <beliefref name="time_zone" >
    <abstract />
```

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```

</beliefref>

<belief name="dep_slot" class="int">
  <fact>87743</fact>
</belief>
<belief name="arr_slot" class="int">
  <fact>106562</fact>
</belief>

<beliefset name="arrivals" class="Long" />
<beliefset name="departures" class="Long" />
</beliefs

```

XML extract 3

```

<plans>
  <plan name="initialize" >
    <body class="AirportInitializationPlan"/>
  </plan>

  <plan name="generate_delay_zrh" >
    <body class="GenerateDelayZrhPlan"/>
    <trigger>
      <messageevent ref="request_delay_zrh"/>
    </trigger>
  </plan>

  <plan name="generate_delay_other" >
    <body class="GenerateDelayOtherPlan"/>
    <trigger>
      <messageevent ref="request_delay_other"/>
    </trigger>
  </plan>
</plans>

```

XML extract 4

```

<events>
  <messageevent name="confirm_initialized" direction="send" type="fipa">

```

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```

    <parameter name="performative" class="String" direction="fixed">
      <value>"confirm_initialized"</value>
    </parameter>
  </messageevent>
  <messageevent name="request_delay_zrh" direction="receive" type="fipa">
    <parameter name="performative" class="String" direction="fixed">
      <value>"request_delay"</value>
    </parameter>
    <match>$beliefbase.icao.equals("LSZH")</match>
  </messageevent>
  <messageevent name="request_delay_other" direction="receive" type="fipa">
    <parameter name="performative" class="String" direction="fixed">
      <value>"request_delay"</value>
    </parameter>
    <match>!$beliefbase.icao.equals("LSZH")</match>
  </messageevent>
  <messageevent name="inform_delay" direction="send" type="fipa">
    <parameter name="performative" class="String" direction="fixed">
      <value>"inform_delay"</value>
    </parameter>
  </messageevent>
</events>

```

XML extract 5

```

<expressions>
  <expression name="get_flight">
    select one Flight $flight
    from $beliefbase.flights
    where $flight.getId() == $id
  </expression>
</expressions>

```

XML extract 6

```

<imports>
  <import>jadex.bridge.fipa.*</import>
  <import>java.lang.Long</import>
  <import>simulator.environment.Flight</import>

```

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```
<import>simulator.environment.CS3Flight</import>  
<import>simulator.environment.CS3Simulation</import>  
</imports>
```


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Extracts refer to Appendix D.1.2 Airline capability

XML extract 7

```
<?xml version="1.0" encoding="UTF-8"?>
<!--
  <H3>Case3: Airline capability.</H3>
  Calculate CI and wait for pax time
-->
<capability xmlns="http://jadex.sourceforge.net/jadex"
  xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
  xsi:schemaLocation="http://jadex.sourceforge.net/jadex
    http://jadex.sourceforge.net/jadex-bdi-2.3.xsd"
  name="CostIndexing"
  package="simulator.airline">
  <!-- Behavior elements -->
</capability>
```

XML extract 8

```
<beliefs>
  <beliefref name="simulation" >
    <abstract/>
  </beliefref>
  <beliefref name="icao" >
    <abstract/>
  </beliefref>
  <beliefsetref name="flights" >
    <abstract/>
  </beliefsetref>
  <beliefref name="type">
    <abstract />
  </beliefref>
</beliefs>
```

XML extract 9

```
<goals>
  <achievegoal name="gen_missing_conn_costs">
    <parameter name="eibt" class="Date" direction="in" optional="true"/>
  </achievegoal>
</goals>
```

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```

    <parameter    name="hard_costs" class="double" direction="out" />
    <parameter    name="soft_costs" class="double" direction="out" />
    <parameterset name="connections" class="Connection" direction="inout" />
</achievegoal>

<achievegoal name="gen_hard_costs">
    <parameter    name="delay" class="long"    direction="in" />
    <parameter    name="costs" class="double" direction="out" />
    <parameterset name="pax"    class="Pax"    direction="in" />
</achievegoal>

