EXPLORATORY RESEARCH

ITACA simulation model

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Copyright Statement

ITACA

INCENTIVISING TECHNOLOGY ADOPTION FOR ACCELERATING CHANGE IN ATM

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Abstract

The goal of ITACA is to accelerate the development, adoption and deployment of new technologies in ATM. In order to contribute to achieving this general objective, ITACA will develop a new set of methodologies and tools enabling the rigorous and comprehensive assessment of policies and regulations aimed at amplifying the uptake of new technologies within ATM. The project has developed an agent-based model of the R&I lifecycle allowing the representation of the complex decisions and interactions between ATM stakeholders and their impact on the implementation of new technologies. This deliverable describes the ITACA agent-based simulation model of the ATM technology adoption and implementation process, from model conceptualisation through model implementation.

Table of Contents

List of Tables

List of Figures

Executive summary

The goal of ITACA is to accelerate the adoption and deployment of new technologies in ATM. The problem of technology adoption refers to the diffusion and acceptance of a new technology or process within a market. The analysis of the characteristics and reasons behind technology diffusion can be tackled through different methods, including empirical assessments, economic models, game theory, and simulation models. The project employed the first three methods to identify levers and barriers for adoption and to devise potential policy measures. This analysis will be complemented and enriched with an agent-based simulation model. This simulation method has been proven to be applicable to technology adoption and policy assessment problems, providing additional insights thanks to the ability to represent the heterogeneity of the agents involved and capture emergent behaviour. This deliverable describes the ITACA agent-based simulation model, from model conceptualisation through model implementation. The inclusion of behavioural economic aspects, such as hyperbolic discounting or prospect theory, in the agents' decision-making will enable the correct representation of real stakeholders and their behaviour.

The experiments that will be performed with the modelling tool are defined by the simulation scenarios, which include the policy (or policies) to be tested, the technologies available to be adopted and different exogenous variables that represent aspects that do not depend on ATM evolution but affect the agents involved (e.g., passenger demand, fuel prices, engine fuel efficiency, consumption and unitary labour costs).

The model consists of different type of agents representing the most relevant actors in ATM technology adoption: (i) the regulatory bodies, which apply policies and regulations; (ii) the technology providers, which develop the technological solutions to be adopted; (iii) ANSPs, which provide ATC services and adopt new technologies; (iv) airports, which also adopt ATM technology; (v) airlines, which perform their operations, pay for ATC and airport services, and adopt new technologies; and (vi) labour unions, which defend the labour conditions of their guild.

The successful benchmarking of regulations and policy measures requires a comprehensive assessment of their impact along different dimensions. To this end, the outputs of the model selected for the analysis are to be representative of the performance of the European ATM system in the situations tested. The ITACA simulation model will consider the following clusters of KPAs and associated indicators: (i) technology adoption KPAs and indicators; (ii) economic KPAs and indicators; and (iii) operational KPAs and indicators.

The model has been implemented as a Python module, able to run in a Windows OS. The scenarios are defined in a configuration file, which specifies some general attributes to the simulation such as the time horizon and the policies to benchmark. The output files contain disaggregated values for each agent at each time step, organised in a tabular format.

In the next stage of the project, a set of participatory simulation experiments involving the direct participation of ATM stakeholders will be used for the calibration and validation of the behavioural assumptions of the agent-based model. The results will be included in ITACA D4.1 'Participatory Simulations: Experiment Results'. Once the tool is fully calibrated, it will be used in WP5 'Policy assessment' to derive recommendations to facilitate technology adoption in ATM.

1 Introduction

1.1 Scope and objectives

Despite the recent reduction of air traffic motivated by the COVID-19 crisis, air traffic will eventually recover and new market entrants may soon take the Air Traffic Management (ATM) system to its limits once more, calling for disruptive solutions able to boost the performance of ATM operations. Emerging technologies, especially digitalisation and automation, have the potential to facilitate this technological upgrade. However, technology evolution is a necessary but not sufficient condition for achieving the uptake of new technologies: innovation is a complex phenomenon, which depends not only on the development of new technologies, but also on the existence of regulation and institutions able to facilitate and foster the implementation of such technologies.

When analysing innovation uptake in ATM, policy makers have to deal with a complex system composed by a large number of stakeholders and political, social and economic interactions. Traditional economic models present some shortcomings to deal with such type of complex sociotechnical systems, due to their rigid assumptions on human behaviour, such as agents' perfect rationality. The combination of Agent-Based Modelling (ABM) and Behavioural Economics (BE) offers a particularly suitable framework to overcome these limitations. ABM offers the possibility to model agents' heterogeneity, non-rational behaviours and biases (e.g., loss aversion), learning processes, evolutionary behaviour and path dependence, which allows the representation of features ignored by traditional technology diffusion analysis (Borshchev & Filippov, 2004) and makes ABM particularly suitable for the study of innovation uptake (Zhang & Vorobeychik, 2019). Behavioural economics builds on several disciplines (psychology, neuroscience, economics, decision science) to develop theories that provide a more realistic representation of human economic decision making than traditional utility maximisation. According to BE, people are not always self-interested, profit-maximising individuals with stable preferences: our thinking is subject to insufficient knowledge, feedback, and processing limitations, which often involves uncertainty and is affected by the context in which we make decisions. Some of the main theories in BE include prospect theory, herd behaviour and hyperbolic discounting (Samson, 2014).

This deliverable presents a modelling framework based on the combination of ABM and BE that allows the comparison of the disaggregated distributional effects and the aggregated social welfare brought about by different policy measures designed to incentivise technology adoption in ATM. Although ABM has been already used for studying technology adoption and policy assessment in networked sectors (Tedeschi et al., 2014), to our knowledge this is the first time that this technique is applied to the ATM field. The objectives of this deliverable are:

- To be used as a practical guide for the handling of agent-based models in the task of policy assessment and technology adoption analysis in the field of ATM.
- To present a modelling framework based on the combination of ABM and BE that allows the comparison of the distributional effects and the social welfare brought about by different policy measures aimed at incentivising technology adoption in ATM.

In the subsequent stage of the project, this modelling framework will be used to conduct a set of case studies set of case studies for the evaluation of different policy measures and regulatory changes.

1.2 Applicable documents

- Grant Agreement No 893443 ITACA – Annex 1 Description of the Action.
- ITACA (2020) D1.1 Project Management Plan, Edition 01.00.00.
- ITACA (2020) D1.2 Data Management Plan, Edition 01.00.00.
- ITACA (2020) D7.1 H - Requirement No. 3, Edition 01.00.00.
- ITACA (2021) D2.1 Identification of levers and barriers for the adoption of new ATM technologies
- ITACA (2022) D4.1 Participatory Simulations: Experiment Results

1.3 Structure of the document

The document is structured as follows:

1. Section 2 provides an overview of the state of the art in the modelling technology adoption and in ABM, discussing its applicability to the ITACA project.
2. Section 3 presents the description of the ITACA simulation model, including its main assumptions, inputs, outputs, the agents that compose the model and their decision-making process.
3. Section 4 describes how the model has been implemented.
4. Section 5 includes the manuals for installation of the software and the user manual to perform new experiments using this simulation tool.
5. Section 6 discusses the limitations of the model developed so far and proposes future evolutions.

1.4 List of acronyms

Acronym	Definition
ABM	Agent Based Model
ACC	Area Control Centre
A-CDM	Airport Collaborative Decision Making
ACE	ATM Cost Effectiveness
ADS-B	Automatic Dependent Surveillance–Broadcast
AENA	Aeropuertos Españoles y Navegación Aérea
AFV	Alternative Fuel Vehicle
AIS	Aeronautical Information Service
ANS	Air Navigation Service
ANSP	Air Navigation Service Provider

Acronym	Definition
API	Application Programming Interface
ATC	Air Traffic Control
ATCO	Air Traffic Control Officer
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
AU	Airspace User
BAU	Business as Usual
BAW	British Airways
BE	Behavioural Economics
BPMN	Business Process Model and Notation
CAA	Civil Aviation Authority
CAS	Complex Adaptive System
CCO	Continuous Climb Operations
CEF	Connecting Europe Facility
CNMC	Comisión Nacional de los Mercados y la Competencia
CNS	Communications, Navigation and Surveillance
COMPAIR	Competition for Air Traffic Management
COVID-19	Coronavirus disease
CSV	Comma Separated Values
DAC	Dynamic Airspace Configuration
DBF	dBase database file
DLH	Lufthansa Group
DG MOVE	EU Commission's department for mobility and transport
DMP	Data Management Plan
DUC	Determined Unit Cost
EASA	European Union Aviation Safety Agency
EATMA	European Air Traffic Management. Architecture
EC	European Commission
ECAC	European Civil Aviation Conference
EIA	U.S. Energy Information Administration
EIN	Aer Lingus

Acronym	Definition
EPO	European Patent Office
EU	European Union
EUROCONTROL	European Organisation for the Safety of Air Navigation
EUROSTAT	Statistical Office of the European Communities.
EZY	EasyJet
FAB	Functional Airspace Block
FIM	Flight Deck Interval Management
GDP	Gross Domestic Product
GDPR	General Data Protection Regulation
GIS	Geographic Information System
GUI	Graphic User Interface
IAG	IAG group
IATA	International Air Transport Association
IBE	Iberia
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
ITACA	Incentivising Technology Adoption for accelerating Change in ATM
KLM	KLM airline
KPA	Key Performance Area
KPI	Key Performance Indicator
LCC	Low-Cost Carrier
MET	Meteorology
MIT	Massachusetts Institute of Technology
MUAC	Maastricht Upper Area Control Centre
NMOC	Network Manager Operations Centre
OD	Origin-destination
ODE	Ordinary Differential Equation
OS	Operating System
PDF	Portable Document Format
PI	Performance Indicator
RYR	Ryanair

Acronym	Definition
SA	Safety Agency
SAR	Search and Rescue
SD	System Dynamics
SDM	SESAR Deployment Manager
SES	Single European Sky
SESAR	Single European Sky ATM Research
SJU	SESAR Joint Undertaken
SU	Service Unit
SWIM	System Wide Information Management
TBS	Time Based Separation
TMA	Terminal Manoeuvring Area
TXT	TXT file extension
UK	United Kingdom
US	United States
USPTO	United States Patent and Trademark Office
UTM	Unmanned Traffic Management
VLG	Vueling
WHL	Wheel file extension
WP	Work Package

2 Application of agent-based modelling to technology adoption

2.1 The problem of technology adoption

The acceptance and spread of new technology in a market is commonly referred to as technology adoption or innovation diffusion. In the vast majority of cases, new technology or innovation are referred to tangible objects, but the concept can be applied far more broadly to consider the spread of ideas, software and practices or processes.

The diffusion of new technologies in a given market is affected by different factors, including: the characteristics of the market (e.g., monopoly or perfect competition), the characteristics of the organisation (e.g., focus on internal developments) and the characteristics of the technology itself (e.g., compatibility with the legacy technology). There are several theories that aim at providing a general explanation for the mechanisms underlying this problem (Rogers, 2010). Nevertheless, each industry possesses its particular features that should not be neglected. The high level of protection that surrounds ATM, the very demanding safety requirements and the large variety of the stakeholders are some of the reasons for the slow pace in technology adoption in ATM. For a complete view of this problem, the reader may refer to ITACA deliverable D2.1 'Identification of levers and barriers for the adoption of new ATM technologies'.

2.2 Modelling paradigms of technology adoption

The wide problem of technology uptake has been researched within sociology, industrial economics and organisation and management sciences, among other disciplines. Each discipline usually has preference for a specific method of analysis. The different methods of analysis of technology adoption can be grouped into the following classes:

- Empirical assessment of technology uptake and diffusion.
- Economic models.
- Game-theoretical models.
- Simulation models.

2.2.1 Empirical assessment

An empirical assessment is a research based on the observation of empirical data, for instance, literature reviews or interviews. It is not a modelling approach but a methodology, which analyses quantitatively or qualitatively the empirical evidence using the experience of the researcher.

Empirical assessment might be used as a support tool in different steps of a model creation process. This is a useful technique for giving an initial set of recommendations or paths to follow in subsequent stages of the research, i.e., as problem identification analysis before the definition of the model. Unfortunately, it is very time-consuming and predictions (and hence scenario analysis) are difficult to make. Furthermore, predictions may be biased by personal opinions or intuition.

The project used this methodology for the initial benchmarking of different policy measures described in deliverable D2.1.

2.2.2 Economic models

Economic models are based on economic theories (e.g., price-demand law or the Keynesian economic theory) and econometrics. Usually, economic models take into account the innovation level as an advantage to have lower costs or higher turnovers. Therefore, the spread of technology is analysed as a means to optimise company performance and eventually overcome competitors. They assume strong hypothesis to enable analytical solvability regardless of the rather complex mechanisms involved. The lack of heterogeneity of the actors and their interactions and the compulsory assumption of rational behaviour for those actors are the main reasons why economic models present shortcomings when facing out-of-equilibrium scenarios.

The project used this methodology in combination with an empirical assessment for the initial benchmarking of different policy measures described in deliverable D2.1, which has led to the definition of a set of case studies that will be further explored through other modelling techniques, in particular through simulation.

2.2.3 Game theoretical models

The concepts of Game Theory establish a mathematical framework to formulate, structure, analyse and eventually understand strategic interaction among rational actors in different scenarios. In this context, a game is defined as the interaction of a finite number of players according to given rules known by them. The variety of possibilities that a player has in the game are called strategies. Those players have very different definition: persons, groups, companies, associations, etc. However, all of them share one important characteristic: they are rational and they try to maximise their own expected outcome. Their interactions will have an impact on each of the players and on the whole group of players, i.e., they are interdependent.

Game theory has been widely used in Economics and in Industrial Organisation, usually employed for modelling company competition within a market, i.e., a game in which the desired outcome is an increase in either the monetary profit, the market share or both. Due to the rapid technological progress, the strategic importance of technology adoption in a competitive marketplace has increased. Company investment in new technologies is usually driven by a desire of gaining an edge over competitors. This exploration of strategic decision making in technology adoption is based on economical and industrial strategies, thus employing the types of games presented before. Technology adoption may be considered in two different ways. First, technology adoption may be analysed using game theoretical models as a means to obtain a better profit, i.e., technology adoption is a strategy rather than an outcome of other strategies; an example of the application of this approach to ATM can be found in Adler et al. (2018). Second, technology adoption can be seen as an outcome of the competition between companies that are reluctant to adopt new technology and policy makers, such as governments.

In ITACA, we have used Game Theory as an element of the economic models developed in D2.1.

2.2.4 Simulation models

Traditional economic models and game theoretical models have analytical solutions, which can thus be computed by hand or in a spreadsheet given a set of inputs and parameters. However, obtaining an analytical solution is not always the case for more complex models, because it can be either impossible or very hard to find (Borshchev & Filippov, 2004). In these cases, simulation or dynamic modelling may be applied. In this context, simulation is considered as a set of rules (e.g., equations, flowcharts or technology adopters´ behaviours) that define the evolution of the system in time. The method to advance in time depends on whether a discrete or continuous model is considered.

Figure 1 shows the differences between some simulation modelling paradigms (Borshchev & Filippov, 2004). In the diagram, the vertical axis represents the level of abstraction of the model. In the lowest abstraction level, we are modelling each individual element of the system (e.g., each person within a society, each individual drop in a rain simulation) while in the highest abstraction level we model the aggregated behaviour of all the individuals forming the system (e.g., the GDP growth or the litres per square metre in a region). In between, there are different ways to abstract the individuals by grouping them into collectives or semi-aggregated values. Two main simulation paradigms have been used for economic and technology adoption simulations:

- **System Dynamics (SD)** is a modelling paradigm of high level of abstraction focused on strategic management. The so-called Bass model (Borshchev & Filippov, 2004) is considered as the basis of the application of this kind of models to technology diffusion. Based on an SD framework, the technology adoption rate is described using an Ordinary Differential Equation (ODE). The model is very useful at providing insights for the study of aggregated values when homogeneous individuals can be assumed (Bass, 2004).
- **Agent-based modelling (ABM)** is a computational modelling paradigm for simulating the actions and interactions of autonomous agents (both individual or collective entities such as organisations or groups) in order to understand the behaviour of the system as a whole and what governs its outcomes. It is designed to describe the behaviour of complex systems due to its bottom-up approach based on the decentralisation of the modelling entities. The ABM paradigm is able to capture agent heterogeneity and enables fine-grained modelling of interactions mediated by social and geographic networks. ABM's attempt to represent the actors of economic systems in a more realistic fashion (Mueller & Pyka, 2016) makes it a particularly promising tool to analyse technology adoption.

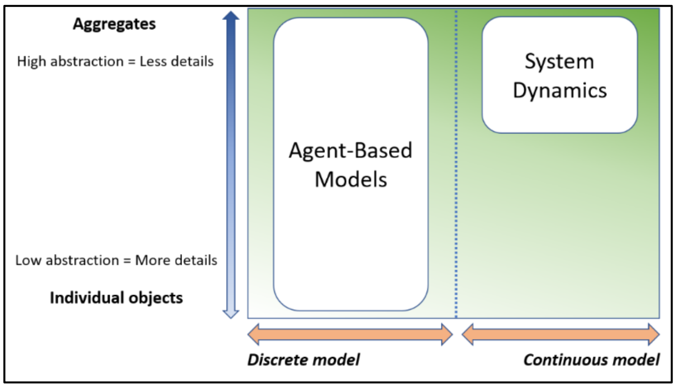


Figure 1: Simulation modelling paradigms: ABM vs System Dynamics

2.3 Agent-based modelling for technology adoption

In this section we will discuss the links between ABM and the modelling of technology adoption. We will start by introducing ABM, providing a high-level overview of its key aspects Secondly, in section 2.3.2 BE is introduced, explaining the fruitful bound between agents' behavioural rules and the concepts that arise from this theory. Applications of ABM in other industries are discussed in section 2.3.3. Finally, section 2.3.4 discusses previous work on the application of ABM to technology adoption in aviation in general and ATM in particular.

2.3.1 Agent-based models

The ultimate goal of system modelling is to describe accurately a system with the minimum number of parameters, keeping it simple enough to gain insights on the behaviour that underlies beneath the surface. This is a major topic in a wide range of structures such as the transport system, economic organisations, ecosystems or biology. All these systems, despite their obvious differences, share some common properties: they are formed by a large number or elements highly interconnected, behaving as complex systems. In these systems, the global behaviour is intrinsically difficult to model due to the dependencies, competitions, relationships and other types of interactions between their parts or between a given system and its environment. Network effects produce non-linearities, emergent behaviour and spontaneous ordering.

ABM is specially designed to describe the behaviour of such systems because of its bottom-up approach. The modelling entities, called agents, are completely defined by the modeller. Each agent possesses a set of rules or behaviour which defines how it reacts to external stimuli from either other agents or its environment. The rules may be fairly simple or more sophisticated, including abilities such as memory, learning and adaptation. Agents can represent multiple entities in the real world. The abstraction level that defines the agents may be quite different depending on the system to be modelled: from defining a company or a group of people within a society to modelling a person's behaviour at the individual level.

The agents are embedded in a network, i.e., each agent has a set of neighbours with reciprocal interactions. There are many different topologies for this network and it is not limited to a fixed network: the agents can move around and change their links.

The agents are not the only elements that define the model. They are enclosed in an environment, which defines the so-called exogenous variables, i.e., the variables that are not inherent to the agents or their relations but may have an effect on their behaviour. Clear examples of that are fuel prices in a transport system or climate in ecosystems.

Through simulations, ABM is capable of representing the emergent behaviour driven by the network effects. Thus, ABM can be considered as a tool for understanding the hidden mechanisms that rule complex systems.

2.3.1.1 Elements

Agents

Agents are the elementary unit of the model. There is no common agreement on the definition of an agent, but they normally share at least some of the following properties (Crooks et al., 2012):

- **Autonomy**: agents are autonomous entities whose behaviour is driven by an internal set of rules. They are able to exchange information with other agents that feeds their internal decision mechanisms. They are free to interact with other agents, at least over a limited range of situations, and this does not necessarily affect their autonomy. Therefore, although agents have boundaries and interactions with the other agents of the simulation, their behaviour is not governed by a centralised control.
- **Heterogeneity**: this is one of the main features of ABM. Each agent in the simulation can have many different characteristics or behaviour (e.g., an agent representing a human may have attributes such as age, gender, job, etc.). Groups of agents can exist, built through the amalgamation of similar autonomous individuals.
- **Proactiveness**: agents are active because they exert independent influence in a simulation. The following active features can be identified:
    - Goal-directed or proactive: agents have goals to achieve.
    - Reactiveness or perceptiveness: agents can be designed to have an awareness or sense of their surroundings. Agents can also be supplied with knowledge of their environment, thus providing them with an awareness of other entities within their environment, for instance.
    - Bounded rationality: throughout the social sciences, the dominant form of modelling is based upon the rational-choice paradigm. Rational choice models generally assume that agents are perfectly rational optimisers with unfettered access to information, foresight, and infinite analytical ability. However, agents can be configured with 'bounded' rationality. This allows the simulation of inductive, discrete and adaptive choices that help agents advance towards achieving their goals.
    - Interactivity or communication: agents have the ability to communicate. For example, agents can query other agents and/or the environment within a neighbourhood.
    - Adaptation and learning (memory): agents can also be designed to be adaptive, which is especially interesting for Complex Adaptive Systems (CAS). Agents can be designed to alter their state depending on previous states, permitting agents to adapt with a form of memory or learning. Agents can adapt at the individual level (e.g., learning alters the probability distribution of a certain behavioural rule) or at the population level (e.g., learning alters the frequency distribution of agents with certain behaviour).

Each agent within the ABM can be seen as a model by itself. This agent "micromodel" is defined by the internal rules and behaviour of the agent relative to its external variables and internal state. Just as a system has a state consisting of the collection of its state variables, an agent has a state that represents the essential variables associated with its current situation. This behaviour may be rather simple, such as fixed rules, or be based on more abstract representations such as neural networks, which link the agent's situation with its action or set of potential actions. Agent behaviour can be modified over time by a learning and adaptation process and may present stochastic variations.