<achievegoal name="gen_soft_costs">
    <parameter    name="delay" class="long"    direction="in" />
    <parameter    name="costs" class="double" direction="out" />
    <parameterset name="pax"    class="Pax"    direction="in" />
</achievegoal>

<achievegoal name="connecting_pax_dest_costs">
    <parameter    name="eibt"      class="Date"      direction="in" />
    <parameter    name="hard_costs" class="double"    direction="out" />
    <parameter    name="soft_costs" class="double"    direction="out" />
    <parameterset name="connecting" class="Connection" direction="in" />
</achievegoal>

<achievegoal name="non_connecting_pax_costs">
    <parameter    name="delay"      class="long"    direction="in" />
    <parameter    name="soft_costs" class="double"    direction="out" />
    <parameterset name="pax"        class="Pax"    direction="in" />
</achievegoal>

<achievegoal name="non_pax_delay_costs">
    <parameter name="duration" class="long"    direction="in" />
    <parameter name="costindex" class="double" direction="in" />
    <parameter name="flight"    class="CS3Flight" direction="in" />
    <parameter name="fuel_costs" class="double" direction="out" />
    <parameter name="crew_costs" class="double" direction="out" />
</achievegoal>
</goals>

```

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XML extract 10

```

<plans>
  <plan name="initialize">
    <body class="AirlineInitializationPlan"/>
  </plan>
  <plan name="waitforpax_calculation" >
    <body class="WaitForPaxCalculationPlan"/>
    <trigger>
      <messageevent ref="request_waiting_time"/>
    </trigger>
  </plan>
  <plan name="ci_calculation">
    <body class="CostIndexCalculationPlan"/>
    <trigger>
      <messageevent ref="request_ci"/>
    </trigger>
  </plan>
  <plan name="allocate_costs">
    <body class="AllocateCostsPlan" />
    <trigger>
      <messageevent ref="request_alloc_costs"/>
    </trigger>
  </plan>

  <plan name="missing_conn_costs">
    <body class="MissingConnCostsPlan" />
    <trigger>
      <goal ref="gen_missing_conn_costs" />
    </trigger>
  </plan>
  <plan name="connecting_pax_dest_costs">
    <body class="ConnectingPaxDestCostsPlan" />
    <trigger>
      <goal ref="connecting_pax_dest_costs" />
    </trigger>
  </plan>
  <plan name="non_connecting_pax_costs">
    <body class="NonConnectingPaxCostsPlan" />
    <trigger>
      <goal ref="non_connecting_pax_costs" />
    </trigger>

```

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```

</plan>
<plan name="non_pax_delay_costs">
  <body class="NonPaxDelayCostsPlan" />
  <trigger>
    <goal ref="non_pax_delay_costs" />
  </trigger>
</plan>

<plan name="soft_costs">
  <body class="SoftCostsPlan" />
  <trigger>
    <goal ref="gen_soft_costs" />
  </trigger>
</plan>

<plan name="hard_costs">
  <body class="HardCostsPlan" />
  <trigger>
    <goal ref="gen_hard_costs" />
  </trigger>
</plan>
</plans>

```

XML extract 11

```

<events>
  <messageevent name="confirm_initialized" direction="send" type="fipa">
    <parameter name="performative" class="String" direction="fixed">
      <value>"confirm_initialized"</value>
    </parameter>
  </messageevent>

  <messageevent name="request_waiting_time" type="fipa" direction="receive">
    <parameter name="performative" class="String" direction="fixed">
      <value>"request_waiting_time"</value>
    </parameter>
  </messageevent>

  <messageevent name="inform_waiting_time" type="fipa" direction="send" >
    <parameter name="performative" class="String" direction="fixed">
      <value>"inform_waiting_time"</value>
    </parameter>
  </messageevent>

```

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```

    </parameter>
  </messageevent>

  <messageevent name="request_ci" type="fipa" direction="receive">
    <parameter name="performative" class="String" direction="fixed">
      <value>"request_ci"</value>
    </parameter>
  </messageevent>