The state of an agent-based model is the collective states of all the agents along with the state of the environment.

Interactions

As in real world systems, agents interact with a subset of other agents, termed the agent's neighbours. This network defines the topology of interactions within the system.

Examples of typical topologies (Macal, 2010) are presented in Figure 2. Networks may be static or dynamic. In static networks, links are pre-specified and do not change. In dynamic networks, links, and possibly nodes, are determined endogenously according to the mechanisms programmed in the model.

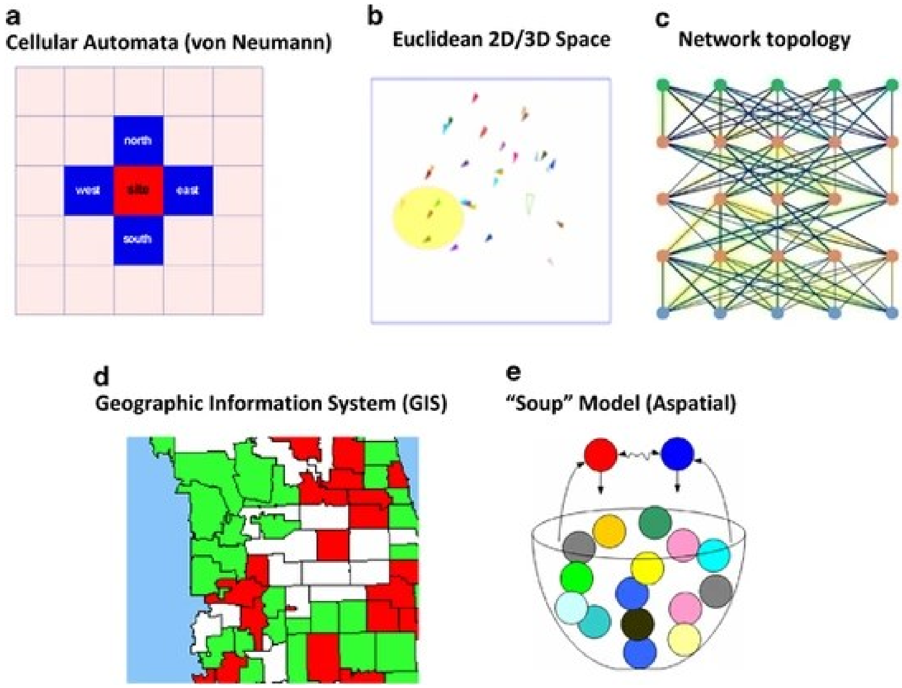


Figure 2: Topologies for agent relationships and social interaction (Macal, 2010)

It is important to note that a topology may not be fixed: relations can be created or deleted, especially in a spatial topology in which agents move and interact only with adjacent neighbours. In some applications, agents can interact according to multiple topologies.

Environment

The environment is the space (not necessarily a geographical space) in which the agents live and interact with each other. As well as their neighbours, the environment influence agents by providing them with pieces of information (e.g., weather conditions at a given location of the environment).

Environment information usually acts as a limiting factor for the model. For example, the environment in an agent-based transportation model would include the infrastructure and capacities of the nodes and links of the road network. These capacities would create congestion effects (reduced travel speeds) and limit the number of agents moving through the transportation network at any given time.

2.3.1.2 Advantages and limitations of ABM

Advantages

Some of the characteristics in which ABM are ahead of more traditional modelling approaches are:

- **Ability to capture emergent behaviour.** In complex systems, the system as a whole behaves in a manner that is not possible to be predicted or defined from the behaviour of its individual parts. For example, it is not possible a priori to derive the principle of Bernoulli (or other fluid dynamics principles) from the individual behaviour of the atoms of hydrogen and oxygen that form the water, but it would emerge under certain conditions. ABM is suitable for simulating emergence given a proper set of behaviours and relations for the agents that accurately reflect the real system. In particular, ABM is the perfect way to capture emergence when:
    - Interaction between agents is non-linear, discontinuous, or discrete (i.e., the behaviour of an agent can be altered dramatically, even discontinuously, by other agents).
    - Populations are highly heterogeneous.
    - The topology of agent interactions is heterogeneous and complex.
    - Agents exhibit complex behaviour, including learning, adaptation and stochastic behaviour.

  Emergent behaviour that is not well understood often leads to poor performance of the model.
- **Provision of a natural environment for the study of a systems**. In many cases, ABM is a straightforward method for describing and simulating individual activities, providing a natural and intuitive description of a system. In terms of programming advantages, ABM is easily extrapolated to object-oriented languages, identifying agents with classes and relations with attributes.
- **Flexibility**. ABM is highly flexible, particularly in relation to geospatial modelling. Spatial simulations, such as the simulation of transport systems, benefit from this flexibility. It is easy to experiment with aggregate agents, sub groups of agents, and single agents, with different levels of abstraction coexisting within a model. A model must be simple enough to understand the mechanisms driving the system and complex enough to arise accurate results. However, the proper level of complexity is not known a priori. Thus, the agent-based approach can be used when the selection of a suitable level requires exploration.
- **Ability to capture mesoscale and microscale behaviour**. Mesoscale (groups of agents) and microscale (individual agents) reactions and adaptation are a key factor for any system model. Given that it considers the interactions between agents, ABM not only allows the study of global emergent behaviour but also the study of reactions in parts of the system.

Limitations

The main shortcomings of ABM are:

- Finding the right level of abstraction for the model may be challenging.
- Identification of multiple components and interactions of a complex system is not always straightforward. In particular, factors linked to human behaviour are affected by irrational

behaviour, subjective choices and complex psychology, and therefore they are difficult to quantify, calibrate, and sometimes justify.

- Computational limitations: there is a practical upper limit to the size of the parameter space that can be checked and this process can be computationally intensive and thus time consuming.

2.3.2 Agent-based modelling and behavioural economics

2.3.2.1 Introduction to behavioural economics

Existing economic and financial models present a number of shortcomings due to the rigid assumptions on human behaviour such as perfect rationality. These limitations become more apparent when society faces an extreme, unexpected event (e.g., global financial crisis, COVID-19 pandemic). In order to overcome these limitations, behavioural economics builds on several disciplines (psychology, neuroscience, economics and decision science) to develop theories about human economic decision making. According to BE, people are not always self-interested, benefit- maximising individuals with stable preferences: our thinking is subject to insufficient knowledge, feedback, and limited processing capability, which often involves uncertainty and is affected by the context in which we make decisions. The inclusion of the insights given by BE theory into simulation models arguably enhances the reliability of the simulated decision-making process. The main theories or hypothesis in BE that approach real human behaviour rules are listed below (Samson, 2014):

- **Prospect theory.** Prospect theory is based on the idea that individuals think in terms of expected utility relative to a reference point rather than in terms of absolute outcomes. Outcomes are then compared to the reference point and classified as ‘gains’ if they are superior to the reference point and as ‘losses’ if they are inferior to the reference point. Prospect theory is based on a s-shaped value function representing gains and losses, as shown in Figure 3.

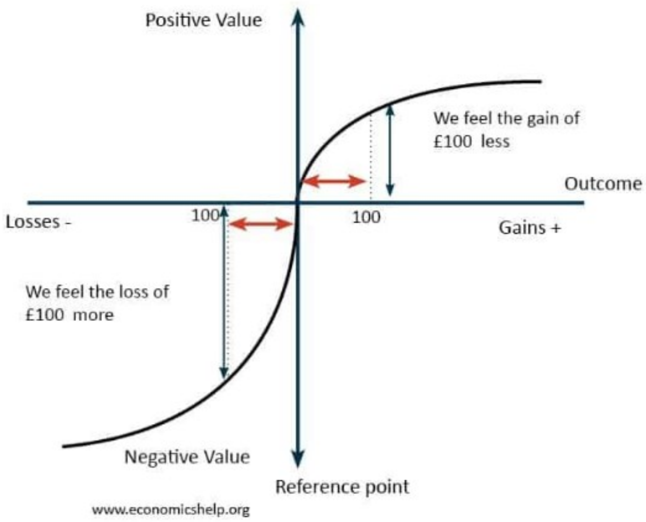


Figure 3: Graphical explanation of the concepts in prospect theory (www.economicshelp.org)

The underlying idea is that people dislike losses more than they like an equivalent gain. As a result, the function is much steeper for losses than for gains, which illustrates loss aversion behaviour. Since individuals dislike losses more than equivalent gains, they are more willing to take risks to avoid a loss. Prospect theory also describes how people have a greater willingness to overweight low probabilities and underweight high probabilities. This impact is well-evidenced in a multitude of trading and valuation contexts.

- **Bounded rationality**. The concept of bounded rationality is one of the psychological foundations of BE and provides the idea that human rationality is limited when people make decisions. Rationality is bounded because there are limits due to our thinking capacity, available information and feasible time to make the decision. Bounded rationality describes individuals as "ecologically rational"; they use heuristics and mental shortcuts seeking a satisfactory solution by applying simple and intelligent algorithms that can lead to near-optimal inferences rather than an optimal one.
- **Hyperbolic discounting**. Intertemporal choice (hyperbolic discounting) is also one of the cornerstones of BE. The expectation of when a reward is received is as critical as the amount of the reward. Given two similar rewards, humans tend to prefer the earlier reward over the later reward and consequently, earlier (quicker), smaller amounts are often favoured over larger, later amounts, to varying individual degrees. Hyperbolic discounting is mathematically described by employing a discount factor that multiplies the value of the reward,

$$g(t) = \frac{1}{1 + k \cdot t},$$

  where $g(t)$ is the discount factor, t is the delay in the reward, and k is a parameter that can be tuned to adjust the behaviour. The discount factor multiplies the value of the reward after a delay time t to determine the reward that a person is willing to accept immediately.
- **Herd behaviour**. People are susceptible to social forces, thus may be coaxed into choices instead of making use of their own information to perform independent decisions. Herd behaviour can be understood as similar to fashions or trends that spread in a fast and broad way within a society. The idea of herding has a long history in philosophy and crowd psychology. It is particularly relevant in the domain of finance, where it has been discussed in relation to the collective irrationality of investors, including stock market bubbles. This herd behaviour idea may be of relevance for assessing the spread of certain new technologies that are endowed with high expectations.

2.3.2.2 ABM aided by behavioural economics

In economics, ABM is increasingly gaining momentum and is considered as an approach with the potential to overcome some of the shortcomings of traditional approaches, which require substantial simplifications of the phenomena under investigation. The aim of ABM is to represent the actors of economic systems in a more realistic fashion, where deviations from the assumed theoretical behaviour play an important role (Mueller & Pyka, 2016). Apart from the homogeneity of actors and their implications, another shortcoming of traditional economic models is the assumption of rational behaviour. As ABM focuses directly on the individual, it enables an intentional non-rational design of economic decisions which allows for experimental adaptation and learning, for example. This enables the modelling of the effects of psychological principles such as reference dependence, loss aversion and non-linear probability weighting postulated by the prospect theory.

Many of the shortcomings presented for other types of models come from a common basis: to guarantee analytical solvability. In contrast to traditional modelling approaches, the variety of agents and their behaviour are not restricted to fit into an analytical framework. In ABM every agent is endowed with an individual set of initial states, which allows for the representation of characteristic features and a representation of individual behaviour. As a consequence, ABM is able to incorporate the insights from BE, enabling:

- Normative understanding, evaluating whether designs proposed for economic policies, institutions and processes will result in socially desirable system performance over time. In the case of policies, they can be tested prior to their implementation (e.g., to check for robustness facing different scenarios or to avoid unforeseen results).
- Qualitative insights and theory generation: the objective here is to understand economic systems through a systematic examination of their potential dynamical behaviours under alternatively specified initial conditions.

2.3.3 Agent-based modelling for technology adoption in different fields

The vast capabilities offered by ABM for technology diffusion research have been investigated by different researchers (Dawid, 2006; Kiesling et al., 2012; Nan et al., 2014). This research shows that ABM is able to predict phenomena not captured by aggregated models and that they can be used as a virtual research laboratory. Previous work not only used ABM to study the mechanisms of technology adoption, but it has also addressed the development of models to support the policy making process of innovation adoption. Tedeschi et al. (2014), for example, study the effect of different economic innovation policies on macroeconomic performance.

There are examples of application of ABM to technology adoption in the energy supply sector, a monopolistic system such as the ATM industry. For instance, Hamilton (2009) assesses technology diffusion when bounded rational agents face uncertainty about the performance of the new technology. In particular, he studied the impact of a spatial externality, which models some kind of 'fashion effect', on patterns of technology diffusion. The key resulting insight is to show how the combination of positive externalities and performance uncertainty at the micro level may cause a sudden and unforeseeable adoption of a new technology at the macro level, regardless of the absolute performance comparison or other managerial and context variables.

In the transport industry there are some references of ABM application to policy assessment regarding the adoption of new technologies. Schwoon (2006) analyses the feasibility of the introduction of hydrogen as a transport fuel using ABM. The problem is driven by cost estimates and technological feasibility assumptions. However, it is a more complex problem, involving the competitiveness of the automobile market and the network formed by producers, users and filling station operators. The results suggest that a tax on conventional cars can successfully promote diffusion even without a major infrastructure program. Consumers and individual producers are affected differently by the tax, anticipating a stronger resistance from the second group towards that tax policy. Zhang et al. (2011) studied the diffusion of alternative fuel vehicles (AFVs), demonstrating the usefulness of ABM to analyse the factors that can speed up the diffusion of eco-innovations. The interdependencies between key participants in the automotive industry were considered by including agents that represent manufacturers, consumers, vehicles (technology) and governmental agencies. In three experiments, mechanisms are considered for speeding the adoption of AFVs: technology push, market pull, and regulatory push. While the first two are shown to have a positive impact on the diffusion of AFVs, a governmental push that focuses on the manufacturers (fuel economy mandates) leads to a decrease in social good (air pollution improvement) because market share for fuel-inefficient vehicles increases.

2.3.4 Agent-based modelling for technology adoption in ATM

The application of ABM to the specific problem of technology adoption in ATM is rather limited. One of the few examples in this area is the work of Liu (2019), in which ABM is used to assess aircraft market diffusion. In this work, rather than focusing on the profit-maximising behaviour of airlines, additional aspects were included, such as environmental and flexibility concerns. The model shows good correlation with historical data, demonstrating its usefulness for aircraft manufacturers to plan the production and delivery of airplanes, for airlines to plan their fleet maintenance strategy and for policy makers with interest in the aviation industry. However, this model presents several limitations such as the binary adoption decision (adopt vs reject) for one singular aircraft model series, whereas in some cases, airliners are choosing between several similar competing models. This fact is of special relevance due to the duopoly formed by Boeing and Airbus in this field. The spatial factor, not considered here, is also of relevance due to pilots or maintenance technicians licenses (e.g., in Europe licenses for Airbus models are more common than for Boeing models, deriving in lower associated costs for flights that operate within this territory).

The example most directly related to the research proposed in ITACA is probably that of the SESAR ER COMPAIR project (www.compair-project.eu). This project developed an agent-based model to analyse the introduction of competition in the ATM market through the tendering of licenses to operate en-route air navigation services, explicitly modelling ANSPs' decisions to invest in new technologies, as part of their strategy to compete in a liberalised market (Torres et al., 2017).

3 Description of the ITACA simulation model

The goal of a model specification phase, whether an ABM or any other sort of simulation model, is to answer the following question: how can the system and its predefined mechanisms be modelled and simulated?

The specification of the ITACA agent-based simulation model includes:

- General hypothesis and assumptions.
- Model inputs, including the exogenous variables affecting the simulation.
- Agents' definition, including their roles, decisions, and interactions.
- The identification of the factors that affect the agents' decisions.
- The definition of the process the model is going to simulate in a comprehensive manner.
- Model outputs.

3.1 Main modelling assumptions

When translating a real system into a model, simplifications of the existing phenomena are to be made until the desired (or feasible) level of abstraction is reached: if the complexity of the model is reaching a level where we are no longer able to understand the processes involved, the experiments conducted are of little interest and we cannot understand these artificial complex systems any better than we understand the real ones (Mueller & Pyka, 2016). Therefore, the ITACA model should be simple enough to obtain insights from it, but be as close to reality as possible.

With this goal in mind, the main modelling hypothesis and assumptions are listed below:

- Policies are inputs for the model, which cannot be modified by the action of the agents. In consequence, external pressures to the policy makers during the elaboration of the policy are not considered.
- The model is focused on simulating the deployment phase, considering the research phase as an external factor to the adopters. Research, development, certification, manufacturing and any other step that precedes the availability of the technology will be translated into time. This time precedes the readiness date of a certain technology, delaying its possible adoption in the simulation. For instance, a complex certification process will be emulated by providing a technology with a longer certification buffer time.
- We focus on the adoption of technology by civil aviation.
- Although aviation is an important sector in the global economy, the relative weight of ATM is relatively small. Therefore, we assume that global trends (e.g., economic growth) will not be affected by the evolution of the ATM industry and can thus be considered as exogenous variables.
- Major disruptions in aircraft design are not considered. Evolution in fuel efficiency is taken into account, based on the forecasts provided by the main aircraft and engine manufacturers.

- We consider demand projections as exogenous to the model, extracting them from the forecasts produced by EUROCONTROL. The model includes price-demand elasticity, which modulates traffic demand levels on different routes depending on ticket prices.
- Although national interests play a role in the process that we are analysing, for the sake of simplicity they are not taken into consideration.
- Airlines' city pairs are fixed. The underlying assumption is that, a priori, technology adoption does not affect the decision of an airline to fly new routes.
- The model includes different route options so that airlines can choose the route that minimises their cost function, considering fuel costs and air navigation charges. The rationale for this assumption is to capture the way route choices can be impacted by air navigation charges, which can in turn be affected by the adoption of new technologies (Delhaye et al., 2021).
- The Network Manager is considered as an early adopter of new technologies, in accordance with SES objectives. It is thus considered as a lever for adoption, performing a regulator role.

3.2 Overview of the ITACA simulation model

The **scenarios** feed the model, containing all the required information to perform the desired analysis. Since we aim at benchmarking policy measures for technology adoption, the scenario must include the policy (or policies) to be tested and the technologies available to be adopted. Other aspects included in scenario definition are the exogenous variables, the time step duration, the initial year and the simulation time horizon.

The **policies** to benchmark have been selected based on their relevance, following a combination of literature review and stakeholder consultation (Delhaye et al., 2021). They include, for example:

- Flexible charging: this measure allows ANSPs to add a certain margin to their unit rates if they adopt a given technology.
- Best equipped-best served: the charges for different airspace users are asymmetric depending on their ATM equipment.
- Subsidies: different stakeholders receive financial aid subject to ATM technology adoption.
- Increased involvement of certification authorities in the research phase: the expected effect of this measure is modelled as the earlier availability of certain ATM solutions and reduced risk perception on the adopters' side.

Available technologies are clustered into different case studies. Some of the past and future ATM solutions considered are Airport Collaborative Decision Making (A-CDM), System Wide Information Management (SWIM), Continuous Climb Operations (CCO) and Dynamic Airspace Configuration (DAC). For each of them, a list of features describes their requirements, implementation costs and expected benefits, which will influence the adoption decision.

Exogenous variables provide boundary conditions to the simulation and can be seen as limiting factors for the action of the agents. They include aspects that do not depend on ATM evolution but affect the agents involved, such as passenger demand, fuel prices, engines' fuel efficiency, and consumption and unitary labour costs.

The model includes different types of **agents** representing the most relevant actors in ATM technology adoption: (i) regulatory bodies, which impose policies and regulations; (ii) technology providers, which develop the technological solutions to be adopted; (iii) ANSPs, which provide ATC services and adopt new technologies; (iv) airports, which also adopt ATM technology; (v) airlines, which perform their operations, pay for ATC and airport services, and adopt new technologies; and (vi) labour unions, which defend the labour conditions of their guild. Each of the mentioned agents possess a given behaviour derived from their own goals (e.g., profit maximisation), interactions with other agents and behavioural biases such as the ones discussed in Section 2.3.2.1. Their goals and biases drive their decisions about technology adoption and operational decisions such as future projections, flight allocation, management of human resources and establishment of navigational unit rates.

By simulating the scenarios, we can obtain distributional and aggregated results for each time step of the simulation. The outputs of the simulations are analysed according to a **performance framework** that includes metrics related to technology adoption, economics and operational performance.

Figure 4 provides an overview of the workflow of the model and its main components. The next section details the information depicted here, including a detail description of the agents' decision-making process.

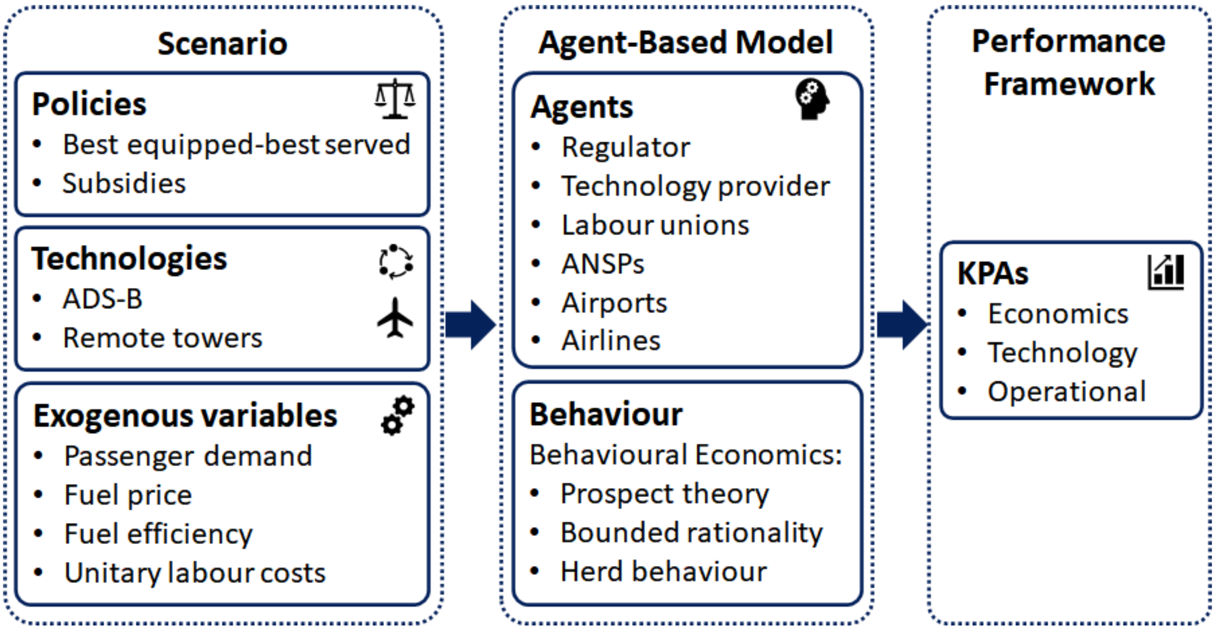


Figure 4: Model overview

3.3 Description of the model components

3.3.1 Model inputs

3.3.1.1 Policies

As mentioned before, the final goal of the ITACA project is to benchmark different policies to provide recommendations. Then, the first input the model needs is to know which policy measures are going to be analysed.