  <messageevent name="inform_ci" type="fipa" direction="send">
    <parameter name="performative" class="String" direction="fixed">
      <value>"inform_ci"</value>
    </parameter>
  </messageevent>

  <messageevent name="request_alloc_costs" type="fipa" direction="receive">
    <parameter name="performative" class="String" direction="fixed">
      <value>"request_allocation_costs"</value>
    </parameter>
  </messageevent>

  <messageevent name="inform_allocated" type="fipa" direction="send">
    <parameter name="performative" class="String" direction="fixed">
      <value>"inform_allocated"</value>
    </parameter>
  </messageevent>
</events>

```

XML extract 12

```

<expressions>
  <expression name="get_flight">
    select one Flight $flight
    from $beliefbase.flights
    where $flight.getId() == $id
  </expression>
  <expression name="prev_flight">
    select one CS3Flight $flight
    from $beliefbase.flights
    where $flight.getArr_airport().equals($current.getDep_airport())
  </expression>
</expressions>

```

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```
        && $flight.getEOBT().before($current.getEOBT())
        && $flight.getIFPS().equals($current.getIFPS())
    order by $flight.getEOBT() desc
</expression>
<expression name="next_flight">
    select one CS3Flight $flight
    from $beliefbase.flights
    where $flight.getDep_airport().equals($current.getArr_airport())
        && $flight.getEOBT().after($current.getEOBT())
        && $flight.getIFPS().equals($current.getIFPS())
    order by $flight.getEOBT() asc
</expression>
</expressions>
```

XML extract 13

```
<imports>
  <import>jadex.bridge.fipa.*</import>
  <import>simulator.environment.Connection</import>
  <import>simulator.environment.Flight</import>
  <import>simulator.environment.CS3Flight</import>
  <import>simulator.environment.CS3Simulation</import>
  <import>simulator.environment.Pax</import>
  <import>java.util.Date</import>
</imports>
```

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Extracts refer to Appendix D.1.3 Aircraft capability

XML extract 14

```

<capability xmlns="http://jadex.sourceforge.net/jadex"
  xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
  xsi:schemaLocation="http://jadex.sourceforge.net/jadex
    http://jadex.sourceforge.net/jadex-bdi-2.3.xsd"
  name="CostIndexing"
  package="simulator.aircraft">
  <!-- Behavior elements -->
</capability>

```

XML extract 15

```

<beliefs>
  <beliefref name="simulation" >
    <abstract/>
  </beliefref>

  <beliefref name="icao" >
    <abstract/>
  </beliefref>

  <beliefsetref name="flights" >
    <abstract/>
  </beliefsetref>

  <beliefref name="model" >
    <abstract/>
  </beliefref>

  <belief name="taxi_in_time" class="int" >
    <fact>600000</fact>
  </belief>

  <belief name="taxi_out_time" class="int" />
</beliefs>

```

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XML extract 16

```
<goals>
  <achievegoal name="startup">
    <parameter name="previous" class="CS3Flight" direction="in"
      optional="true" />
    <parameter name="current" class="CS3Flight" direction="in" />
    <parameter name="time" class="long" direction="out" />
  </achievegoal>

  <performgoal name="request_aoc" >
    <parameter name="current" class="CS3Flight" direction="in" />
  </performgoal>

  <performgoal name="ready" >
    <parameter name="previous" class="CS3Flight" direction="in"
      optional="true" />
    <parameter name="current" class="CS3Flight" direction="in" />
  </performgoal>

  <performgoal name="taxi_out" >
    <parameter name="current" class="CS3Flight" direction="in" />
    <parameter name="taxi_out_delay" class="int" direction="in" />
  </performgoal>

  <performgoal name="take_off" >
    <parameter name="current" class="CS3Flight" direction="in" />
  </performgoal>

  <performgoal name="cruise" >
    <parameter name="current" class="CS3Flight" direction="in" />
  </performgoal>

  <performgoal name="approximation" >
    <parameter name="current" class="CS3Flight" direction="in" />
  </performgoal>

  <performgoal name="landing" >
    <parameter name="current" class="CS3Flight" direction="in" />
  </performgoal>
</goals>
```