ITACA deliverable D2.1 selected the policies to be further analysed. They are summarised in Table 1, indicating the issue they aim to solve.

Table 1: Policies

Policy	Current situation	Description	Related issue to solve
Cost plus pricing	Cost recovery	ANSPs can recover their costs and add a margin to their charges if they implement a certain technology.	Overcome current charging regulation, which creates low incentives for technology adoption.
Best equipped-best served	Fair service provision/charging	The provision of ATC services (or the charging scheme) to airspace users differs with the ATM equipment adopted.	Overcome last-mover advantage for technologies with network effects and/or decreasing costs with scale.
Demonstration projects	-	To increase the number of demonstration projects, validation efforts, and dissemination of new technologies	Overcome inherent reluctance to change, opposition of social partners, and safety concerns by showing the benefits of new technologies and hence decreasing uncertainty.
Involvement of the safety agency	-	Involvement of the safety agency in the research phase.	Overcome safety concerns.
Subsidies	Subsidies	Direct subsidies subject to prior technology implementation.	Overcome the discord between high costs and goal to lower ANSP charges; overcome strict budget constraints; overcome principal agent problem (the main investor is not the main beneficiary).

In order to include these policies in the model, we have to perform an abstraction exercise and decide on how they are going to be modelled. The modelling approach for each of them is shown in Table 2.

Table 2: Policy modelling approaches

Policy	Modelling approach
Charging regulation	In the case of adoption, each technology has an associated variable margin that depends on the unit rate (e.g., +20% of unit rate).
Best equipped-best served	Asymmetric service provision is modelled as an asymmetric distribution of delays. This depends on whether the airline adopts or not a given technology. Asymmetric charging calculations (ANSPs unit rates and airport fees) include a discount factor if a certain technology is adopted. There are different ways of achieving this: • Asymmetric charging regulation (non-adopters pay for the discounts). • Earmarked external funding.
Demonstration projects	Uncertainty related to technology implementation costs is reduced by a certain percentage (e.g., 10% less uncertainty).
Involvement of the safety agency	Uncertainty related to expected research phase time and development phase time are reduced for the different technologies in which the safety agency has been involved in. Reduction of the risk perception given the favourable advice provided by the safety agency.
Conditional subsidies	Funding and subsidies are allocated to the different adopters. This funding would come from EC mechanisms (e.g., CEF) as well as from national governments, without distinction of the source in the simulation. The selection would depend on implementation. The amount would depend on: • Costs of implementation: full recovery. • Operational benefits: additional incentives applied to certain technologies with high benefits at system level.

3.3.1.2 Technologies

Considering that the aim of the policies is to incentivise technology adoption, the model must include technologies in its scenarios. The model should not be biased by our selection of the policy measures to be selected, so different case studies are considered including a number of ATM solutions. This task is performed in WP5, so the final list of ATM technologies considered will be presented in D5.1 Policy assessment.

The model is capable of including different technologies under consideration for the experiments. To make them comparable for the different agents, they are modelled attending to a number of characteristics that provide enough information to the agents to make the adoption or rejection decision and to know the change in their operational tasks due to the new technology (e.g., fuel saving, ATCO hour productivity, etc.). The features selected to represent technologies are listed in Table 3.

Table 3: Technology features

Feature	Agents affected	Variables affecting the simulation
Costs	Airlines	• Retrofit (€/aircraft) • Increased cost for new aircraft (€) - difference between old and new technology • Training cost (€/staff)
	Airport	• Cost of implementation in a big airport (€) • Cost of implementation in a small airport (€) • Training cost (€/staff)
	ANSP en-route	• Cost of implementation (€/ACC) • Training cost (€/ATCO)
	ANSP terminal	• Cost of implementation (€/TMA) • Training cost (€/ATCO)
Benefits	Airlines	• Fuel saving (kg fuel / flight) • Delay reduction (minutes / flight)
	Airports	• Capacity increase (€ / airport) • Cost reduction (€ / airport)
	ANSP en-route	• ATCO hour productivity increase (%) • Capacity increase (%)
	ANSP terminal	• ATCO hour productivity increase (%) • Capacity increase (%)
Compatibility with existing technology	All	• Yes/No
Duration of technology research phase	All	• Years
In service life	All	• Years
Implementation requirements	All	• Technological • Operational • Effort • Time
Effect on labour conditions	Labour unions	• Effect on salary reduction • Effect on redundancies

3.3.1.3 Exogenous variables

The agents in an ABM need an environment in which they can interact with each other. This environment, defined by the exogenous variables, influences agents by providing them with information that affects their decisions. The exogenous variables considered in the ITACA model are described below.

Table 4: Exogenous variables

Exogenous variable	Description	Agents directly influenced
Passenger demand	The overall passenger demand between airport pairs is set as an external value to the agents. It affects the revenues of all the different agents involved in the industry. The past demand between airport pairs is obtained from EUROSTAT. To obtain projections of those values, the model considers the traffic annual growth rates from EUROCONTROL's 2040 traffic demand forecasts. The effect of the COVID-19 pandemic has not been taken into account. Passenger demand includes price-demand elasticity, which modifies the demand that is captured by the airlines in relation to the ticket fares. Elasticity values are taken from IATA (2007).	Airlines, airports, en-route ANSPs and terminal ANSPs
Fuel Price	Fuel prices are subject to market rules out of the scope of the problem under investigation. Fuel is an important operational cost for airlines; thus, variations of its price are reflected in the model. The variation is the same for different spatial locations. Historical and forecasted Jet-A fuel prices (€/kg) up to 2050 provided by the US Energy Information Administration (EIA) are considered (EIA, 2021).	Airlines
Engine efficiency	Fuel consumption evolves over time with technology evolutions not related with ATM. The model considers two types of engines: one for a typical narrow-body aircraft (CFM Leap 1A) and another one for a wide-body aircraft (Rolls-Royce Trent XWB 84). The fuel flow for those engines (kg/s) at 4 different stages of the flight (take off, cruise, approach and idle) is retrieved from the ICAO Aircraft Engine Emissions Databank. This data, together with the annual reduction rate of average fuel burn of new aircraft estimated by Kharina & Rutherford (2015), allows us to estimate past and future engine efficiencies.	Airlines

Exogenous variable	Description	Agents directly influenced
Unitary labour costs	The labour costs of different positions are needed for the cost calculation of the agents: pilot unitary costs (MIT, 2020), non-cabin staff unitary costs (IAG, 2019), ATCO unitary costs (BOE, 2019), non-ATCO ANSP staff unitary costs (EUROCONTROL, 2017), and airport staff costs. The obtained labour costs are adapted to different regions employing unitary labour costs at country level (EUROSTAT, 2021).	Airlines, airports, en-route ANSPs and terminal ANSPs

3.3.2 Agents

One of the main components of the model are the agents, which represent the actors involved in European ATM, their roles and behaviour.

In a first attempt to find all the relevant agents for the model, the following actors were identified: ANSPs (en-route and terminal), airports, airlines, technology providers, aircraft manufacturers, EU policy makers, national governments, safety agencies, funding agencies (European and national funding agencies), labour unions, the Network Manager and the research community.

Aircraft manufacturers work closely with ATM technology providers, to equip new aircrafts with the latest ATM technology. Their behaviour and tasks are merged with the technology provider agent, for simplicity.

National governments are assumed to behave in line with the EC, with the primary interest of maintaining safety and security levels at the highest standards (Zeki, 2020). The policy maker agent will take their role in the simulations. Although political interests and sovereignty may sometimes act as barriers to adoption, for the sake of simplicity we have left this aspect out of the scope of the model.

Safety agencies are in charge of maintaining the standards in the industry (approving new processes, infrastructures, technologies and aircraft) and to provide licenses to the operators (ANSPs, airlines and airports). They will not be explicitly modelled, but their actions will be modelled as variations of technology development time and uncertainty related to technology certification.

Funding agencies rely on policy makers' decisions (national government or the EC) and, thus, their role and actions will be embedded within the policy makers' agent.

EUROCONTROL has several roles in the European ATM system. Its activities include network management through the Network Manager Operations Centre (NMOC), civil-military cooperation activities, provision of air navigation services in a cross-border area (MUAC), R&D and training. Considering its close relationship with the EC and SESAR, it possesses a leading role in relation with technology adoption. MUAC and the NMOC are early adopters for new ATM equipment and the organisation disseminates and engage the users to adopt new ATM solutions. Moreover, it is assumed that, when elaborating a new mandate, the European Commission, the Network Manager, the European Union Aviation Safety Agency (EASA) and the SESAR Deployment Manager (SDM) coordinate among themselves in order to make a decision about what, when and how to deploy a new technology. For these reasons, the Network Manager role and tasks have been included in the policy maker agent.

The research community does not to take an active role in the deployment process, despite its importance in the development stage. Therefore it has not been included in the model.

Considering that some of the selected actors share some commonalities, in relation to the problem the model addresses, they are clustered into four groups:

- Adopters:
  - Agents included: en-route and terminal ANSPs, airports and airlines.
  - Main role and objective: to optimise their objective function (i.e., to achieve an optimal result in their operational tasks). New technology is for them an enabler to achieve this.
  - Decisions: technology adoption.
  - Agents they interact with: all.
- Technology providers or industry:
  - Agents included: technology providers (ground/airborne, including aircraft manufacturers).
  - Main role and objective: to provide a set of ATM technologies to the adopters.
  - Decisions: set market prices.
  - Agents they interact with: adopters.
- Regulators:
  - Agents included: policy makers.
  - Main role and objective: to monitor and execute the applicable policies in order to ensure global welfare.
  - Decisions: decisions derived from the policies and regulations in place.
  - Agents they interact with: adopters and labour union.
- Labour unions:
  - Agents included: labour unions.
  - Main role and objective: to lobby regulator and adopters in order to defend the labour conditions of their guild.
  - Decisions: obstruct or support a deployment.
  - Agents they interact with: adopters and regulator.

The adopters' group is formed by the stakeholders who are in a position to adopt new ATM technologies. The model aims at providing a representation as realistic as possible of their mechanisms and drivers for technology uptake; on the other hand, the behaviour of the technology providers, labour unions and regulator agents will be represented by simpler behavioural rules.

In the context of ITACA, we differentiate between en-route and terminal air navigation services (ANS). The former provides services during the en-route operations. The later includes approach ANS (ascending, descending) and aerodrome ANS (landing, take-off and taxi operations). This distinction is important since terminal ANS have been partially or fully privatised in some European countries (e.g., UK, Spain, Sweden and Germany). En-route and terminal ANSPs may have different objectives (cost-recovery vs profit maximisation). The interviews with different ATM stakeholders reported in deliverable D2.1 show that the technology adoption dynamics may be significantly different depending on the ownership model (private vs public) and the revenue scheme (cost recovery vs liberalised market).

Each of the selected agents are described with further detail in the following subsections.

3.3.2.1 En-route ANSPs

The role of en-route ANSPs is to manage air traffic by providing ATM services and, in some cases, CNS, MET, SAR and/or AIS services. These services are provided to the airspace users (mainly airlines) in exchange for the payment of navigational charges (economic compensation).

ANSPs have different features that influence their behaviour. We have considered the following clusters of features:

- Business model. The business model depends on the ownership (public vs private) and the financial model of the ANSP. The current financial model of the ANSPs in Europe follows a cost-recovery scheme based on a traffic and cost risk sharing mechanism, incorporating also an adjustment mechanism for past over-recovery or under-recovery scenarios (EUROCONTROL, 2018). Under this scheme, ANSPs are required to equal their revenues to their costs, based on traffic projections. The costs breakdown indicates the amounts allocated for labour, non-staff operational costs, depreciation or exceptional items. The cost-sharing amendments and traffic risk-sharing costs result in an increase or reduction of the previously mentioned costs. The revenues of these organisations come exclusively from the navigational charges paid by the airspace users.
- Financial status. It is a measure of the health of the organisation. Taking into account assets and liabilities, cash flow, debt, capital expenditure and depreciation, the willingness to invest for new technology will be different.
- Technology. Deployed technology influences the performance of the organisation and the compatibility between legacy and new technology influences the willingness to change.
- Labour agreements: labour unitary costs and/or hours.

The goal of an en-route ANSP depends mainly on the type of ownership: public ANSPs will seek a balance between SES KPAs (safety, environment, airspace capacity and cost efficiency) ensuring a minimum level as per SES objectives, while private ANSPs will optimise profits while complying with minimum KPAs levels.

To achieve these goals, ANSPs make different technology adoption and operational decisions:

- Technology adoption.
- Deploy in time / delay the deployment (depending on the interests).

- Capacity allocation.
- Increase / decrease air traffic control charges.
- Human resources: to hire, dismiss, agree labour conditions, etc.
- Financial decisions related to debt.

Their interactions with other actors are:

- Airlines pay charges in exchange of air navigation services.
- Technology providers provide ATM technology options to the en-route ANSPs.
- ANSPs coordinate with other ANSPs for technology acquisition.
- Labour unions influence human resources decisions and labour conditions.
- Policy makers and regulatory bodies:
    - Funding agencies influence financial decisions.
    - Safety agencies influence technology adoption and deployment time. They set minimum safety levels.
    - The EC sets economic and operational regulation (competition, financial scheme, etc.).

They interact with the environment through:

- Macroeconomic conditions (e.g., unitary labour costs).
- Traffic demand, dependent on airspace volume, complexity, seasonality, etc.

3.3.2.2 Terminal ANSPs

The features that influence terminal ANSPs are similar to the ones related to en-route ANSPs. Terminal ANSPs in the SES area are subject to performance and charging schemes, similarly to en-route ANSPs in relation with the cost recovery scheme.

The goal of terminal ANSPs depend mainly on the type of ownership: public ANSPs will seek a balance between SES KPAs (safety, environment, airspace capacity and cost efficiency), ensuring a minimum level as per SES objectives, while private ANSPs will maximise profits while complying with minimum KPAs levels.

To achieve these goals, they make technology adoption and operational decisions:

- Technology adoption.
- Deploy in time or delay the deployment (depending on the interests)
- Increase or decrease air traffic control charges.
- Human resources: to hire, dismiss, agree labour conditions, etc.
- Present a bid for tender, in case that the provision of terminal ATC has been liberalised.

Their interactions with other agents are:

- Airlines pay charges in exchange of air navigation services.
- Technology providers provide ATM technology options to the terminal ANSPs.
- ANSPs coordinate with other ANSPs for technology acquisition.
- Airports tender control towers (wherever applicable) and impose performance and/or technology requirements in calls for tenders.
- Labour unions influence terminal ANSPs' human resources decisions and labour conditions.
- Policy makers and regulatory bodies:
  - Funding agencies influence financial decisions.
  - Safety agencies influence technology adoption and deployment time. They set minimum safety levels.
  - The EC sets economic and operational regulation (competition, financial scheme, objectives, etc.).

They interact with the environment through:

- Macroeconomic conditions (e.g., unitary labour costs).
- Traffic demand, dependent on airspace volume, complexity, seasonality, etc.

3.3.2.3 Airports

Airports are a well-known actor by the end user of air transport (passengers) because they are the interface between land and air traffic.

The features that influence airports' behaviour are:

- Business model, including in this category the cost breakdown, the ownership of the airport and its revenues. In European airports, the ownership share in 2013 was 82% public, 7% hybrid and 11% private, while the management share was 54% public, 23% hybrid, 23% private, (DG MOVE, 2013). Airports charge airlines for using their infrastructure, security, landing and additional services provided by the airport operators. However, in contrast with ANSPs, around 40% of their revenue is not related to aeronautical activities (retail concessions, car parking fees, etc.).
- Financial status: assets and liabilities, cash flow, debt, capital expenditure and depreciation.
- Technology: new technology characteristics and compatibility with legacy technology.
- Labour agreements: labour unitary costs.

Airports' goal is assumed to be to maximise profit. When they are managed by a public entity, a minimum level of service is guaranteed.

The decisions made by the airport agents include:

- Technology adoption.
- Set airport fees.

- Launch tenders for tower ATC.
- Human resources: hire and dismiss, agree on labour conditions, etc.

Their interactions with other agents are:

- Airlines pay charges in exchange for airport services (passengers, landing, security, etc.).
- Terminal ANSPs provide terminal ANS in the airport if selected by tender.
- Technology providers provide ATM technology options to the airports.
- Labour unions influence airports' human resources decisions and labour conditions.
- Policy makers and regulatory bodies:
    - Funding agencies influence financial decisions.
    - Safety agencies influence technology adoption and deployment time. They set safety minimum levels.
    - The EC sets economic and operational regulation (competition, financial scheme, etc.).

They interact with the environment through:

- Macroeconomic conditions (e.g., unitary labour costs).
- Traffic demand, dependent on airspace volume, complexity, seasonality, etc.

3.3.2.4 Airlines

Airlines are the last adopter agent, whose role includes the transport of passengers and/or freight safely and in time from their origin to their destination. They are the main airspace users.

The features that influence airlines' behaviour are:

- Business model. Airlines' business model depends on whether they are a legacy airline or a low-cost carrier (LCC). The cost breakdown is highly dependent on the business model, finding large differences in fuel costs (legacy 18-26% of total costs vs LCC 23-36%), labour costs (legacy 24-29% vs LCC 14%), airport fees and ground handling (legacy 10% vs LCC 15-30%), and navigational charges (legacy 3% vs LCC 7-11%). The revenues are given by the airfare paid by passengers and the number of passengers carried. This can be characterised by the airline load factor, i.e., the average percentage of aircraft occupancy, and the average airfare.
- Financial status: assets and liabilities, cash flow, debt, capital expenditure and depreciation.
- Technology: new technology characteristics and compatibility with legacy technology.
- Labour agreements: labour unitary costs.

Airlines' main goal is to maximise profit, considering that they are all privately owned companies operating in a highly competitive environment.

The decisions made by airlines include:

- Network planning: to create or remove flights in the route network depending on the expected demand.

- Aircraft planning: to add or remove aircrafts depending on the required flights.
- Technology adoption: by adopting new aircraft or by retrofitting existing aircraft.
- Route selection: to decide on the different path alternatives to fly between an OD pair, depending on fuel costs and navigational charges.
- Human resources: hire, dismiss, agree labour conditions, etc.

Their interactions with other agents are:

- En-route and terminal ANSPs: airlines pay charges for the provision of air navigation services.
- Airports: airlines pay charges for the provision of airport services.
- Technology providers: they provide ATM technology to the airlines.
- Policy makers define and implement regulations.
- Labour unions: pilot and cabin crew associations defend their labour conditions.

They interact with the environment through:

- Macroeconomic conditions (e.g., labour costs, fuel price).
- Route network (city pairs).
- Traffic demand.

3.3.2.5 Regulator

The regulator agent is considered as a pan-European body (e.g., EC, SESAR) that is able to impose regulations to all the stakeholders included in the simulation.

Its role is to design and execute policies, as well as monitor compliance.

This agent does not have features associated.

Its main goal is to optimise the KPIs concerning distributional effects and aggregated global welfare.

The decisions made by the regulator agent are the ones associated with the policies applied in the case under study.

3.3.2.6 Technology providers

The technology providers are in charge of developing new technologies and offering a set of options to be implemented.

Technology providers are influenced by their business model, financial status, market opportunities of the technologies, labour agreements, etc. However, the relationship between their behaviour and these features is not represented in the model.

The goal of technology providers is to maximise profit.

In order to reach their goal, they modulate market prices for the provision of technologies. The pace of innovation is imposed to this agent: the scenario under study defines an availability date for new technologies.

Their interactions with other agents are based on providing technology to the technology adopter agents (airlines, ANSPs, airports).

They interact with the environment through the technology evolution pace.

3.3.2.7 Labour unions

Labour unions are associations of professionals (e.g., pilots union, ATCO associations) that defend the interests of the groups they represent. Their role is to influence adopters on their decisions.

Their lobby capacity is influenced by the following features of the union:

- Professional group represented (linked to a certain adopter).
- Thresholds for strike decision, considering salary reductions, redundancies or labour conditions (holidays, working hours…).
- Lobby strategy: conciliatory vs aggressive.

The goal of this agent is to maintain or improve the labour conditions or their guild.

To that end, the decisions that may make are:

- Obstruct or support a deployment.
- Start or end a strike.

Their interactions with other agents are:

- Airlines try to find a balance between employees and company interests.
- Airports try to find a balance between employees and company interests.
- En-route and terminal ANSPs try to find a balance between employees and company interests.

They interact with the environment through macroeconomic conditions (e.g., unitary labour costs).

3.3.3 Model outputs and performance framework

The successful benchmarking of regulations and policy measures requires a comprehensive assessment of their impact along different dimensions. To that end, the outputs of the model selected for the analysis are to be representative of the performance of the European ATM system in the situations tested.