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XML extract 17

```

<plans>
  <plan name="initialization">
    <body class="AircraftInitializationPlan" />
  </plan>
  <plan name="flight_simulation">
    <body class="FlightSimulationPlan" />
    <trigger>
      <messageevent ref="perform_simulation" />
    </trigger>
  </plan>

  <plan name="startup">
    <parameter name="current" class="CS3Flight">
      <goalmapping ref="startup.current" />
    </parameter>
    <parameter name="previous" class="CS3Flight" optional="true">
      <goalmapping ref="startup.previous" />
    </parameter>
    <parameter name="time" class="long" direction="out">
      <goalmapping ref="startup.time" />
    </parameter>
    <body class="StartupPlan" />
    <trigger>
      <goal ref="startup" />
    </trigger>
  </plan>

  <plan name="request_aoc">
    <parameter name="current" class="CS3Flight" direction="in">
      <goalmapping ref="request_aoc.current" />
    </parameter>
    <body class="RequestAOCPlan" />
    <trigger>
      <goal ref="request_aoc" />
    </trigger>
  </plan>

```

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```

<plan name="ready">
  <parameter name="current" class="CS3Flight" >
    <goalmapping ref="ready.current" />
  </parameter>
  <parameter name="previous" class="CS3Flight" optional="false">
    <goalmapping ref="ready.previous" />
  </parameter>
  <body class="ReadyPlan" />
  <trigger>
    <goal ref="ready" />
  </trigger>
</plan>

<plan name="taxi_out">
  <parameter name="current" class="CS3Flight">
    <goalmapping ref="taxi_out.current" />
  </parameter>
  <body class="TaxiOutPlan" />
  <trigger>
    <goal ref="taxi_out" />
  </trigger>
</plan>

<plan name="take_off">
  <parameter name="current" class="CS3Flight">
    <goalmapping ref="take_off.current" />
  </parameter>
  <body class="TakeOffPlan" />
  <trigger>
    <goal ref="take_off" />
  </trigger>
</plan>

<plan name="cruise">
  <parameter name="current" class="CS3Flight" direction="in">
    <goalmapping ref="cruise.current" />
  </parameter>
  <body class="CruisingPlan" />
  <trigger>
    <goal ref="cruise" />
  </trigger>
</plan>

```

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```

<plan name="approximation">
  <parameter name="current" class="CS3Flight" direction="in">
    <goalmapping ref="approximation.current" />
  </parameter>
  <body class="ApproximationPlan" />
  <trigger>
    <goal ref="approximation" />
  </trigger>
</plan>

<plan name="landing">
  <parameter name="current" class="CS3Flight">
    <goalmapping ref="landing.current" />
  </parameter>
  <body class="LandingPlan" />
  <trigger>
    <goal ref="landing" />
  </trigger>
</plan>
</plans>

```

XML extract 18

```

<events>
  <messageevent name="perform_simulation" type="fipa" direction="receive">
    <parameter name="performative" class="String" direction="fixed">
      <value>"perform_simulation"</value>
    </parameter>
  </messageevent>
  <messageevent name="confirm_simulation" type="fipa" direction="send">
    <parameter name="performative" class="String" direction="fixed">
      <value>"confirm_simulation"</value>
    </parameter>
  </messageevent>

  <messageevent name="request_waiting_time" type="fipa" direction="send">
    <parameter name="performative" class="String" direction="fixed">
      <value>"request_waiting_time"</value>
    </parameter>

```

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```

<!-- Initialized with unique random value. -->
<parameter name="reply_with" class="String">
  <value>SUtil.createUniqueId($scope.getAgentName())</value>
</parameter>
</messageevent>