This project aims to be consistent with previous literature, in particular with ICAO Performance Framework (ICAO 2008), the SES Performance Scheme and the SESAR Performance Framework. Although the terms performance indicator and key performance indicator are often used as synonyms in other contexts, both the SES Performance Scheme and the SESAR Performance

Framework differentiate between them. Therefore, in this project we will make the same distinction. For the sake of clarity, we will define the following concepts:

- Key Performance Area (KPA): a broad focus area encompassing one or several goals or objectives.
- Performance Indicators (PIs): indicators used for the purpose of performance monitoring, benchmarking and reviewing.
- Key Performance Indicators (KPIs): indicators used for measuring and/or summarising the current position and the direction and rate of change of progress towards a particular goal or objective. They are those PIs used for the purpose of performance target setting.
- Model outputs: they consist of any measurable variable or parameter within the model. Indicators are defined in terms of output values or functions of them.

We have first selected a subset of indicators from the mentioned literature that are considered more relevant for the objectives of the project. The criteria for the selection are based on finding a balance between the fields investigated, so that indicators are relevant for policy makers, and on the expected capabilities of the model. Then, we have complemented these indicators with additional indicators aimed to capture dimensions that fall outside the scope of the aforementioned performance schemes, but are considered necessary for a comprehensive assessment framework.

Following the approach defined by SESAR ER COMPAIR project, we classify indicators according to the following dimensions:

- Quantitative indicators vs qualitative indicators:
  - Quantitative indicators use numbers and express amounts or quantities.
  - Qualitative indicators use words, symbols or colours to express attitudes and views.
- Local indicators vs global indicators:
  - Local indicators are measured at airport/national/FAB level.
  - Global indicators are measured at network level.
- System-wide indicators vs stakeholder-specific indicators:
  - System-wide (or social) indicators are measured at societal level (e.g., social welfare).
  - Indicators linked to a specific stakeholder (e.g., airline surplus).

The ITACA project will consider the following clusters of KPAs and associated indicators:

- Technology adoption KPAs and indicators.
- Economic KPAs and indicators.
- Operational KPAs and indicators.

There may be certain indicators that are not included in the model (either because they are subject to more qualitative considerations, because there is not enough information, or because they cannot be modelled in a reliable manner), but still are worth considering for providing a complete picture of the possible implications of the policy measures under study.

The minimum set of indicators that should be evaluated is highlighted in bold font. The indicators in italics are considered as "nice-to-have", but it still has to be evaluated whether they can be modelled or assessed in a reliable manner.

Table 5 shows the technology adoption KPAs and associated KPIs considered for the model. Table 6 shows the economic KPAs and associated KPIs considered for the model. Table 7 summarises the operational KPAs and associated KPI measured in the model.

Table 5: Technology adoption KPAs and indicators

KPA	Indicator	Type of indicator	Source
Technology adoption effectiveness	**Time for adoption (global / per agent type)**	Quantitative, global, system-wide/ stakeholder specific	Own
	Market share of each technology (global / per agent type)		Own

Table 6: Economic KPAs and indicators

KPA		Indicator	Type of indicator	Source
Economic efficiency		**Social welfare = Consumer and producer surplus (sum of the effects on terminal ANSPs, en-route ANSPs, airlines, airports, passengers) + net benefits to third parties (externalities)**	Quantitative, global, system-wide.	COMPAIR
Distributional effects	En-route ANSP	**En-route ANSP surplus = En-route ANSPs (Benefit - Cost)**	Quantitative, global, stakeholder specific.	
	Terminal ANSP	**Terminal ANSPs surplus = Terminal ANSPs (Benefit - Cost)**		
	Airline	**Airline surplus = Airlines (Benefit - Cost)**		
	Airport	**Airport surplus = Airport (Benefit - Cost)**		
	Passenger	**Passenger surplus = Passenger (Benefit - Cost)**		
	Regulator	*Government surplus = Government (Benefit - Cost). It includes cost of regulation, financial controls and regulatory oversight.*		
Society effects	Labour unions acceptance	*Number of strikes*	Quantitative, global, system-wide/stakeholder specific	Own

KPA		Indicator	Type of indicator	Source
	Passenger options	*Active routes*	Quantitative, global, system-wide.	Own
	Employment	*Total number of employments related to aviation*	Quantitative, global, system-wide.	Own
Resilience and vulnerability		*Economic efficiency and distributional effects under a range of pre-defined external disturbances*	Quantitative, global, system-wide/ stakeholder specific	COMPAIR

Table 7: Operational KPAs and indicators

KPA		Indicator	Type of indicator	Source
Environment (SES KPA)	Fuel efficiency	*Average horizontal en-route flight efficiency*	Quantitative, global, system-wide.	SES
		Distribution of horizontal en-route flight efficiency	Quantitative, global, stakeholder specific.	Own
	Emissions	**Average fuel burn per flight**	Quantitative, global, system-wide	SESAR
Predictability and punctuality	En-route ANS	*Average minutes of en-route delay attributable to en-route ANS*	Quantitative, global, stakeholder specific.	SES
		Distribution of average en-route delays attributable to en-route ANS	Quantitative, local, stakeholder specific.	Own
	Terminal ANS	*Average minutes of arrival delay attributable to terminal ANS*	Quantitative, global, stakeholder specific.	SES
		Distribution of average arrival delays attributable to ANS	Quantitative, local, stakeholder specific.	Own
Capacity (SES KPA)	Airspace capacity	**En-route throughput per unit time**	Quantitative, local, system-wide.	SESAR

KPA		Indicator	Type of indicator	Source
		TMA throughput per unit time	Quantitative, local, system-wide	SESAR
Cost-efficiency (SES KPA)	En-route ANS	**Average union-wide Determined Unit Cost (DUC) for en-route ANS**	Quantitative, global, stakeholder specific.	SES
		Individual Determined Unit Cost (DUC)[1] for en-route ANS	Quantitative, local, stakeholder specific	Own
	Terminal ANS	**Average union-wide Determined Unit Cost (DUC) for terminal ANS**	Quantitative, global, stakeholder specific.	SES
		Individual Determined Unit Cost (DUC)[1] for terminal ANS	Quantitative, local, stakeholder specific.	Own
Operational resilience	Structural changes	*Capacity, cost efficiency, environmental impact and punctuality under a range of pre-defined external disturbances*	Quantitative, global/local, system-wide.	COMPAIR

3.3.4 Decision-making process

The process of interaction between the agents aims to replicate the tasks performed by ATM stakeholders, both for technology adoption and daily operations. Business Process Model and Notation (BPMN) diagrams are used to describe the model workflow.

3.3.4.1 General process

Figure 5 presents the actions that each of the agent groups performs during the simulation. Each type of agent is represented by a horizontal pool, their tasks are represented with yellow boxes, the decisions are described as orange diamonds, the paper icons represent pieces of information (data) and the simulation starts at the green dots and ends at the red ones. The arrows connect tasks and define the flow of the process. The process starts with the technology feasibility analysis, by which the adopters decide whether to adopt or not some of the available ATM technologies, the

[1] This KPI is computed in the same way as in the EUROCONTROL ACE reports, as the ratio of en-route or terminal ANS costs (in real terms) to service units at charging zone level. For the calculation of total costs in the simulation we consider the labour costs, operating costs, depreciation costs, exceptional items and possible regulatory penalties.

initialisation of the policies and the knowledge of ideas and concerns of labour unions. Their decision will be influenced by internal and external factors, such as the policies in place and the influence of labour unions. Regardless the decision, they perform their operational tasks, which will provide economic results and lessons learnt at the end of each time step. These results will influence future adoption decisions: for instance, an ANSP will be more likely to adopt new technology if past experiences were positive.

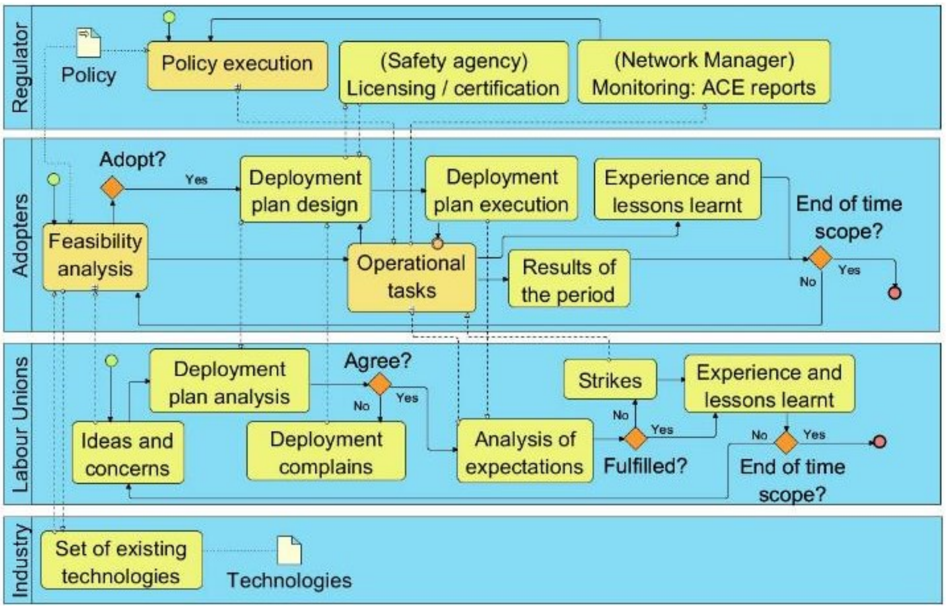


Figure 5: General simulation process

3.3.4.2 Feasibility analysis

Figure 6 shows the process that drives the adoption/rejection decision.

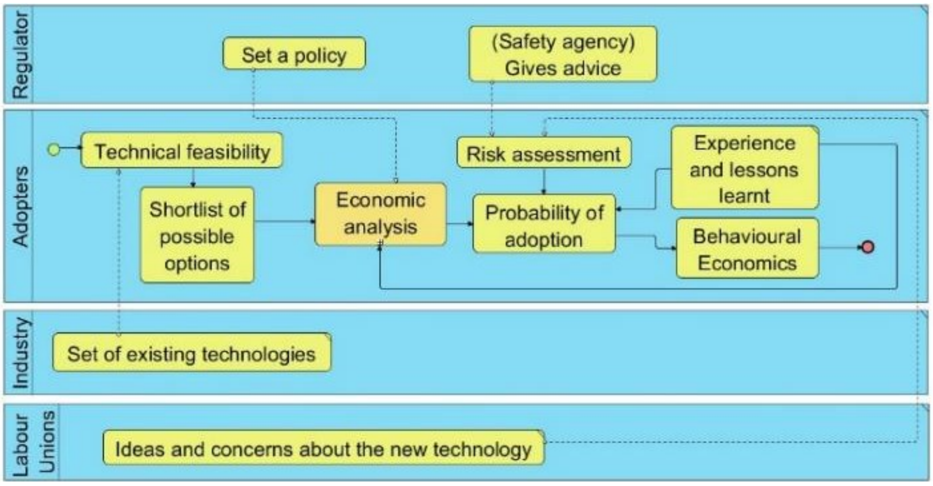


Figure 6: Feasibility analysis process

The technology feasibility analysis is common for all the different adopters. The specific parameters of each agent will determine the final decision. This process includes the following steps:

Technical feasibility

Each adopter reviews the list of available technologies at time t_i. If a technology can be implemented by the agent (depending on whether the solution is applicable to en-route ANSPs, terminal ANSPs, airlines or airports), it is stored in a shortlist of possible options. If no technology is applicable, the process is ended.

Economic analysis

For each technology stored in the shortlist, the agent performs an economic analysis consisting in comparing a business as usual (BAU) scenario with an adoption scenario.

Business as usual (no adoption) scenario

The BAU or rejection scenario is defined by the costs, benefits and profit for each agent.

The expected costs over time, $c_{BAU}(t)$, are estimated, adding possible policy penalties (e.g., for the best equipped best served policy, the penalisation for non-equipped airlines shall be considered).

The expected benefits, $b_{BAU}(t)$, are estimated, based on projections of the exogenous variables.

The net result or profit over time, $pr_{BAU}(t)$, is calculated as the difference between benefits and costs.

Adoption scenario

The adoption scenario estimates the costs, revenues and profit given the adoption of a technology $tech_i$ for a certain period.

The expected costs over time are estimated as:

$$c_{tech\,i}(t) = c_{BAU}(t) + c_{implementation} - c_{reduction}(t),$$

where $c_{implementation}(t)$ is the cost of implementation of $tech_i$ and $c_{reduction}(t)$ is the reduction in operating costs derived from the adoption of the technology.

Considering the features of the technology listed in section 3.3.1.2, the cost of implementation of a solution for the different adopters are:

- For an en-route ANSP, it is calculated as

$$c_{implementation} = c_{ACC} \cdot n_{ACC} + c_{training_{ATCO}} \cdot n_{ATCO},$$

  where c_{ACC} is the cost of implementation per ACC, n_{ACC} is the number of ACCs managed by the ANSP, $c_{training_{ATCO}}$ is the unitary cost of training per ATCO and n_{ATCO} is the number of ATCOs working in the ANSP. As we consider linear depreciation, the cost per year during its expected life is calculated as $c_{depreciation} = c_{implementation}/life_{equipment}$.

- For a terminal ANSP, the implementation costs are:

$$c_{implementation} = c_{TMA} \cdot n_{TMA} + c_{training_{ATCO}} \cdot n_{ATCO},$$

where c_{TMA} is the cost of implementation per TMA, n_{TMA} is the number of TMAs managed by the ANSP, $c_{training_{ATCO}}$ is the unitary cost of training per ATCO and n_{ATCO} is the number of ATCOs working in the ANSP.

- For an airline, the implementation costs are calculated as:

$$c_{implementation} = c_{retrofit} \cdot n_{aircraft} + c_{new\ aircraft} \cdot n_{projected\ aircraft} + c_{training} \cdot (n_{pilot} + n_{crew}),$$

where $c_{retrofit}$ is the cost of retrofit per aircraft, $n_{aircraft}$ is the number of aircrafts owned by the airline, $c_{new\ aircraft}$ is the increase in cost to new aircraft purchases due to the new technology, $n_{projected\ aircraft}$ is the number of aircrafts expected to be acquired in the projection period, $c_{training}$ is the unitary training cost per staff, n_{pilot} is the number of pilots working at the airline and n_{crew} is the number of cabin crew at the airline.

- For an airport agent, the implementation costs are:

$$c_{implementation} = c_{equipment} + c_{training} \cdot n_{staff},$$

where $c_{equipment}$ is the cost of the ATM equipment acquired, $c_{training}$ is the unitary training cost per staff and n_{staff} is the number of airport staff that needs training.

On the other side, technologies may have the effect of a sustained reduction in costs over time. The different agents are assumed to reduce their associated costs in different ways:

- In the case of en-route and terminal ANSPs, the reduction in their costs is derived from the reduction of ATCO hours on duty, considering that their hour-productivity has been increased by the action of the new technology. It should be noted as well that airspace capacity may have increased due to the action of the technology:

$$cap_{new} = cap_{current}(1 + \Delta cap(\%)).$$

With the capacity increase, it is possible to estimate the change in traffic managed by the ANSP by comparing the projected demand with the capacity.

$$traf_{current} = \min\left(demand_{projected}, cap_{current}\right)$$
$$traf_{new} = \min\left(demand_{projected}, cap_{new}\right).$$

Then, the ATCO hour productivities can be estimated as:

$$prod_{current} = flh_{ATCO}/wh_{ATCO},$$

where $prod_{current}$ is the current ATCO hour productivity, flh_{ATCO} is the number of flight hours controlled by an ATCO and wh_{ATCO} is the number of working hours (on duty) per ATCO. The new productivity, due to the effect of the technology, is given by the increase in productivity included in the features of the technology:

$$prod_{new} = prod_{current}(1 + \Delta prod_{ACTO}(\%)).$$

The total ATCO on duty working hours required to meet expected traffic can be computed as:

$$total\ wh_{current} = traf_{current}/prod_{current}$$

$$total\ wh_{new} = traf_{new}/prod_{new}$$

The difference in working hours represents the savings in costs for the ANSPs. If we multiply this difference by the unitary ATCO cost per working hour, the cost reduction is obtained:

$$c_{reduction} = (\,total\ wh_{current} - total\ wh_{new}) \cdot cu_{ATCO}$$

- Cost reduction for airlines is given by the fuel savings and the delay reduction:

$$c_{reduction} = \left(fuel_{flight} + delay_{flight}\right) \cdot n_{flights},$$

where $fuel_{flight}$ are the average savings in fuel, expressed in €, per flight, $delay_{flight}$ are the average savings due to punctuality, expressed in €, per flight. and $n_{flights}$ are the number of flights equipped with the technology. Both variables for savings in fuel and delay are provided by the features of the technology.

- Airports

Cost reduction in airports involve reduction in the costs of processes, staff reduction, etc. Estimations for cost reductions of the given technologies are proposed for big and small airports.

The expected benefits over time, $b_{tech\ i}(t)$, are estimated, adding possible policy incentives (e.g., in the flexible charging regulation case, incentives for ANSPs shall be taken into account). As in the case of the costs, the benefits are not the same for each adopter. Considering the features of the technology listed in section 3.3.1.2, the benefits are calculated as follows:

- For ANSPs, since their source of revenues are the navigational charges, an increase in revenues due to the technology must be derived from an increase in traffic. As mentioned before, the traffic captured depends on the future traffic demand and the capacity of the ANSP, conditioned by the technology,

$$\Delta traf = traf_{new} - traf_{current}.$$

The increase in traffic is directly translated into an increase in revenues:

$$b_{tech\ i} = \Delta traf \cdot ur,$$

where ur is the unit rate of the ANSP.

- Airlines

It is assumed that Airlines do not obtain a direct benefit for adopting a new technology. The increase in airspace capacity is a result of technology adoption on the side of ANSPs.

- Airports

Airport revenues are calculated similarly to ANSPs' revenues: the increase in traffic produced by the technology is the source of revenues. Therefore, making a parallelism, if the technology increases airports' capacity

$$cap_{new} = cap_{current}(1 + \Delta cap(\%))$$

the traffic captured may be increased, depending on the demand,

$$traf_{current} = \min(demand_{projected}, cap_{current})$$
$$traf_{new} = \min(demand_{projected}, cap_{new})$$

$$\Delta traf = traf_{new} - traf_{current}$$

and the revenues due to the technology are calculated as:

$$b_{tech\,i} = \Delta traf \cdot charge_{pax}$$

The net result or profit over time, $pr_{tech\,i}(t)$, is calculated as the difference between benefits and costs.

A list containing costs over time and a list containing benefits over time are obtained for each adoption and BAU scenario.

Profit weighting

Profits are weighted according to 2 different biases:

- Hyperbolic discounting. It is a time preference model for the relative valuation of a reward. Immediate rewards are preferred than the promise of a higher reward after a long period of time. Hyperbolic discounting is mathematically described by employing a discount factor that multiplies the value of the reward,

$$g(t) = \frac{1}{1+k \cdot t},$$

  where k is a constant that can be tuned to adjust the behaviour.
- Herd behaviour. It has the opposite effect. The more agents have had adopted the technology in previous time steps, the higher benefit perception the adopter has. This effect is modelled by employing the following modified sigmoid function

$$S(n_{adopt}; a, b, c) = 1 + \frac{b}{1+e^{-a(n_{adopt}-c)}},$$

  where a, b and c are fitting parameters for the curve, which adapt the behaviour of the agents.

Risk assessment

For each technology, a risk assessment is conducted, obtaining a probability of successful adoption. This probability p is defined taking into account: (i) experiences and lessons learnt; (ii) the policies in place that aim at reducing the risk associated to a solution; (iii) the characteristics of the technology (compatibility, trialability, implementation requirements, and effect on labour unions).

Prospect theory

Prospect theory is a behavioural bias which states that decisions are made in terms of expected utility relative to a reference point (e.g., current wealth) rather than absolute outcomes. Based on that, the probabilities of success/failure of the technology and the expected costs and profit are used to compute the following weighted expected utility:

$$V = \sum \pi(p_i) \cdot v(x_i)\,,$$

where V is the expected utility, p_i the probabilities of losing/winning (failed/successful technology), π is a weighting function for the probabilities that captures the idea that people tend to overreact to small probability events, but underreact to large probabilities, x_i are the outcomes of each option, and v is the value function (an s-shaped asymmetrical function that reflects the loss aversion). This formulation, proposed by Kahneman & Tversky (2013), is based on two concepts: (i) loss aversion, an asymmetric form of risk aversion and (ii) asymmetric weighting of probabilities: excessive weight is attributed to events with low probabilities and insufficient weight to events with high probability. The expected utility, in our particular case, is:

$$V = \pi(p)v(x_1) + \pi(1-p)v(x_2)\,,$$

where x_1 is the perceived profit with respect to the reference point considering that the adoption is successful and the technology provides all the expected benefits, i.e.,

$$x_1 = \sum_{t=t_0}^{t_0+T} g(t)S(n_{adopt})[pr_{tech\,i}(t) - pr_{BAU}(t)]\,,$$

where t_0 is the moment of the analysis and T is the time horizon for benefits specified for each agent type (e.g., 5 years). The expected loss, x_2, is calculated similarly, by considering no increase in benefit due to the technology with respect to BAU,

$$x_2 = -\sum_{t=t_0}^{t_0+T} [c_{tech\,i}(t) - c_{BAU}(t)]\,.$$

The probability weighting function has the form

$$\pi(p) = \frac{p \cdot \delta}{(p \cdot \delta + (1-p)^{\delta})^{\frac{1}{\delta}}}\,,$$

with $\delta = 0.65$, which is the value estimated by Kahneman & Tversky (2013) from experimental data. Note that $\delta = 1$ corresponds to $\pi = p$.