<messageevent name="inform_waiting_time" type="fipa" direction="receive" >
  <parameter name="performative" class="String" direction="fixed">
    <value>"inform_waiting_time"</value>
  </parameter>
</messageevent>

<messageevent name="request_ci" type="fipa" direction="send">
  <parameter name="performative" class="String" direction="fixed">
    <value>"request_ci"</value>
  </parameter>
  <!-- Initialized with unique random value. -->
  <parameter name="reply_with" class="String">
    <value>SUtil.createUniqueId($scope.getAgentName())</value>
  </parameter>
</messageevent>

<messageevent name="inform_ci" type="fipa" direction="receive">
  <parameter name="performative" class="String" direction="fixed">
    <value>"inform_ci"</value>
  </parameter>
</messageevent>

<messageevent name="request_delay" direction="send" type="fipa">
  <parameter name="performative" class="String" direction="fixed">
    <value>"request_delay"</value>
  </parameter>
  <!-- Initialized with unique random value. -->
  <parameter name="reply_with" class="String">
    <value>SUtil.createUniqueId($scope.getAgentName())</value>
  </parameter>
</messageevent>

<messageevent name="inform_delay" direction="receive" type="fipa">
  <parameter name="performative" class="String" direction="fixed">
    <value>"inform_delay"</value>

```

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```
</parameter>
</messageevent>

<messageevent name="confirm_initialized" direction="send" type="fipa">
  <parameter name="performative" class="String" direction="fixed">
    <value>"confirm_initialized"</value>
  </parameter>
</messageevent>
</events>
```

XML extract 19

```
<imports>
  <import>jadex.bridge.fipa.*</import>
  <import>jadex.commons.SUtil</import>
  <import>simulator.environment.CS3Flight</import>
  <import>simulator.environment.CS3Simulation</import>
  <import>java.util.Date</import>
</imports>
```

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Extracts refer to Appendix D.1.4 Manager

XML extract 20

```

<agent xmlns="http://jadex.sourceforge.net/jadex"
  xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
  xsi:schemaLocation="http://jadex.sourceforge.net/jadex
    http://jadex.sourceforge.net/jadex-bdi-2.3.xsd"
  name="Manager"
  package="simulator.manager">
<!-- Behavior elements -->
</agent>

```

XML extract 21

```

<capabilities>
  <!-- Capability to start other agents. -->
  <capability name="cmscap" file="jadex.bdi.planlib.cms.CMS" />
</capabilities>

```

XML extract 22

```

<beliefs>
  <belief name="simulation" class="Simulation" />

  <beliefset name="flights" class="Flight" />
  <beliefset name="aircrafts" class="Aircraft" />
  <beliefset name="airlines" class="Airline" />
  <beliefset name="airports" class="Airport" />
</beliefs>

```

XML extract 23

```

<goals>
  <!-- Used to start other agents. -->
  <achievegoalref name="cms_create_component">
    <concrete ref="cmscap.cms_create_component" />
  </achievegoalref>

```

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```

<performgoal name="create_agents">
  <parameterset name="agents" class="Agent" direction="in"/>
</performgoal>

<performgoal name="create_indicators" />
</goals>

```

XML extract 24

```

<plans>
  <plan name="protocol" >
    <body class="ManagerProtocolPlan" />
    <waitqueue>
      <messageevent ref="confirm_simulation"/>
      <messageevent ref="inform_allocated"/>
    </waitqueue>
  </plan>

  <plan name="create_agents" >
    <body class="CreateAgentsPlan" />
    <trigger>
      <goal ref="create_agents" />
    </trigger>
    <waitqueue>
      <messageevent ref="confirm_initialized"/>
    </waitqueue>
  </plan>

  <plan name="create_indicators" >
    <body class="CreateIndicatorsPlan" />
    <trigger>
      <goal ref="create_indicators"/>
    </trigger>
  </plan>
</plans>

```

XML extract 25