The value function, as mentioned, overestimate losses compared to the same gain. It is given by

$$v(x) = \begin{cases} x^{\alpha} & x \geq 0 \\ -\lambda(-x)^{\alpha} & x < 0 \end{cases}\,,$$

where x is a euro gain or loss. The authors estimate $\alpha = 0.88$ and $\lambda = 2.25$ from experimental data.

Evaluation of the results

If a technology provides a positive expected utility, it is a candidate for adoption. The different candidates for adoption are sorted attending to their expected utility. Depending on the financial reserves available for investing of each adopter, one or several technologies from this list will be adopted.

3.3.4.3 Operational tasks

The operational process is shown in Figure 7. At a first stage, the ANSPs and airports determine their charges, hirings and dismissals for the period. Airports tender tower control services to Terminal ANSPs when applicable. After that, airlines analyse the costs of the different routes, taking into account changes in fuel costs and navigational charges and select the frequency of their routes, which may be zero. For the sake of model simplicity, airline routes are fixed, so they are not allowed to enter new markets. The final decision of the airlines will determine the benefits obtained by the rest of stakeholders. To illustrate the way operations are modelled, in the following section we describe in more detail the example of en-route ANSP operations.

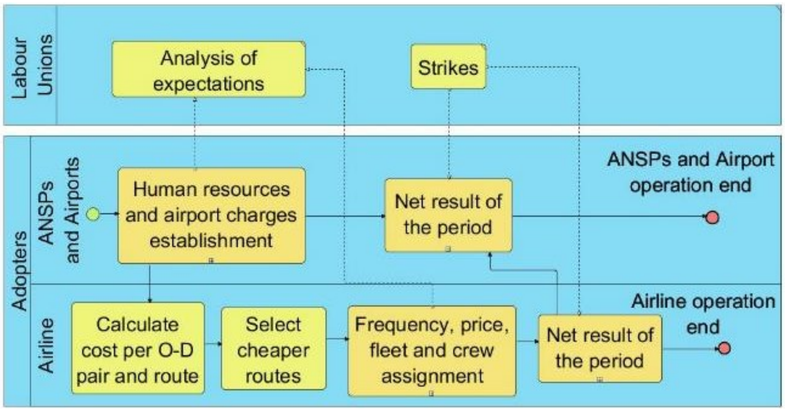


Figure 7: Operational tasks process

Cost calculation per adopter

En-route ANSPs

- Labour costs account for 65% of total costs on average, according to EUROCONTROL (2017). On average, half of a European ANSP workforce is composed by Air Traffic Controllers (ATCOs). ATCO salaries are usually higher than the retribution of other job groups in the company. Then, this distinction is reflected in the labour cost calculation:

$$c_{labour} = c_{ATCO} \cdot n_{ATCO} + f \cdot c_{avg} \cdot n_{staff},$$

  where: c_{ATCO} is the unitary cost of one ATCO full time, n_{ATCO} is the number of ATCOs in the company, c_{avg} is the average salary of the country, n_{staff} is the number of non-ATCO staff, and f is a factor between 2 and 3, which reflects typical higher salaries in the aviation industry.

- Operational costs account for approximately 16% of total costs. Operational costs are assumed to increase with the number of service units (SU) managed by the ANSP. On the other hand, new technologies can make some operations more efficient, reducing operational costs. This can be expressed mathematically as:

$$c_{op} = a \cdot SU \cdot (1 - e_{tech}),$$

  where c_{op} are the costs of operation, a is a factor that indicates the cost per service unit, and e_{tech} represents the efficiency improvement due to the new technologies.

- Depreciation costs account for around 11.5% of total costs. This depends on the previous equipment, facilities and other assets purchased. The amount is directly related to the cost of technology adoption and the expected life of the equipment. We assume linear depreciation of the ATM technologies with zero marginal value at the end of their life.
- The cost of capital accounts for approximately 6.5% of total costs. This part of the costs is related to the debt and equity of the company and it has been set as 0.06 times the total costs of the previous periods.
- Exceptional items account for around 1.2% of total costs. Exceptional costs are modelled by employing a random function with average 1.2% and maximum 5% of previous period total costs.
- Regulatory costs are the costs related to the application of the policies benchmarked in the simulation.

Terminal ANSP

- Labour costs account for 68.5% of total costs on average, according to (EUROCONTROL, 2017). We assume the same split of ATCOs and other staff as for en-route ANSPs. The calculation of labour costs is the same as for the previous group, except that the Terminal ATCOs (approach and tower) are supposed to have lower unitary costs associated.
- Operational costs (16% of total costs) are calculated in the same fashion as for en-route ANSPs.
- Depreciation costs account for around 8.5% of total costs. They are dependent on previous equipment, assuming linear depreciation.
- The cost of capital, which accounts for 5.5% of total costs, is set as 0.055 times the total costs of the previous periods.
- Exceptional items (1% of total costs) are modelled by employing a random function with average 1% and maximum 5% of previous period total costs.
- Regulatory costs are those related to the application of the policies benchmarked in the simulation.

Airlines

- Labour costs account for around 25% of total costs for legacy airlines and 14% for low-cost carriers, according to airline annual accounts: (IAG, 2019), (Ryanair, 2019), (Lufthansa, 2019) and (EasyJet, 2019). In order to have scalable metrics for cost calculation, the distribution of labour is expressed in staff per aircraft, i.e., how many pilots, cabin crew and management staff is needed to fly one aircraft. The cost of labour can be calculated as:

  $$c_{labour} = c_{pilot} \cdot n_{pilot} + f \cdot c_{avg} \cdot n_{staff},$$

  where c_{pilot} is the average cost of a pilot, n_{pilot} the total number of pilots in the company (adjusted with the fleet size), c_{avg} is the average salary of the countries where the airline operates, n_{staff} is the number of non-cabin staff and f is a factor between 2 and 3, which reflects the typical higher salaries in the aviation industry.

- Operational costs include fuel (which accounts for around 22% of total costs in legacy airlines and up to a 36% in some LCCs), maintenance (10% for legacy and 5% for LCCs), airport fees

(10% for legacy and around 20% for LCCs) and navigation charges (around 3% for legacy and 9% for LCCs).

To calculate fuel cost per flight, one should take into account engine efficiency e_{eff}, fuel price p_{fuel} and fuel consumption f_{flight}. The two first factors are exogenous variables, while the last one can be calculated as follows:

$$f_{flight} = f_{cl} \cdot t_{cl} + f_{cr} \cdot t_{cr} + f_{app} \cdot t_{app},$$

where f_{cl} is the fuel flow in climb operation, t_{cl} is the time for climbing to cruise speed, f_{cr} is the fuel flow in cruise, t_{cr} the time in cruise, f_{app} is the fuel flow in approach mode, and t_{app} the time for approach. We assume that t_{cl} is 15 minutes, with a climb horizontal distance of 50 km and t_{app} is 20 minutes with an approach horizontal distance equal to 75 km. Then, the cruise time is estimated as:

$$t_{cr} = (d_{route} - d_{cl} - d_{app}) \, / \, v_{cr}.$$

The total cost of the fuel for a flight is then:

$$c_{fuel} = p_{fuel} \cdot e_{eff} \cdot f_{flight}.$$

Maintenance costs are calculated as a fixed factor of the previous year total cost.

Airport fees have been estimated by assuming a value of 12€ per passenger in a small airport and 21€ per passenger in a hub airport.

Lastly, navigational charges shall be added to the calculation. En-route navigation charges are calculated as:

$$c_{route} = \sum ur_{ANSP\ i} \cdot \left(\frac{d_{ANSP\ i}}{100}\right) \cdot \sqrt{\frac{MTOW}{50}}$$

where $ur_{ANSP\ i}$ is the unit rate of the ANSP i, $d_{ANSP\ i}$ is the distance flight over territory controlled by this ANSP in km and $MTOW$ is the Maximum Take-Off Weight of the aircraft in tonnes.

Terminal navigation charges are calculated in a similar way:

$$c_{term} = ur_{ANSP} \cdot \left(\frac{MTOW}{50}\right)^{0.7}.$$

- Depreciation costs depend on previous and new aircraft orders, assuming linear depreciation. The aircraft lifetime depends on whether the airline is a legacy or low-cost carrier, as the latter tend to use aircraft for a longer timeframe.
- The cost of capital is modelled with a fixed factor depending on the agent.
- Exceptional items are modelled by employing a random function with average 1.2% and maximum 5% of previous period total costs.
- Regulatory costs are related to the application of the policies benchmarked in the simulation.

Airports

- Labour costs account for around 21.7% of total costs on average (ICAO, 2014). The labour costs may vary considerably depending on the business model of the airport. We assume an average unitary cost per employee, considering salary homogeneity.
- Operational costs (40% of total costs) are assumed to increase with the number of passengers. We assume a linear function with a constant passenger unit factor:
  - $c_{op} = u_{op} \cdot pax.$
- Depreciation costs (22.8% of total costs) depend on previous equipment, assuming linear depreciation. Larger investments, such the construction of new runways, will not be considered.
- The cost of capital (15.2% of total costs) is modelled as a fixed rate (0.15) of the previous period total costs.
- Exceptional items (1% of total costs) are modelled by employing a random function with average 1% and maximum 5% of previous period total costs.
- Regulatory costs are those costs related to the application of the policies benchmarked in the simulation.

Benefit calculation

En-route and terminal ANSPs

The source of income for ANSPs are air navigation charges. They are defined previously by c_{route} and c_{term} respectively.

Airlines

Airline benefits are based on passenger ticket fares. Although some companies perform a mixed business, passenger and freight transport, we consider this out of the scope of our study. Ticket fares are heterogeneous depending on the route, season, time to departure, etc. The dynamics of airfare price setting is highly complex and brings little added value to the matter we aim to analyse with our model, so the ticket fare is calculated to compensate the cost of flying the route plus a certain margin, which is larger for legacy airlines than for LCCs.

Airports

Airport revenues come from two sources: aeronautical and non-aeronautical revenue. The latter include retail concessions, car parking, etc. and the former includes the charges to airspace users for the utilisation of the airport facilities and services. Non-aeronautical revenue, which accounts for around 38% of the total European airport revenues (ICAO, 2014), is estimated as a function of the total number of passengers. We use the exponential function $g \cdot pax^{\alpha}$, where g is a constant for modulating slope, pax are the number of annual passengers in millions, and $\alpha > 1$ is the exponential factor. This factor is greater than 1 to penalise the revenues of airports with less than 1 million passengers, considering the profits of different airports categorised by size (ICAO, 2014).

3.3.4.4 Example: En-route ANSP human resources, charges and capacity setting

The allocation of ATCOs, capacity determination and navigational charges establishment process is shown in Figure 8, following a cost-recovery scheme: (i) the next period service units are forecasted; (ii) with that information, the capacity is determined so as to serve the demand, including the number of ATCOs needed; (iii) costs are estimated based on the previous assumptions; (iv) adjustments from previous period imbalances are applied to the costs, due to mismatches between forecasts and real operations; and (v) the unit rates are set so that the adjusted costs equal the expected benefits from charges.

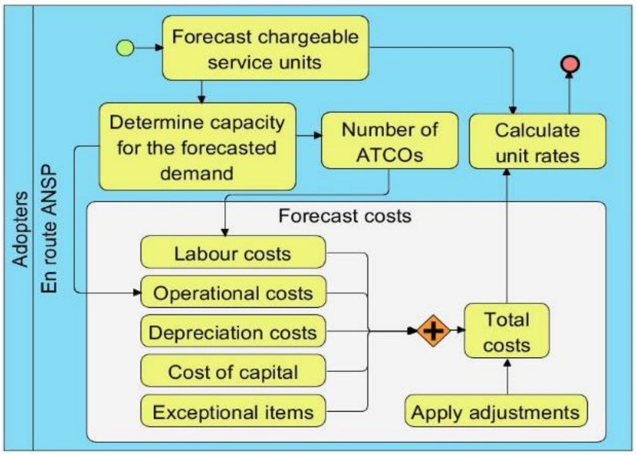


Figure 8: En-route ANSP human resources, charges and capacity establishment

At the end of their operational tasks, taking into account the provision of services and the payment of charges by the airspace users, the agent calculates its net result of the time step, which will update its financial accounts. The process is shown in Figure 9. The costs are broken down into labour costs, operational costs, depreciation costs, cost of capital and exceptional items.

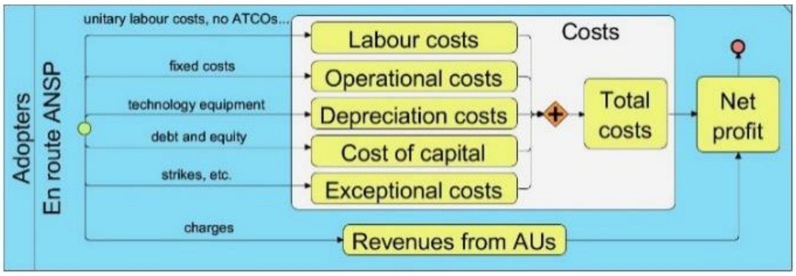


Figure 9: En-route ANSP result of the period calculation

3.4 Calibration and validation

The validation of agent-based models implies assessing the extent to which the model, from assumptions to results, is capable of approximating reality. Calibration and validation of the behavioural assumptions of the agent-based model is to be done through a set of participatory simulation experiments involving the direct participation of ATM stakeholders. The experimental plan for the validation of the ITACA model is included in Appendix A. The results will be included in D4.1 Participatory Simulations: Experiment Results.

4 Technical design

4.1 Programming language and libraries

The simulation engine of the ITACA model has been coded in Python 3, an open source, high-level, interpreted, interactive and object-oriented scripting language. It has efficient high-level data structures and a simple but effective approach to object-oriented programming. Python is designed to be an ideal language for scripting and rapid application development in many areas on most platforms.

The Python interpreter and the extensive standard library are freely available in source or binary form for all major platforms from the Python web site, https://www.python.org/, and may be freely distributed. The same site also contains distributions of and pointers to many free third-party Python modules, programs and tools, and additional documentation.

The coding performed in the ITACA project follows PEP 8 style guide for Pyhton code (https://www.python.org/dev/peps/pep-0008).

Apart from the Python standard library, other libraries that add functionalities to the code are required to run the ITACA model. The list of required libraries, recommended version, description and dependencies are included in Table 8.

Table 8: Python third-party libraries included

Library	Version	Description	Dependencies
NumPy	1.21.2	NumPy is a library for the Python programming language, adding support for large, multi-dimensional arrays and matrices, along with a large collection of high-level mathematical functions to operate on these arrays.	-
matplotlib	3.5.1	Matplotlib is a plotting library for the Python programming language and its numerical mathematics extension NumPy. It provides an object-oriented API for embedding plots into applications using general-purpose GUI toolkits.	NumPy 1.11
scikit-learn	1.0.1	Scikit-learn is a free software machine learning library for the Python programming language. It features various classification, regression and clustering algorithms.	NumPy 1.14.6 scipy 1.1.0 joblib 0.11 threadpoolctl 2.0.0 cython 0.28.5
GDAL	3.2.3	Geospatial Data Abstraction Library	-

Library	Version	Description	Dependencies
fiona	1.8.19	Fiona reads and writes geographic data files and thereby helps Python programmers integrate geographic information systems with other computer systems. Fiona contains extension modules that link the Geospatial Data Abstraction Library (GDAL).	GDAL/OGR 1.8
shapely	1.8.0	Shapely is a Python package for set-theoretic analysis and manipulation of planar features using (via Python's ctypes module) functions from the well-known and widely deployed GEOS library.	-
geopandas	0.10.2	GeoPandas is an open-source project to make working with geospatial data in python easier. GeoPandas extends the datatypes used by pandas to allow spatial operations on geometric types. Geometric operations are performed by shapely. Geopandas further depends on fiona for file access and matplotlib for plotting.	NumPy Pandas 0.25 shapely fiona pyproj 2.2.0
dbfread	2.0.7	DBF is a file format used by databases such dBase, Visual FoxPro, and FoxBase+. This library reads DBF files and returns the data as native Python data types for further processing. It is primarily intended for batch jobs and one-off scripts.	-

4.2 Inputs

In addition to the configuration file, there are other input resources required. The input data structure is mainly responsible for the management of the information in relation with the scenarios, the different entities that can be part of the scenarios (airports, airlines, aircraft, etc.) and its characterisation. It is detailed files is as follows:

1. Itaca-prototype
    - 1.1. resoures
        - 1.1.1. config_file.cfg
        - 1.1.2. Input
            - 1.1.2.1. agents
                - 1.1.2.1.1. airline.csv
                - 1.1.2.1.2. airport.csv
                - 1.1.2.1.3. airport_codes.csv
                - 1.1.2.1.4. ansp_enroute.csv
                - 1.1.2.1.5. ansp_terminal.csv
                - 1.1.2.1.6. labour_unions.csv
            - 1.1.2.2. auxiliar_objects
                - 1.1.2.2.1. routes_shape

1.1.2.3. exogenous
  1.1.2.3.1. fuel_price.csv
  1.1.2.3.2. engine_efficiency
    1.1.2.3.2.1. engines.csv
    1.1.2.3.2.2. engine_efficiency.csv
  1.1.2.3.3. passenger_demand
    1.1.2.3.3.1. od_movements
    1.1.2.3.3.2. traffic_demand_annual_growth.csv
  1.1.2.3.4. unitary_labour_cost
    1.1.2.3.4.1. Airline
    1.1.2.3.4.2. Airport
    1.1.2.3.4.3. EnrouteAnsp
    1.1.2.3.4.4. TerminalAnsp
    1.1.2.3.4.5. average_historic_salaries.csv

1.1.2.4. solutions
  1.1.2.4.1. solutions.csv

The required input data for the model to run is stored in a folder within the ITACA prototype module called 'resources'. The values for the inputs mentioned in Section 3.3.1 and initial values for the agents, considered as inputs for the model, are defined in different data files. We will explain the data provided, its format and a description of the sources employed to obtain the data.

4.2.1 Agents

The initial conditions or characteristics of the different agents are stored in files contained in the agents' directory: airlines, airports, en-route ANSPs, terminal ANSPs and labour unions. Each CSV file is organised in columns, so each column is related to a given feature and each row is related to a particular agent.

The following tables explain the characteristics defined in the columns of the files.

Table 9: Airlines' input features

Feature	Description
airline_id	ID identifying the airline represented with the code 'ALNxx', where xx refers to 2 digits (e.g., ALN02).
icao_code	ICAO code of the airline represented: DLH, BAW, IBE, VLG, EIN, KLM, EZY, RYR.
type	Type of airline: 'Legacy' or 'Low-cost'.
load_factor	Airline's average load factor (number between 0 and 1).
investment_strategy	Type of investment strategy, related to its behaviour and the willingness to adopt new technology: conservative, moderate or aggressive.
asset	Company assets at the beginning of the simulation.

Feature	Description
capital	Capital of the company at the beginning of the simulation.
debt	Debt of the company at the beginning of the simulation.

Table 10: Airports' input features

Feature	Description
airport_id	ID identifying the airport represented with its ICAO code.
n_staff	Number of staff employed by the airport operator.
towers	Tower associated with the airport.
flights	Number of annual flights (arrivals + departures).
pax	Number of annual passengers.
pax_per_movement	Number of passengers per aircraft movement (calculated).
pax_per_staff	Number of passengers per employee (calculated).
charge_pax	Average charges per passenger to the airlines (including landing fees).
pax_factor	Operating costs per passenger.
ownership	Ownership: private or public owned.
investment_strategy	Type of investment strategy, related to its behaviour and the willingness to adopt new technology: conservative, moderate or aggressive.
asset	Company assets at the beginning of the simulation.
capital	Capital of the company at the beginning of the simulation.
debt	Debt of the company at the beginning of the simulation.

Table 11: Airport code equivalences

Feature	Description
Airport	Name of the airport.
Country	Country of the airport.
IATA airport code	IATA code of the airport
ICAO airport code	ICAO code of the airport

Table 12: En-route ANSPs' input features

Feature	Description
ansp_id	ID identifying the en-route ANSP represented with the code 'ERAxx', where xx refers to 2 digits (e.g., ERA01).
n_atco	Number of ATCO.
n_other_staff	Number of non-ATCO staff.
accs	ACCs managed by the ANSP.
labour_cost	Operating labour costs of the initial year.
op_cost	Operating costs (excluded labour) of the initial year.
dep_cost	Depreciation costs of the initial year.
ownership	Ownership: private or public owned.
investment_strategy	Type of investment strategy, related to its behaviour and the willingness to adopt new technology: conservative, moderate or aggressive.
atco_productivity	ATCO hour productivity: flight hours controlled per ATCO hour in operations.
country	Country of the ANSP.
airspace_code	Airspace code according to ICAO's airspace segmentation (e.g., LE for continental Spain).
unit_rate	Unit rate defined by the ANSP to charge airlines.
service_units	Service units managed in the initial year.
assets	Company assets at the beginning of the simulation.
capital	Capital of the company at the beginning of the simulation.
debt	Debt of the company at the beginning of the simulation.

Table 13: Terminal ANSPs' input features

Feature	Description
ansp_id	ID identifying the terminal ANSP represented with the code 'TRAxx', where xx refers to 2 digits (e.g., TRA21).
n_atco	Number of ATCO.
n_other_staff	Number of non-ATCO staff.
towers	Towers managed by the terminal ANSP.
labour_cost	Operating labour costs of the initial year.
op_cost	Operating costs (excluded labour) of the initial year.

Feature	Description
dep_cost	Depreciation costs of the initial year.
ownership	Ownership: private or public owned.
country	Country of the ANSP.
airspace_code	Airspace code according to ICAO’s airspace segmentation (e.g., LE for continental Spain).
unit_rate	Unit rate defined by the ANSP to charge airlines.
service_units	Service units managed in the initial year.
assets	Company assets at the beginning of the simulation.
capital	Capital of the company at the beginning of the simulation.
debt	Debt of the company at the beginning of the simulation.

Table 14: Labour unions' input features

Feature	Description
union_id	ID identifying the labour union represented with the code ‘LUxx’, where xx refers to 2 digits (e.g., LU01).
guild	Guild represented: ATCO, pilot, general staff.
strategy	Strategy against abuses to the guild represented: conciliative or aggressive.
dismissal_threshold	Number of people to be dismissed to start strong actions (strike).

4.2.2 Auxiliary objects

The auxiliary objects used by the simulator are the definition of the routes: OD pairs for which it is known the path alternatives (as a shapefile) and characteristics for each alternative such as total distance, distance per ANSP or flight time. They are stored in the following directory: ‘itaca-prototype\resources\input\auxiliar_objects\routes_shape’.

By adding/removing the OD pairs available, the model modifies the airports and ANSPs in the simulation.

4.2.3 Exogenous variables

The exogenous variables are stored in the following directory ‘itaca-prototype\resources\input\exogenous’.

The fuel price only requires one file, stored in the mentioned directory. This file is formed only by 2 columns: year and correspondent fuel price in €/kg. Each row represents the price for the given year.

The engine_efficiency directory stores the characteristics of the engines considered in the file 'engines.csv' and the annual change in engine efficiency per year in 'engine_efficiency.csv'. The latter is similarly structured as the fuel price: one column defines the year and a second column specifies the correspondent percentual annual change in engine efficiency, considering positive values an improvement in efficiency, i.e., a reduction in fuel consumption. Table 15 shows the characteristics that define each engine.

Table 15: Engine features

Feature	Description
Manufacturer	Name of the manufacturer.
Engine	Identifier for the engine.
reference_year	Year of manufacture.
takeoff	Fuel consumption (kg/s) in take-off operation (full power).
climb	Fuel consumption (kg/s) in climb operation (80% power).
cruise	Fuel consumption (kg/s) in cruise operation (50% power).
idle	Fuel consumption (kg/s) in idle operation.

The 'passenger_demand' directory stores the past demand for the different OD pairs and projections for future demand. The historical data is contained in the folder 'od_movements', containing files for historical movements at the airports of each European country involved for a range of years from 2000 to 2019. The demand growth projections are included in the CSV file called 'traffic_demand_annual_growth.csv', for which each row represents the growth in a given European country. It includes the following features in each column:

Table 16: Traffic demand annual growth features

Feature	Description
country	Country of the projection.
country_code	2-letter code of the country.
airspace_code	ICAO airspace code.
Global growth	Most optimistic projection for traffic growth given by EUROCONTROL.
Regulation & Growth	Optimistic projection for traffic growth given by EUROCONTROL.
Happy Localism	Regular projection for traffic growth given by EUROCONTROL.
Fragmenting World	Most pessimistic projection for traffic growth given by EUROCONTROL.

The unitary labour costs are represented for each agent affected in the directory 'unitary_labour_costs'. For each agent except airports, two files are included: one including the costs breakdown of different real airlines and ANSPs and the second one including the breakdown of employees (cabin crew, pilots administrative, etc. for airlines). Airlines staff file also includes an estimation for pilots' unitary labour costs. The file 'average_historic_salaries.csv' include historic average salaries in the different European countries. This data is used to estimate airports' staff labour costs.

4.2.4 Solutions

The list of solutions included in the case studies are stored in a CSV file at the following path: 'itaca-prototype\resources\input\solutions\solutions.csv'.

This file includes per column an entry for each variable affecting the agents listed in Section 3.3.1.2. Each row corresponds to an ATM technology solution.

4.3 Software modules

Each different module forming ITACA's agent-based model, contain a class that performs its particular role in the simulation: to define an agent, an auxiliar object such as an aircraft, to handle the configuration parameters or to orchestrate the sequence of action of the agents. The model is structured in the following modules defined by Python scripts (.py):

1. schdeuler.py
2. itaca_adoption
    - 2.1. agents
        - 2.1.1. labour_union.py
        - 2.1.2. technology_provider.py
        - 2.1.3. adopters
            - 2.1.3.1. adopter.py
            - 2.1.3.2. airline.py
            - 2.1.3.3. airport.py
            - 2.1.3.4. ansp.py
            - 2.1.3.5. ansp_enroute.py
            - 2.1.3.6. ansp_terminal.py
    - 2.2. auxiliar
        - 2.2.1. aircraft.py
        - 2.2.2. flight.py
        - 2.2.3. route.py
        - 2.2.4. technology.py
    - 2.3. configurator
        - 2.3.1. configuration_functions.py
        - 2.3.2. configurator.py
    - 2.4. exceptions
        - 2.4.1. experiment_termination_exception.py
    - 2.5. exogenous_variables
        - 2.5.1. engine_efficiency.py
        - 2.5.2. fuel_price.py

- 2.5.3.passenger_demand.py
- 2.5.4.unitary_labour_costs.py
- 2.6. scenario
  - 2.6.1.scenario.py
- 2.7. simulation
  - 2.7.1.log.py
  - 2.7.2.simulation.py
- 2.8. time_step_status
  - 2.8.1.time_step_status.py
- 2.9. utils
  - 2.9.1.auxiliar_functions.py

The Configurator module reads the configurator file and translates the configuration data into a dictionary, which is easily handled by the other modules.

As described in Section 4.2.3, the exogenous variables are defined by some inputs data (CSV files). That data is stored in dictionaries for the different years of simulation by the exogenous_variables modules: engine_efficiency.py, fuel_price.py, passenger_demand.py and unitary_labour_costs.py.

In the scenario.py file it is contained the Scenario object, which creates and stores the exogenous variables by calling the previously mentioned modules, creates the list of agents and their characteristics to be simulated and creates the dictionary of technological solutions available to be adopted in the simulation. The Scenario object is initialised with the routes object, including all the routes to be simulated, and some general parameters included in the configuration file.

The script time_step_status.py contains the TimeStepStatus object, which is basically an object that stores information of the simulation at each time step so it can be used by the different agents and functions of the simulator.

The Simulation object, contained in the file simulation.py, initialises the experiment, executes the time step evolution and saves the results.

The initialisation of the experiment consists in creating the agent objects as defined in the scenario, creating the exogenous variables objects defined in the configuration file, the time step status object and the initial set of flights. The flights are generated per route attending to route's demand: the number of flights created to fly a route is equal to the average demand for the route in a day divided by the average number of passengers per flight. Aircrafts are created, randomly assigned to an airline and assigned to the maximum number of flights for an aircraft per day.

During the execution of the time step evolution, the agents perform their tasks as described in Section 3.3.4. Given the commonalities between adopters, the ANSP, airline and airport agents inherit from the adopter agent. In the same line, en-route and terminal ANSPs inherit from the ANSP agent. The functions that perform each agent are described below:

- The technology provider agent possesses a function to release the technologies to the adopters when they are ready.
- The labour unions have a function to check if their expectations have been met and another one to react in case they are not met.

- The adopter agent performs the activities that are common to all the adopters: the feasibility analysis process.
- The en-route ANSP agents recalculate the annual unit rate following the cost recovery system. To do so, the agents project the expected service units for the next period, adjust the number of ATCOs (based on their hour-productivity), project the expected costs and, based on the projected costs, determine the unit rate.
- The terminal ANSP agents perform similar operations but according to the charging functions of terminal ATC and their own goals.
- The airport agent estimates the expected number of passengers for the next period considering a set of airport charges. Based on those estimations, the airport agent makes staff decisions (hire or dismiss), changing the final profit outcome. The charge selected from the set analysed is the one that optimises the profit of the airport.
- The airline agents reallocate flights based on the expected demand of the routes and the costs of flying that route. Given the new fuel prices and unit rates, airfares are modified in order to maintain a certain margin of benefices. The change in prices is used to determine the real demand, including price-demand elasticity effects. The real demand is used to reallocate the flights (add if possible and delete if there is an excess in the offer). Based on the number of aircrafts, the agents adjust the number of employees of each class required.

Some auxiliary objects are required by the agents to perform their operations:

- The aircraft object represents a single aircraft. It has assigned a model, a manufacture year, an engine model, consumption rates based on the manufacture year, seat capacity and number of required cabin crew. Each aircraft is linked to the airline that owns it and the flights that it performs each day.
- The flight object represents a single flight. It has associated an aircraft, airline, route, time and distance. The flight object calculates its own costs (fuel, navigational charges, airport fees) and airfare, information that is used by the airline agent.
- The route object includes the different alternatives for an OD pair route and information such as distance per ANSP and travel time for each alternative.
- The technology object stores the features of a given technology listed in Section 3.3.1.2.

After each time step, the results are logged with the functions of the Log object, which writes into TXT files the desired variables from the time_step_status.

The 'main' module of this ABM simulator is called Scheduler. It orchestrates the execution of the modules previously mentioned. The process is the following:

1. To create a configuration object by calling the Configurator module.
2. To create the output files.
3. To calculate the steps of the simulation and setup the routes.
4. To load the Scenario, using the variables stored in the configuration dictionary
5. To create the experiments, formed by Simulation objects initialised with the scenario
6. To execute each experiment

Other modules provide additional functionalities, such as the experiment_termination_exception module, to handle exceptions (errors) during execution, and the auxiliar_functions module, which contains functions to translate ICAO to IATA airport codes or to create a dictionary from a CSV file.

4.4 Outputs

The logging functions included to the model save the configuration file used for the experiments, files defining the shape of the charging zones, files storing the shape of the routes and different TXT files which store agents' inputs, the exogenous variables, the number of experiments and periods for each experiment and results at each time step for the agents involved in the simulation. All the TXT files included follow a CSV syntax, storing the data in lines and separating the pieces of data with semicolons (;).

The structure of the outputs is as follows:

1. output
    - 1.1. acc
    - 1.2. routes
    - 1.3. exogenous
        - 1.3.1. unitary_labour_cost
            - 1.3.1.1. airline.txt
            - 1.3.1.2. airport.txt
            - 1.3.1.3. enroute_ansp.txt
            - 1.3.1.4. terminal_ansp.txt
        - 1.3.2. demand.txt
        - 1.3.3. engine_efficiency.txt
        - 1.3.4. fuel_price.txt
    - 1.4. inputs
    - 1.5. time_step_results
        - 1.5.1. Airlines.txt
        - 1.5.2. Airports.txt
        - 1.5.3. Enroute_ANSP.txt
        - 1.5.4. Terminal_ANSP.txt
        - 1.5.5. route_choice.txt
    - 1.6. config_file.txt
    - 1.7. experiments.txt
    - 1.8. periods.txt

The directories 'acc' and 'routes' include the shapefiles defining the charging zones of the ANSPs and the pairwise route options between airports.

In the 'exogenous' folder, the files defining the exogenous variables at each time step are logged.

The inputs mentioned in Section 4.2 and the configuration file are copied into the output folder for traceability.

The files 'experiments.txt' and 'periods.txt' record the number of experiments and number of periods and years simulated respectively.

The intermediate results of the simulation are stored in the 'time_step_results' folder. There is one file per adopter agent and another one to track the routes chosen by the airlines, affected by the demand and prices. The variables are structured in columns in the different files. The following tables show the features saved in each file.

Table 17: Airlines' time step result features

Feature	Description
experiment_id	Number of the experiment.
step	Number of the simulation time step.
year	Year in the simulation.
airline_id	Identifier for the airline.
icao_code	Airline ICAO code.
type	Type of airline: legacy vs LCC.
n_pilot	Number of pilots in the airline.
n_other_staff	Number of staff excluding pilots in the airline.
n_routes	Number of routes where the airline flies.
n_aircrafts	Number of aircrafts used for operations.
n_flights	Number of flights per day flown by the airline.
airfare	Average airfare of the airline.
load_factor	Average load factor of the airline.
labour_cost	Total labour costs of the time step.
op_cost	Total operating costs, except labour, of the time step.
cost	Total costs of the time step.
op_revenue	Total operating revenue of the time step.
profit	Profit of the time step.
equipment	Technology equipped.

Table 18: Airports' time step result features

Feature	Description
experiment_id	Number of the experiment.
time_step	Number of the simulation time step.
year	Year in the simulation.
airport_id	Identifier for the airport.

Feature	Description
country	Country where the airport is located.
ownership	Ownership: private or public owned.
n_staff	Number of staff employed by the airport operator.
pax	Number of annual passengers.
pax_per_staff	Number of passengers per employee (calculated).
projected_pax	Projected number of passengers in the next period.
charge_pax	Average charges per passenger to the airlines (including landing fees).
towers	Tower associated with the airport.
labour_cost	Total labour costs of the time step.
op_cost	Total operating costs, except labour, of the time step.
cost	Total costs of the time step.
aero_revenue	Aeronautical revenue of the time step.
non_aero_revenue	Non aeronautical revenue of the time step.
revenue	Total operating revenue of the time step.
profit	Profit of the time step.
equipment	Technology equipped.

Table 19: En-route ANSPs' time step results features

Feature	Description
experiment_id	Number of the experiment.
step	Number of the simulation time step.
year	Year in the simulation.
ansp_id	Identifier for the ANSP.
airspace_id	ICAO airspace code.
accs	ACCs managed by the ANSP.
n_atco	Number of ATCOs employed.
unit_rate	Unit rate at the corresponding year.
service_units	Service units for the period.
labour_cost	Total labour costs of the time step.
op_cost	Total operating costs, except labour, of the time step.
total_cost	Total costs of the time step.

Feature	Description
operational_revenue	Total operating revenue of the time step.
profit	Profit of the time step.
equipment	Technology equipped.

Table 20: Terminal ANSPs' time step result features

Feature	Description
experiment_id	Number of the experiment.
step	Number of the simulation time step.
year	Year in the simulation.
ansp_id	Identifier for the ANSP.
towers	Towers managed by the ANSP.
n_atco	Number of ATCOs employed.
unit_rate	Unit rate at the corresponding year.
service_units	Service units for the period.
labour_cost	Total labour costs of the time step.
op_cost	Total operating costs, except labour, of the time step.
total_cost	Total costs of the time step.
operational_revenue	Total operating revenue of the time step.
profit	Profit of the time step.
equipment	Technology equipped.

Table 21: Route choice time step results

Feature	Description
experiment_id	Number of the experiment.
step	Number of the simulation time step.
year	Year in the simulation.
od_pair	Origin-destination pair of the route.
route_id	Identifier for the route.
origin	Origin airport ICAO code.
destination	Destination airport ICAO code.
alternative	Route path alternative.

Feature	Description
distance	Total distance of the path.
flights_day	Number of flights per day in the route.
cost	Cost of flying the route for the airlines, including labour.
charge_cost	Costs related to navigational charges.
fuel_cost	Cost of fuel.
op_cost	Total operating cost, excluding labour.
charge/total_cost	Percentage of cost due to navigational charges.

5 Operational manuals

5.1 Deployment manual

The aim of this manual is to provide a guide describing the installation process of the components of the simulation platform.

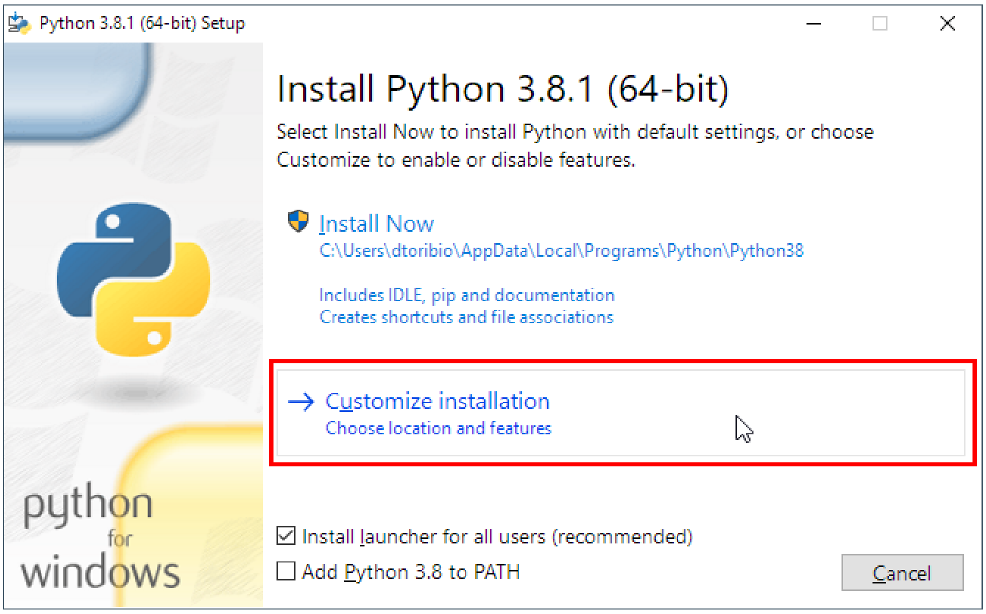
The installation process in intended to be supported by a Windows 10 OS running in a computer with a 64-bit architecture, which is the most usual one for desktop and laptop computers at this moment. Other OS (macOS, Linux) will follow a different installation process. Please refer to the developers' pages of the following language and required packages to successfully complete the installation process.

5.1.1 Python 3 installation

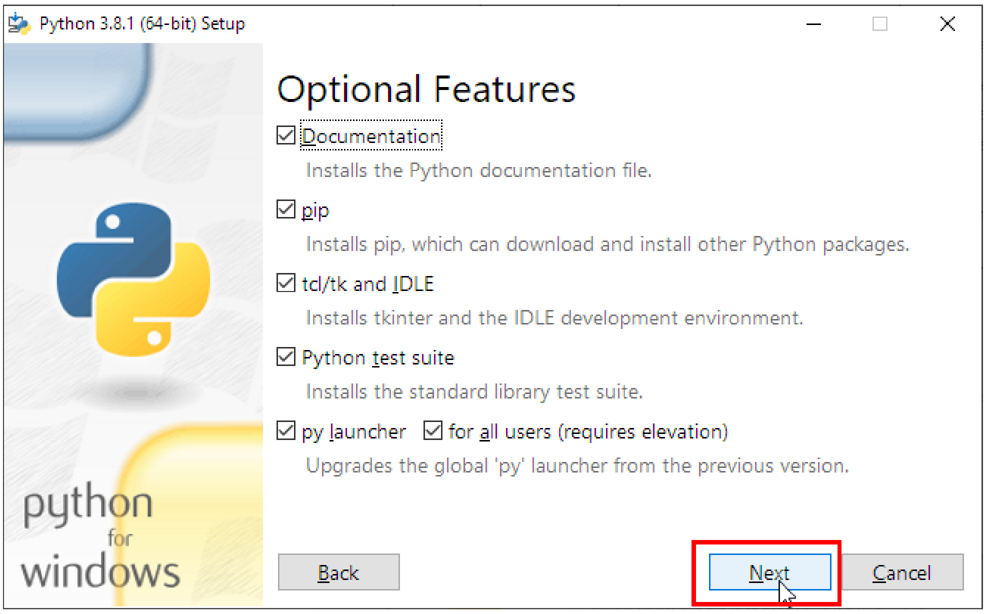
First of all, we must install Python 3. We will install a 3.8.1 Python for 64-bit architectures.

To do so, first download the installation executable from the developers' webpage (https://www.python.org/ftp/python/3.8.1/python-3.8.1-amd64.exe). We suggested to install the version used for the development of the model, but later Python 3 versions can be found in the following link: https://www.python.org/downloads/ .

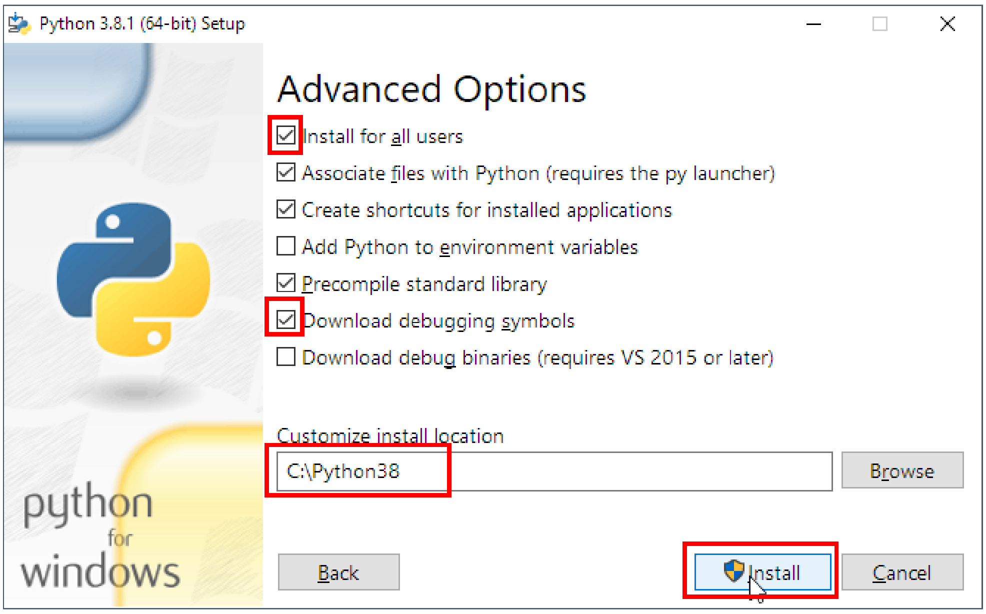
Open the executable file and click in "Customize installation".