```

<events>
  <messageevent name="confirm_initialized" direction="receive" type="fipa">

```

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```

    <parameter name="performative" class="String" direction="fixed" >
      <value>"confirm_initialized"</value>
    </parameter>
  </messageevent>

  <messageevent name="perform_simulation" direction="send" type="fipa">
    <parameter name="performative" class="String" direction="fixed" >
      <value>"perform_simulation"</value>
    </parameter>
  </messageevent>

  <messageevent name="confirm_simulation" direction="receive" type="fipa">
    <parameter name="performative" class="String" direction="fixed" >
      <value>"confirm_simulation"</value>
    </parameter>
  </messageevent>

  <messageevent name="request_allocation_costs" direction="send" type="fipa">
    <parameter name="performative" class="String" direction="fixed" >
      <value>"request_allocation_costs"</value>
    </parameter>
  </messageevent>

  <!-- Message received by the manager to generate the indicators -->
  <messageevent name="inform_allocated" direction="receive" type="fipa" >
    <parameter name="performative" class="String" direction="fixed" >
      <value>"inform_allocated"</value>
    </parameter>
  </messageevent>
</events>

```

XML extract 26

```

<expressions>
  <expression name="query_airport_flights">
    select CS3Flight $flight
    from $beliefbase.flights
    where $flight.getDep_airport().getId().equals($id) ||
           $flight.getArr_airport().getId().equals($id)
  </expression>

  <expression name="query_airline_flights">

```


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```
select CS3Flight $flight
from $beliefbase.flights
where $flight.getCarrier().getId().equals($id)
</expression>

<expression name="query_flights">
select CS3Flight $flight
from $beliefbase.flights
order by flight.getIFPS()
</expression>

<expression name="query_flight" >
select CS3Flight $flight
from $beliefbase.flights
where $flight.getId() == $id
</expression>
</expressions>
```

XML extract 27

```
<imports>
<import>jadex.bridge.fipa.*</import>
<import>simulator.environment.Simulation</import>
<import>simulator.environment.Flight</import>
<import>simulator.environment.CS3Flight</import>
<import>simulator.environment.CS3Simulation</import>
<import>simulator.environment.CS3Regulation</import>
<import>simulator.environment.Agent</import>
<import>simulator.environment.Airline</import>
<import>simulator.environment.Airport</import>
<import>simulator.environment.Aircraft</import>
</imports>
```

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Extracts refer to Appendix D.1.5 Application

XML extract 28

```

<?xml version="1.0" encoding="UTF-8"?>
<!--
  <H3>Case 3 : Simulator</H3>
-->
<applicationtype xmlns="http://jadex.sourceforge.net/jadex"
  xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
  xsi:schemaLocation="http://jadex.sourceforge.net/jadex
  http://jadex.sourceforge.net/jadex-application-2.3.xsd"
  name="C3"
  package="simulator">

  <componenttypes>
    <componenttype name="Airport "
      filename="simulator/airport/Airport.agent.xml"/>
    <componenttype name="Airline"
      filename="simulator/airline/Airline.agent.xml"/>
    <componenttype name="Aircraft"
      filename="simulator/manager/Manager.agent.xml"/>
    <componenttype name="Manager"
      filename="simulator/manager/Manager.agent.xml"/>
  </componenttypes>

  <arguments>
    <argument name="fuelprice" class="float" >0.6f</argument>
    <argument name="co2ratio" class="float" >3.16f</argument>
    <argument name="segmentid" class="String">"FERDI_BUPAL"</argument>
    <argument name="airportid" class="String">"LSZH"</argument>
    <argument name="uncertainty" class="boolean">true</argument>
    <argument name="regulationid" class="int" />
  </arguments>

  <configurations>
    <configuration name="s010">
      <arguments>
        <argument name="fuelprice">0.9f</argument>
        <argument name="regulationid">1</argument>
      </arguments>
    </configuration>
  </configurations>

```

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```
<components>
  <component type="Manager" name="manager" configuration="standard"
            master="true" />
</components>
</configuration>
...
</configurations>
</applicationtype>
```

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