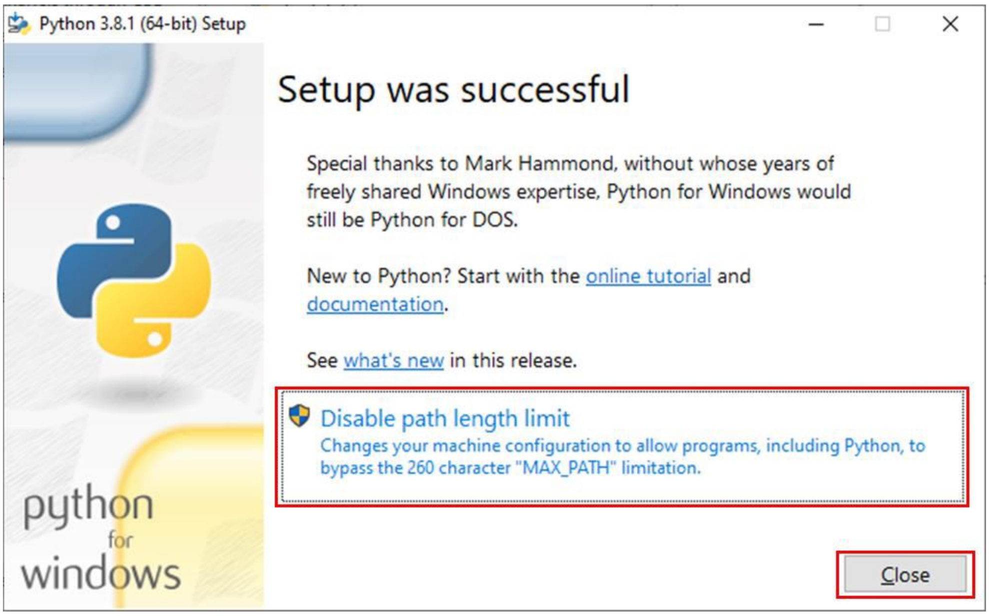
Click on the "Next" button.



Select "Install for all users" and "Download debugging symbols". Change the path to "C:\Python38". Click "Install".



Click in the “Disable path length limit” option and close.



Some System variables need to be defined in order for the OS, some of the plugins and Eclipse to work properly. System variables can be created, edited and deleted in the control panel. The system might need to be rebooted for the changes to take effect.

We have to edit the system variable ‘PATH’. To do so, we should go to the System section of the Windows control panel and click on the “System advanced configuration” option. This will take us to the System Properties page. If we click on the “Environment Variables” button, a window will pop up showing the environment variables: user variables and system variables.

By clicking on the system variable called ‘PATH’, we will see the directories contained by the path. We must add 2 values to the ‘PATH’ variable: the directory of the Python installations (C:\Python38) and the Scripts directory (C:\Python38\Scripts). Figure 10 shows how the variable should look like.

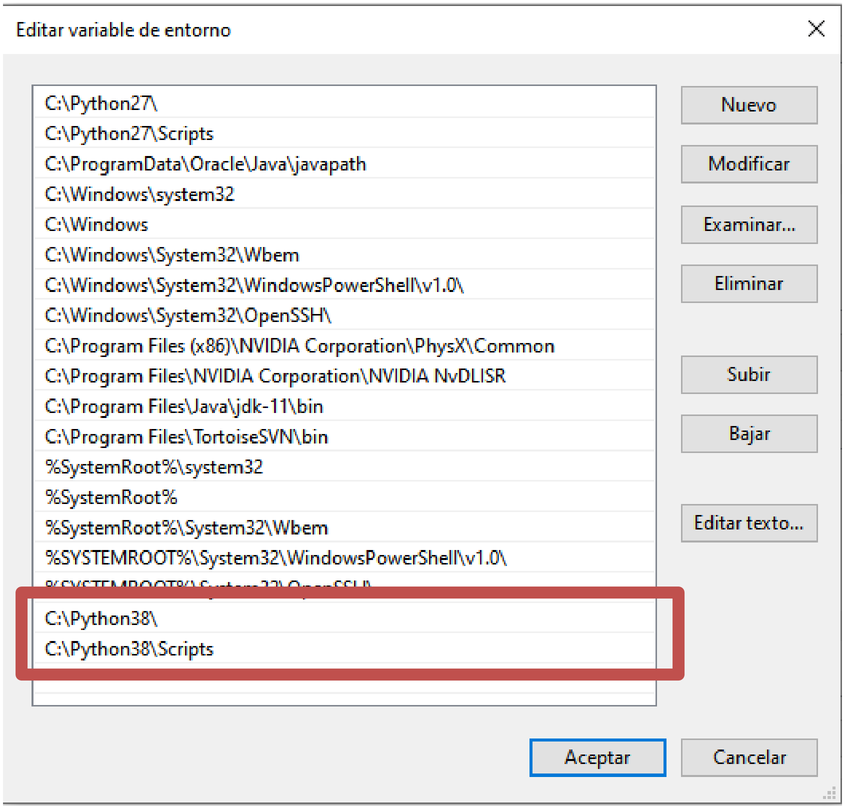


Figure 10: Path variable values after installation

Now, we are going to create a shortcut to run Python 3 in the windows console using the command python3. We have to execute the following command: `mklink /H C:\Python38\python3.exe C:\Python38\python.exe`:

```
PS C:\Users\mbaena> mklink /H C:\Python38\python3.exe C:\Python38\python.exe
Symbolic link created for C:\Python38\python3.exe <<===>> C:\Python38\python.exe
```

Now, we can check that the process is correct by running the following command: `python3 --version`. The output must be as follows:

```
PS C:\Users\mbaena>python3 --version
Python 3.8.1
```

Note: If we had the console open before changing the PATH system variable, we have to close it and open a new console in order to reload the system variables definition.

5.1.2 Installation of the required libraries

Pip is a management software that allows to download and install multiple libraries. We must ensure that pip it is installed for Python 3. The following command must be executed: `python3 -m ensurepip`.

```
PS C:\workspace3\itaca-prototype\trunk> python3 -m ensurepip
Looking in links: c:\Users\mbaena\AppData\Local\Temp\tmpijxvv3tx
Requirement already satisfied: setuptools in c:\python38\lib\site-packages (41.2.0)
Requirement already satisfied: pip in c:\python38\lib\site-packages (21.2.4)
```

Now, we are going to upgrade it to the version used in the development of the ITACA model. We must run the command: `python3 -m pip install pip==21.2.4`

```
PS C:\Users\mbaena> python3 -m pip install pip==21.2.4
Collecting pip==21.2.4
  Using cached
https://files.pythonhosted.org/packages/ca/31/b88ef447d595963c01060998cb329251648acf4a067
721b0452c45527eb8/pip-21.2.4-py3-none-any.whl
Installing collected packages: pip
  Found existing installation: pip 19.3.1
    Uninstalling pip-19.3.1:
      Successfully uninstalled pip-19.3.1
Successfully installed pip-21.2.4
```

Employing the pip command, we are able to install the required packages. We should run the following commands in the Windows PowerShell in the presented order:

1. `python3 -m pip install numpy==1.21.2`
2. `python3 -m pip install matplotlib==3.5.1`
3. `python3 -m pip install scikit-learn==1.0.1`
4. `python3 -m pip install dbfread==2.0.7`
5. `python3 -m pip install shapely==1.8.0`
6. `python3 -m pip install gdal==3.2.3`
7. `python3 -m pip install Fiona==1.8.19`
8. `python3 -m pip install geopandas==0.10.2`

In case that no errors occur during the installation of any of the packages, the process is finished.

5.1.3 Model software modules

The ITACA model prototype folder has to be stored locally in the computer where Python and the required modules have been installed. Note the path to this folder in your computer; some variables need to be changed in the configuration file.

5.1.4 Troubleshooting

The installation of *Fiona* with pip presents issues in some cases. In that case, we should download the WHL file of the *Fiona* package. Paste https://www.lfd.uci.edu/~gohlke/pythonlibs/#fiona in your web browser and download the file named 'Fiona-1.8.19-cp38-cp38-win_amd64.whl'. To install it, use the following command: python3 -m pip install <path to the downloaded WHL file>. Your command prompt should look like:

```
PS C:\workspace3\itaca-prototype> python3 -m pip install C:\Users\mbaena\Downloads\Fiona-
1.8.19-cp38-cp38-win_amd64.whl
Processing c:\users\mbaena\downloads\fiona-1.8.19-cp38-cp38-win_amd64.whl
Collecting attrs>=17
  Using cached attrs-21.2.0-py2.py3-none-any.whl (53 kB)
  Using cached click-7.1.2-py2.py3-none-any.whl (82 kB)
Installing collected packages: click, attrs, Fiona
  Attempting uninstall: click
    Found existing installation: click 8.0.1
    Uninstalling click-8.0.1:
      Successfully uninstalled click-8.0.1
Successfully installed Fiona-1.8.19 attrs-21.2.0 click-7.1.2
```

Once *Fiona* is correctly installed, we have to install *geopandas* with the *pip* command. You should see the following message in your command prompt:

```
PS C:\workspace3\itaca-prototype> python3 -m pip install geopandas
Collecting geopandas
  Using cached geopandas-0.10.2-py2.py3-none-any.whl (1.0 MB)
Installing collected packages: geopandas
Successfully installed geopandas-0.10.2
```

5.2 User manual

The ITACA project provides a simulation platform that enables the benchmarking of policy measures aimed at incentivising the adoption of ATM technologies. The interface between the user and the application is through the execution of Python modules with a command-line shell. The modules have been designed for Windows platforms, so it is recommended to use Windows default command-line interpreter (cmd.exe) or PowerShell.

The experiment to be executed is defined by the configuration file, which acts as initialisation file for the program. This file defines the scenario that the simulator will run by providing some initial conditions to the model. After executing the experiment, the output files defined in Section 4.4 are obtained.

In this section we will explain how to modify the configuration file, how to execute a scenario and how to interpretate the results obtained.

5.2.1 Configuration

The configuration file is divided into two sections: general inputs for the model and agents' initialisation files. The former includes the inputs described in Section 4.2, temporal attributes, economic parameters, the number of simulations and output folder path. The later defines the paths to the files that define the number of initial agents and its parameters and initial parameters for other auxiliar objects such as routes or aircrafts.

An example of the general attributes of the simulation in the configuration file can be seen below:

```
[temporal_attributes]
year_0 = 2017
temporal_horizon = 2022
time_step_duration = 6

[economic_attributes]
price_demand_elasticity = -1.4
annual_salary_change = 1.1

[technology]
case_study = CS02
technologies_path = resources\input\solutions\solutions.csv

[policy]
active_policies =

[exogenous]
passenger_demand = resources\input\exogenous\passenger_demand
fuel_prices = resources\input\exogenous\fuel_price.csv
engine_efficiency = resources\input\exogenous\engine_efficiency
unitary_labour_cost = resources\input\exogenous\unitary_labour_cost

[other]
dismissal_cost_factor = 3
hiring_cost_factor = 2
avg_pax_flight = 144

[simulation]
total_simulations = 1

[output]
output_dir = C:\ITACA
```

The sections defining the general attributes are:

- [temporal_attributes]

  `year_0` - Initial year of the simulation

  `temporal_horizon` - Final year of the simulation

  `time_step_duration` - Duration of each time step in the simulation. It is measured in months and may have only the values 1, 2, 3, 4, 6 or 12. The default value is 6.

- [economic_attributes]

  `price_demand_elasticity` – Elasticity of the demand with respect to the ticket fare. It should be negative in the range [-2, 0]. The default value is -1.4.

  `annual_salary_change` – Annual percentual change in salaries. The default value is 1.1%.

- [technology]

  `case_study` – Case study to be simulated. The case studies will be defined in D5.1 Policy assessment.

  `technology_path` – Path to the file which includes the technologies to be simulated in each case study with their characteristics.

- [policy]

  `active_policies` – Name of the policies that will be tested in the execution: “Flexible charging”, “Best equipped”, “Demonstration”, “SA involvement” or “Subsidies”.

- [exogenous]

  `passenger_demand` – Path to the directory containing the files related to passenger demand (historical for each route and projections).

  `fuel_prices` - Path to the file containing the fuel prices (historical for each route and projections).

  `engine_efficiency` - Path to the directory containing the files related to engine efficiency (historical for each route and projections).

  `unitary_labour_cost` - Path to the directory containing the files related to unitary labour costs per year.

- [other]

  `dismissal_cost_factor` – This factor represents the increased cost of a dismissal. This factor multiplies the monthly average unitary labour cost. The default value is 3.

  `hiring_cost_factor` - This factor represents the increased cost of a hiring a new employee. This factor multiplies the monthly average unitary labour cost. The default value is 2.

  `avg_pax_flight` – Represents the estimated average number of passengers per flight, used for passenger demand estimation. The default value is set to 144, equal to an 80% load factor for an A320 in maximum capacity configuration (180 passengers).

- [simulation]

  `total_simulations` – Number of simulations to execute.

- [output]

  `output_dir` – Path to the directory that stores the output files.

The sections and paths to agents' initial parameters are shown below:

```
[ansp_enroute]
ansp_enroute_path = resources\input\agents\ansp_enroute.csv

[ansp_terminal]
ansp_terminal_path = resources\input\agents\ansp_terminal.csv

[airports]
airports_path = resources\input\agents\airport.csv

[airlines]
airlines_path = resources\input\agents\airline.csv

[labour_unions]
labour_unions_path = resources\input\agents\labour_unions.csv

[accs]
acc_shape_path =resources\input\auxiliar_objects\ACC_shape\compair_data\ChargingZones.shp

[towers]
towers_path = resources\input\auxiliar_objects\control_tower.csv

[routes]
route_shape_path = resources\input\auxiliar_objects\routes_shape\clusters

[aircraft]
aircraft_path = resources\input\auxiliar_objects\aircraft.csv
```

It is recommended not to change those sections. In case that some initial conditions would like to be modified, the file of the agent in question should be edited. It is possible to add or delete airlines, but the list of ANSPs and airports should not be modified because they are defined according to existing ones, related to the routes included in the model. The attributes of any agent can be modified, keeping in mind that large deviations may lead to unexpected behaviour.

5.2.2 Experiment

As explained before, the scheduler.py module is the main module of the model. It should be run, specifying the configuration file to be executed in the following form:

1. Open a PowerShell console. Press Windows+R to open the Run dialog box, then type "powershell" in the text box and press the Enter.
2. Use the command `cd <path to the itaca model directory>`.

   The console should show: `PS C:\"your_path"\itaca-prototype>`
3. To run the experiment previously defined in the configuration file, type the command `python3 .\scheduler.py .\resources\config_file.cfg`
4. The intermediate messages will be shown in the command line and the outputs, stored in the path specified in the configuration file with the label correspondent.

In some cases, it is useful to automatise the obtention of results from several scenarios, which are defined by different combinations of the parameters included in the configuration file. In that case, it is possible to create several configuration files, defining each scenario, save them in a local folder and create a batch file that runs the model with each one of the configuration files one after the other.

The following example shows a batch file that runs 2 different scenarios:

```
ECHO Batch file to execute the following scenarios: CS02 sc1, CS02 sc2
cd C:\workspace3\itaca-prototype\trunk\
timeout 5
python3 .\scheduler.py .\resources\batch\CS02\config_file_sc1.cfg
timeout 5
python3 .\scheduler.py .\resources\batch\CS02\config_file_sc2.cfg
pause
```

5.2.3 Results

For explanation on the structure and content of the result files, refer to Section 4.4. As explained, the files are structured in a CSV format. One can use a spreadsheet software to handle the results easily. We recommend using Microsoft Excel, which allows for further post-processing of the data such as creation of graphics.

To load an output file in Excel, you only have to import it with the 'Data' tab, selecting the option 'From Text/CSV' (see Figure 11). A new window will prompt up, make sure that the delimiter is set as 'semicolon' and select 'Load'.

The data is loaded as a table, the values of each column can be sorted or filtered, for example to see the evolution of one agent in particular.

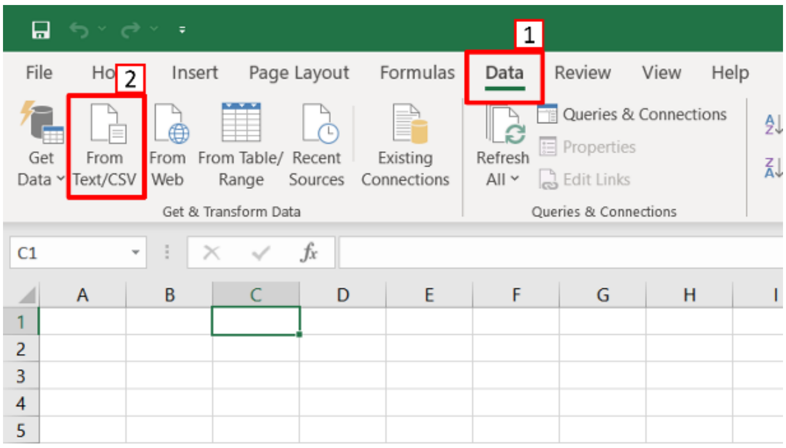


Figure 11: Excel data import

6 Future evolutions

Finding the right level of abstraction and identifying the correct actors for complex agent-based simulations are difficult tasks. The ITACA simulation model has room for improvement in both aspects.

The agents simulated were selected taking into account their importance in the deployment and adoption of technologies. While all the technology adopters have been represented, other regulatory actors such as the Safety Agencies have been emulated in a rather simplistic way due to the intrinsic complexity of their decisions. Their behaviour and internal mechanisms should be known better in order to replicate them in a simulation model. The inclusion of this actor and its relationship with technology providers and adopters would improve the benchmarking of the policy measures tested.

The assumptions and simplifications made to model the agents selected and the environment that represent the real system are necessary to enhance the importance of the mechanisms involved in technology adoption and obtain explanatory results. However, simplifications always entail trade-offs.

In our model, we have focused on the deployment phase of the adoption, leaving the research phase as an aspect external. While this may be true for airlines and airports, ANSPs are strongly involved in several R&D activities: SESAR projects and research and develop partnerships with technology providers, usually to develop technologies specific to their own operational case. The inclusion of detailed mechanisms of collaboration between adopters and technology providers in the R&D phase would enhance the realism of the simulation and would open the door to the benchmarking of policies that incentivise this collaboration.

Another simplification is the rather selfish goals of the adopter agents. The model assumes that the agents' decision of technology adoption seeks the achievement of their individual goals, resulting in investments aiming at their own economic benefit only. Although this statement is true a priori, especially when talking about private organisations operating in a highly competitive environment, the willingness to maximise the global outcome has been neglected. Environmentally friendly actions or network level improvements are examples in which organisations may look for the optimal choice in terms of their own economic benefit. Future evolutions of the model should include a mechanism to emulate this kind of altruist bias in agents' decision-making.

Finally, due to the flexibility of agent-based models, new potential policies as well as additional indicators may be included in future versions of the simulator.

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Appendix A Experimental plan for the validation of the ITACA simulation model

A.1 Overview

The ITACA project aims to shed light on the factors and the drivers and barriers for the adoption of new technologies in ATM, with the goal of supporting the identification, formulation and implementation of policies and regulations that accelerate ATM modernisation. An initial qualitative and quantitative study of the levels and barriers for ATM technology uptake has been performed. The result of this assessment is a list of policy measures which should be implementable in a relatively short time frame. These will then be further assessed within the ITACA project using an agent-based model.

Validation activities are to be performed at two levels:

1. ITACA ABM validation, which aims at verifying the assessment tool that will be created during the project. The related validation activities consist in participatory experiments that will be performed in WP4. This draft focuses on the planning of these activities.
2. Policy measures and recommendations validation, aiming at validating the conceptual policies to accelerate technology adoption through extensive simulations employing the ITACA ABM assessment framework. These tasks are included in WP5. The planning of policy validation activities will be included in a next update of this document.

The validation of agent-based models implies assessing the extent to which the model, from assumptions to results, is capable of approximating reality. To this end, different methods have been proposed, but yet no widely accepted procedure has emerged (Le Pira et al., 2017). Gaming methods have been suggested as a way of validating agent-based models, but relatively little work has been done on actually implementing a useful combination in a rigorous way. In the social simulation community, there have been attempts to validate agent-based models with games, and in the behavioural economics field the use of game-like experiments and parallel ABM is also well noted.

The combination of an explicitly modelled set of technological policy options into an agent-based model and a participatory game that are based on the same conceptual structure, and thus comparable with each other, is a relevant methodological contribution of the project. This contribution is perfectly linked with the objectives of the project, envisioning a detailed validation of the simulation model in WP4.

A.2 Methodology

The ITACA simulation model will provide quantitative results (e.g., stakeholders surplus, terminal ANS costs, etc.) while further analysis of those simulation outputs will produce qualitative results (policy assessment). The validation activities described here target the first ones.

Behavioural assumptions and decision-making parameters will be validated through series of gaming experiments that involve real ATM stakeholders. There exist three main methods to calibrate and validate agent-based models against participatory simulations and games: (i) the comparison of the outcomes of the agent-based simulations at the aggregated level against similar set up participatory simulations; (ii) the comparison of the state-changes of individual stakeholder behaviour in the participatory simulation versus that of the similar agents; and (iii) human-in-the-loop simulations, where the role of some individual agent is taken by humans, so that the software agents can then learn the behavioural patterns of the human, for instance through machine learning. Within ITACA we will adopt the first two methods. The approach based on the comparison of outputs at the aggregated level will be used to evaluate which parameter configurations of the agent-based model match the outcomes of the participatory simulation. The calibration process will consist in adjusting inputs to match the valid (human-observed) outputs. The proposed approach is described in detail by Tykhonov et al. (2008) and Barreteau et al. (2010). The comparison of the individual state-changes of the stakeholders that participate in the behavioural experiments versus those of the corresponding agents will be used to analyse the sensitivity of stakeholders' behaviour to different policy proposals, following the approach described by Meijer (2012) and by Anand et al. (2016).

For further details on the planning, methodology and outcomes of the model validation activities, we encourage the reader to read D4.1 Participatory Simulations: Experiment Results.

The model considered several performance areas when defining their outputs and Key Performance Indicators (KPI), which are based on SES, ICAO and SESAR Key Performance Areas (KPA) and indicators. Additional economic KPAs and KPIs have been added in order to eventually assess the overall social welfare, surplus and distributional effects of the different policies tested by the model.

The ABM validation activities will compare the outcomes within said KPAs obtained by both model and ATM experts in the participatory experiments. Additional validation of the correct selection of KPIs might be included in the study.

A.3 Validation approach

A.3.1 ITACA ABM validation

The validation activities of the ABM model include two phases: a first phase that analyses the general assumptions of the model and a second phase that validates the parameters of the modelling driving the decision-making behaviour.

Model and validation assumptions

For a correct assessment, gaming experiments should be based on the same hypotheses and assumptions considered for the ABM. Those hypotheses are listed in D3.1 ITACA simulation model. For the sake of clarity, we will list them here, despite incurring in duplicities:

- Stakeholders involved:
    - ATM ecosystem is a worldwide structure formed by many different types of actors. On the operational side we may think about stakeholders such as Air Navigation Service Providers (ANSPs) for en-route and terminal phases, the Network Manager (e.g., EUROCONTROL in Europe), airports or airlines and remaining Airspace Users (AUs). ATC tasks require specific equipment, designed and developed by technology providers and aircraft manufacturers. Universities and research centres also collaborate in Research & Development of said technologies. In addition, many of the stakeholders mentioned are linked to labour unions representing some of the professional groups involved (e.g., Air Traffic Controller Operators labour union). Finally, above all of them we can find the regulatory bodies, including certification authorities, safety agencies and national

governments. We are going to focus on the following groups, classified attending to their role in the technology adoption process:

- Adopters: ANSPs, Airports, Airlines, Network Manager*. Main Role and Objective: Achieve an optimum result in their operational tasks. New technology is for them an enabler to achieve this goal. Decisions: Technology adoption. Agents they interact with: All.
- Technology providers: Technology providers (ground/airborne, including aircraft manufacturers). Main Role and Objective: Provide a set of ATM technologies to the adopters. Decisions: Set market prices. Agents they interact with: Adopters.
- Regulators: Policy Makers, Safety Agencies, Network Manager*. Main Role and Objective: Monitor and execute the applicable policies in order to ensure the global welfare. Decisions: Decisions derived from the policy in case and its compliance by the adopters. Agents they interact with: Adopters.
- Labour unions: Labour unions. Main Role and Objective: Lobby adopters in order to defend the labour conditions of their guild. Decisions: Obstruct or support a deployment. Agents they interact with: Adopters.

  - We focus on civil aviation, neglecting the adoption of technology made by the military.

- Dependencies on other sectors/industries:
  - Major disruptions in aircraft design are not considered. Evolution in fuel efficiency is taken into account, using forecasts from the major aircraft and engine manufacturers.
  - Trends in aircraft type preferences are not modelled (e.g., narrow-body vs wide-body aircraft in short haul flights).
  - We consider competence with other existing and new transport modes (e.g., rail, hyperloop) to be out of the scope of this study.
- The so-called exogenous variables are variables that affect the state of the agents in the simulation, are imposed on the model and whose value is determined outside the model. Some of the variables that we consider suitable to be imposed to the model are the following:
  - Although aviation is an important sector in global economy, ATM is relatively small compared to it. Therefore, we assume that global trends will not be affected due to changes in the ATM industry.
  - Economic indicators such as GDP projections, inflation, fuel price and unitary labour cost (per state) forecasts are not affected by the evolution of the simulation.
  - Socio-demographic indicators, including traffic demand and population growth, are variables exogenous to the model.
  - Technological development and engine efficiency over time is imposed in the simulation. Agents are capable of selecting between the different technologies available.
  - Policies are imposed in each different scenario. One reason is that policy measures always define the rules that every actor must follow. Moreover, selecting by hand the policies to be tested as exogenous variables, what-if tests may be performed.

- The technology adoption process is affected in the model by the following factors:
  - Economic
    - A strong emphasis is placed on Cost-Benefit Analysis of the technologies, including assessment of risks and uncertainties in their future outcomes.
    - Economical perception and decisions are modulated according to Behavioural Economics insights. The inclusion of biases such as loss aversion and hyperbolic discounting increases the realism present in actors' decision-making. The including of said factors are one of the novelties of this work.
  - Technical
    - Features inherent to ATM technologies are also taken into account for deciding whether to implement it or not.
    - Some technical aspects considered are: technology complexity, implementation times or interoperability of the new technologies with legacy ones.
  - Social
    - Expectations and beliefs of labour unions. When their expectations are not met or their particular sector faces redundancies, strikes may be taken in order to oblige stakeholders to change their decisions regarding a given technology.
    - No lobby is considered in the definition or implementation of the policies.
  - Political
    - Regulatory measures and policies affect the aforementioned factors, changing the final outcome of the different stakeholders involved in the simulation.
    - Although political interest plays a role in the process that we are analysing, it is not taken into consideration. The mechanisms underlying this factor are too complicated and subjective to be taken into account. As a result, effects such as protection of national industry and reluctance to adoption of options endangering airspace sovereignty (e.g., multi-national ANSPs) will not be captured.

Nevertheless, additional assumptions may apply for the elaboration of the gaming experiments.

The following type of variables have been identified with relation to the validation of the ABM model:

- Independent: Stakeholders' decisions.
- Dependent: Outputs (e.g., social welfare, ANSP surplus, etc.).
- Control: exogenous variables

1st Phase of the Participatory Experiments

The questionnaire to be used in the participatory experiments is designed specifically for the purposes of the project, to validate ABM assumptions. The majority of the questions are close-ended; the answers are either binary (yes or no and accept or reject), numerical (specifically participants are asked in two occasions to evaluate the risk in percentage of the minimum and maximum risk for a technology to be a success or failure respectively) or participants are asked to sort different solutions based on their probability to be accepted and implemented. In the last part of the questionnaire, as it is explained in more detail below, there is one open-ended question about why participants would change their previous answers based on the answers of other agents. While the format of that last question is open-ended, we expect that the different answers will be limited, in the sense that there will be only but a few reasons why experts would change their answer, e.g. they believe that the other agent is more experienced in this particular subject. Therefore the analysis would be to sort the different answers based on their frequency.

Since the questionnaire is designed specifically for the purposes of this project, it has passed two stages of validation. The first draft passed a face validity by being examined internally at KTH by 3 different experts, which their input further fine-tuned the questionnaire. Finally, the first two interviews with ATM experts, in addition to collect data for the experiment itself, will also be used to pinpoint any discrepancies in the questionnaire and finalize its form. Due to the nature of this research, being able to test the questionnaire with more experts will not be possible. The number of experts in the field and the subset of that experts to whom we have access and are likely to be willing to participate in the project is quite limited. Given the restrictions with regards to the number of potential participants and the fact that they are well established experts in their field, we determined that 2 experts, in addition to the face validation, would be enough to fine-tune and validate the questionnaire.

The participants, as already mentioned, will be ATM experts from ITACA's Advisory Board, participating individually in the experiment. In the beginning of the interview, participants are informed about the assumptions based on which the behavioural experiment is built. Then, in the remaining of the interview, they fill out a questionnaire, which consists of 4 parts as follows:

1. Four different technology proposals are introduced, indicating expected costs and benefits for each of them. Two of the proposals concern technologies that have been introduced in the past in ATM, whereas two concern technologies that have future potentials.
2. Participants identify themselves with regards to their expertise, so a connection with the agents (airport, airline, ANSP or Network Manager) in the model can be made. Then, the main part of the interview takes place, in which participants answer questions related to the technologies presented earlier, i.e. accept or reject, and questions related to the behavioural aspects of the model.
3. Participants, under the role of the stakeholder they represent, are asked to rank the technology proposals based on their likelihood to be accepted by the other agents. The objective of this part of the interview is to check the perspective that agents have about the rest of the agents, and if the assumptions that have been considered about them match the vision that the people involved in ATM have.
4. In the last part of the questionnaire, participants are asked whether they would change their answer knowing the answers of the rest of the agents. The objective of this part of the interview is to assess what do they think regarding the decisions-making process of the rest of stakeholders and how their behaviour would affect their own decision-making process.

The results of the questionnaire are analysed as follows:

- Categorical: Answers like yes or no and accept or reject will be converted in frequencies, e.g. 80% yes and 20% no, on which thereafter the t-statistics test will be applied to determine whether statistically significant difference exists.

- Ordinal: In Part 3, where participants are asked to sort the technologies based on their probability to be accepted by the other agents, the ranking of each answer will determine the number which is assigned to it, e.g. 1: Automatic Dependent Surveillance–Broadcast (ADS-B), 2: Unmanned Traffic Management (UTM), 3: Time Based Separation (TBS), 4: Flight Deck Interval Management (FIM). Then, like we would do if we were using the Likert scale, the average will be calculated and again the t-statistics test will be applied to determine whether statistically significant difference exists.
- Numerical: Being the most straightforward ones to calculate, e.g. there is 80% probability that a technology would be beneficial, the t-statistics test will be applied to determine whether statistically significant difference exists.
- Open-ended: As explained above, in the one question that is open-ended, we expect that the different answers will be limited. Therefore, their frequency will be calculated and again the t-statistics test will be applied to determine whether statistically significant difference exists.

2nd Phase of the Participatory Experiments

Experts will participate in a participatory simulation containing ITACA's simulation model output that aims at validating the decision-making process of the agents (stakeholders). Pre-computed data will be stored in a database for several scenarios, which would be the combination of behavioural parameters for the different agents, showing the real output of the model for the decisions they will perform in the experiments.

The participatory simulation would have two modes, a single-player and a multi-player. In the single-player mode, there will be two options to interact with the model:

1. *Playing in the model:* the participant will assume the role of an agent, the agent that corresponds to his or her expertise. The remaining agents will be run by the model itself. The aim of this method is to validate the model in an individual/agent level, by actually having experts playing the role of agents.
2. *Playing with the model:* the participant tweaks the parameters of the model to see how the model reacts. The aim of this method is to validate the model in a system/aggregated level.

In the multi-player mode, only the first method will be implemented, i.e. *playing in the model*. In this case, several participants will assume the role of all or some of agents; in the latter case, the remaining agents will be run by the model itself. The aim of this method is to validate the model in an individual/agent level by giving more emphasis to the relationships among agents, as opposed to the single-player mode. It has not been determined whether the second option, i.e. *playing with the model*, will be implemented. The reason for that is the challenge it poses to have multiple participants tweaking parameters at the same time. While it is technically feasible, it would be very difficult, if possible, to produce results that could be analysed, since in many cases it would not be possible to determine which change produced a certain result.

Intuitively, the multi-player mode should be preferred, since it provides increased insight into the relationships between agents. However, it comes will some disadvantages, due to which a large part of the participatory simulation will be conducted in single-player mode. These disadvantages are:

- The logistical challenges of coordinating 10+ professionals.
- Due to the tight schedule of the participants, at the best-case scenario, two to three sessions will be conducted, each one consisting of 20-30 exercises. It is not a bad outcome but still it is not enough to have concrete conclusions.

- As explained above, multiple participants would produce multiple and simultaneous inputs, which would make the analysis and the determination of correlations and causations cumbersome.
- It is inherently more difficult to build an interface and the mechanics for a multi-player game compared to a single-player one.

A.4 Data and software collection and generation

A.4.1 Purpose of the data collection/generation

The goal of the ITACA data collection activities is to provide access to the data extracted from the interviews, gaming sessions and other feedback during the project, as well as data required for the definition and calibration of the agent-based model. These data will be analysed and combined during the project to extract relevant information about the technology adoption process in the European ATM sector.

The data generated by the project will consist of the data resulting from the analysis and modelling tasks conducted over the data collected. These tasks will allow the project to translate the observed behaviour into relevant indicators and explanatory insights for the adoption of technology in the ATM system.

The collected datasets and the data generated from them that will be stored can be grouped according to the following categories:

- (C1) - Interview data
- (C2) - Behavioural experiments' data
- (C3) - Agent-based model definition and calibration data
- (C4) - Policy assessment data

A.4.2 Features of the collected/generated data

Data is essential for all the project objectives, which are listed here:

- (O1) - The identification of drivers and barriers for technological change in ATM and selection of a set of policy measures, which requires the data obtained from personal interviews and expert consultation as well as the data generated from the economic modelling, which will be numerically illustrated
- (O2) - The development of an agent-based model of the R&I lifecycle, which will incorporate the data required for model definition and calibration
- (O3) - The validation of the model through a set of participatory simulation experiments involving the direct participation of ATM stakeholders, which will require the data extracted from these experiments
- (O4) - The provision of a set of policy assessments, which will be based on the data generated by the model.

The following table summarises datasets identified at the moment of the elaboration of this document that are foreseen to be collected or generated in relation with the elaboration of ITACA's ABM (C3) and its validation activities(C2).

Dataset	Description	Category	Collected / Generated	Origin	Format	Expected Size	Used by	Openly available
Raw data from behavioural experiments	The insights from role-playing games (e.g., written answers) conducted in WP4 will be gathered in different formats for further analysis. Expected to contribute to objective O3.	C2	Collected	ITACA Advisory Board	Excel, PDF	5 MB / person	KTH	No, due to GDPR rules. Aggregated and anonymised results will be included in deliverable D4.1 ensuring ethics requirements.
Recordings of behavioural experiments	The role-playing games conducted in WP4 will be recorded for further analysis. Expected to contribute to objective O3.	C2	Collected	ITACA Advisory Board	MP4	500 MB / person	KTH	No, due to GDPR rules. Aggregated and anonymised results will be included in deliverable D4.1 ensuring ethics requirements.
Processed data from behavioural experiments’	T4.2 and T4.3 will conduct behavioural experiments in order to obtain data comparable with the outputs of the agent-based model. This data will be used to support the calibration and validation of the agent-based model. The results are basically the processed data obtained from the two previous datasets. Expected to contribute to objectives O2 and O3.	C2	Generated	ITACA Advisory Board	Excel/ PDF/ Word/ PowerPoint	20 MB / person	KTH and Nommon	Yes, ensuring ethics requirements
EUROCONTROL ACE reports	ATM Cost-Effectiveness (ACE) reports of the different ANSPs within the EUROCONTROL area. Expected to contribute to objectives O1 and O2.	C3	Collected	EUROCONTROL	PDF	6 MB / year	Nommon and TML	Yes, available at EUROCONTROL website

Dataset	Description	Category	Collected / Generated	Origin	Format	Expected Size	Used by	Openly available
ICAO Aircraft Engine Emissions Databank	The ICAO Aircraft Engine Emissions Databank contains information on exhaust emissions of production aircraft engines. The databank covers engine types which emissions are regulated, namely turbojet and turbofan engines with a static thrust greater than 26.7 kilonewtons. Expected to contribute to objective O2.	C3	Collected	EASA	xlsx	663 kB	Nommon	Yes
Airport charges	Different sources consulted for gathering airport charges data across Europe, including Airlines 4 Europe (2016) Analysis of Airport Charges, AENA price guides or individual airports' table of charges (e.g., Dublin airport). Expected to contribute to objective O2.	C3	Collected	A4E AENA Dublin Airport	pdf	2 MB	Nommon	Yes
Airports' financial data	Airport economic data (e.g., costs and revenues) for different type of airports: private, public and hybrid. Expected to contribute to objective O2.	C3	Collected	ICAO	pdf	2 MB	Nommon	Yes
Airport operations data	Includes traffic, arrival and departure delays, vertical flight efficiency, taxi-out additional time among other airport figures. Expected to contribute to objective O2.	C3	Collected	EUROCONTROL	xlsx	100 MB	Nommon	Yes

Dataset	Description	Category	Collected / Generated	Origin	Format	Expected Size	Used by	Openly available
Terminal ANSP cost efficiency	The dataset contains the costs for the provision of terminal air navigation services, which is related to the following services: airport control services, airport flight information services including air traffic advisory services, and alerting services; air traffic services related to the approach and departure of aircraft within a certain distance of an airport on the basis of operational requirements; an appropriate allocation of all other air navigation services components, reflecting a proportionate attribution between en-route and terminal services. Expected to contribute to objective O2.	C3	Collected	EUROCONTROL	xlsx	67 kB	Nommon	Yes
Terminal ANSP ownership	Different sources review the heterogeneous privatisation process in terminal ATC services suffered in some European countries. Expected to contribute to objective O2.	C3	Collected	CNMC CAA ATM Policy	pdf	10 MB	Nommon	Yes

Dataset	Description	Category	Collected / Generated	Origin	Format	Expected Size	Used by	Openly available
En-route cost efficiency	Dataset containing the en-route total ANS costs (including ATM/CNS, MET, Payment to regulatory and governmental authorities and EUROCONTROL contribution), service units and unitary costs at country and FAB level. Expected to contribute to objective O2.	C3	Collected	EUROCONTROL	xlsx	66 kB / year	Nommon	Yes
En-route ANSP Operations data	IFR Flights, ATFM delays and horizontal flight efficiency. Expected to contribute to objective O2.	C3	Collected	EUROCONTROL	xlsx	84 MB	Nommon	Yes
ANSP Environmental data	The total CO2 emissions for each State are contained in the database. They were calculated based on departing IFR flights billed by the EUROCONTROL Route Charges Office, aircraft type and actual flown distance (full trajectory from origin to destination). Expected to contribute to objective O2.	C3	Collected	EUROCONTROL	xlsx	400 kB	Nommon	Yes
Fuel price	Historic prices and forecasts for jet fuel, kerosene or petroleum. Expected to contribute to objective O2.	C3	Collected	EIA	xlsx	400 kB	Nommon	Yes

Dataset	Description	Category	Collected / Generated	Origin	Format	Expected Size	Used by	Openly available
Traffic demand forecasts	The first annex to the summary report "European Aviation in 2040" presents the update of the EUROCONTROL 20-year forecast of IFR flight movements in Europe up to 2040. This forecast uses four scenarios to explore the future of the aviation and the risks that lie ahead: Global Growth, Regulation and Growth (most-likely), Happy Localism and Fragmenting World. Figures for IFR at different levels are provided: top 20 airports, ECAC level and country level. Expected to contribute to objective O2.	C3	Collected	EUROCONTROL	pdf	10 MB	Nommon	Yes
Adopters' financial datasets	These datasets refer to annual reviews, quarterly reports from stakeholders such as airlines, ANSPs or airports. These results are public and can be found in the investor and shareholders´ websites of those organisations. Expected to contribute to objectives O1 and O2.	C3	Collected	Adopters' investor relations	PDF	10 MB / adopter	Nommon and TML	Yes, available at stakeholders' investors and shareholders´ websites
Policy datasets	Historical policy implementation related to ATM stakeholders Expected to contribute to objective O2.	C3	Collected	EC	PDF	5 MB	Nommon	Yes, collected from public sources

Dataset	Description	Category	Collected / Generated	Origin	Format	Expected Size	Used by	Openly available
Historical strike datasets	Reports dealing with the effects of aviation strikes on the different ATM stakeholders: monetary losses, aircraft delay, etc. Expected to contribute to objective O2.	C3	Collected	EC / DG MOVE	PDF	5 MB	Nommon	Yes, collected from public sources
Funding programmes datasets	Funding received by different stakeholders of interest aimed at development (H2020) and deployment (CEF) Expected to contribute to objective O2.	C3	Collected	EC	PDF	5 MB	Nommon	Yes, collected from public sources
Historical technology development pace datasets	Number of patents or major technology outbreaks in ATM Expected to contribute to objective O2.	C3	Collected	Multiple sources (EPO, USPTO…)	PDF	5 MB	Nommon	Yes, collected from public sources

A.5 Research coordination and development

A.5.1 Research data management

The project aims to ensure that all the research data is findable, accessible, interoperable and reusable (FAIR) as well as that ethics and data security aspects are properly addressed.

The mechanisms for sharing, verification, curation, preservation, reuse and further exploitation of the data used by the ITACA project are established in the Data Management Plan (DMP). The ITACA DMP includes information on:

- what data will be collected, processed and generated,
- the handling of research data during and after the end of the project,
- which methodologies and standards will be applied,
- whether data will be shared/made open access, and
- how data will be curated and preserved (including after the end of the project).

All the data will be documented and stored in such a manner that they will be searchable efficiently. This philosophy will increase the potential reuse of these data, both inside and beyond the project. The effective application of this principle requires the implementation of a consistent and meaningful meta-information for each dataset. To that end, ITACA adopted conventions on for metadata creation, naming, searching and control version management as stated in the DMP.

The data collected by the project may be re-used by third parties only if allowed by the data owner. Under request, ITACA will provide the metadata to ease the identification of the datasets.

The re-usability of the data generated by the project will be subject to the general principles for dissemination and transfer of results set in the ITACA Consortium Agreement and Grant Agreement. In particular, all the data generated will be shared for re-usability unless:

- The protection of one Consortium Member's results or background would be adversely affected.
- Legitimate academic or commercial interests of one Consortium Member in relation to the results or background would be significantly harmed.
- Compliance with ethical aspects

The ITACA Consortium will ensure that no privacy or data protection rights are violated and that data management procedures comply with all relevant national and EU legislation. In particular, the Consortium will ensure full compliance with the European General Data Protection Regulation (Regulation (EU) 2016/679). Further details on ethical aspects are included in deliverable D7.1 H - Requirement No. 3. The Consortium will implement the necessary technical and organisational measures to ensure data security and prevent tampering, loss, or unauthorised access.

Personal data (names, organisations, nationality, e-mail, phone, opinions, etc.) will be collected when contacting external experts to ask for information and inputs, which includes the validation activities described in this document. The data will be stored in the Project Information System, in a space restricted to the ITACA Consortium.

A.5.2 Research data dissemination

The data will be made open accessible in different ways according to their confidentiality:

- Data which is only for the use of the Consortium will be accessible through the ITACA Data Repository for Consortium members, but not for the general public.
- Data generated by the project and catalogued as public will be accessible through the ITACA website and an open access repository.

The ITACA beneficiaries will deposit an electronic copy of the scientific publications and public deliverables produced during the scope of the project relating to foreground in an institutional or subject-based repository at the moment of publication, e.g. via the OpenAIRE portal (www.OpenAIRE.eu). In addition, beneficiaries will make their best efforts to ensure that this electronic copy becomes freely and electronically available to anyone through this repository (i.e., that it becomes "open access") immediately. The same applies for the open and re-usable data (e.g., csv files with processed data) needed for the validation of the aforementioned deliverables and publications.

A.6 References

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Appendix B Requirements

The ITACA requirements are attached in the following embedded document:

ITACA_ABM_requirements.xlsm

Appendix C Diagrams

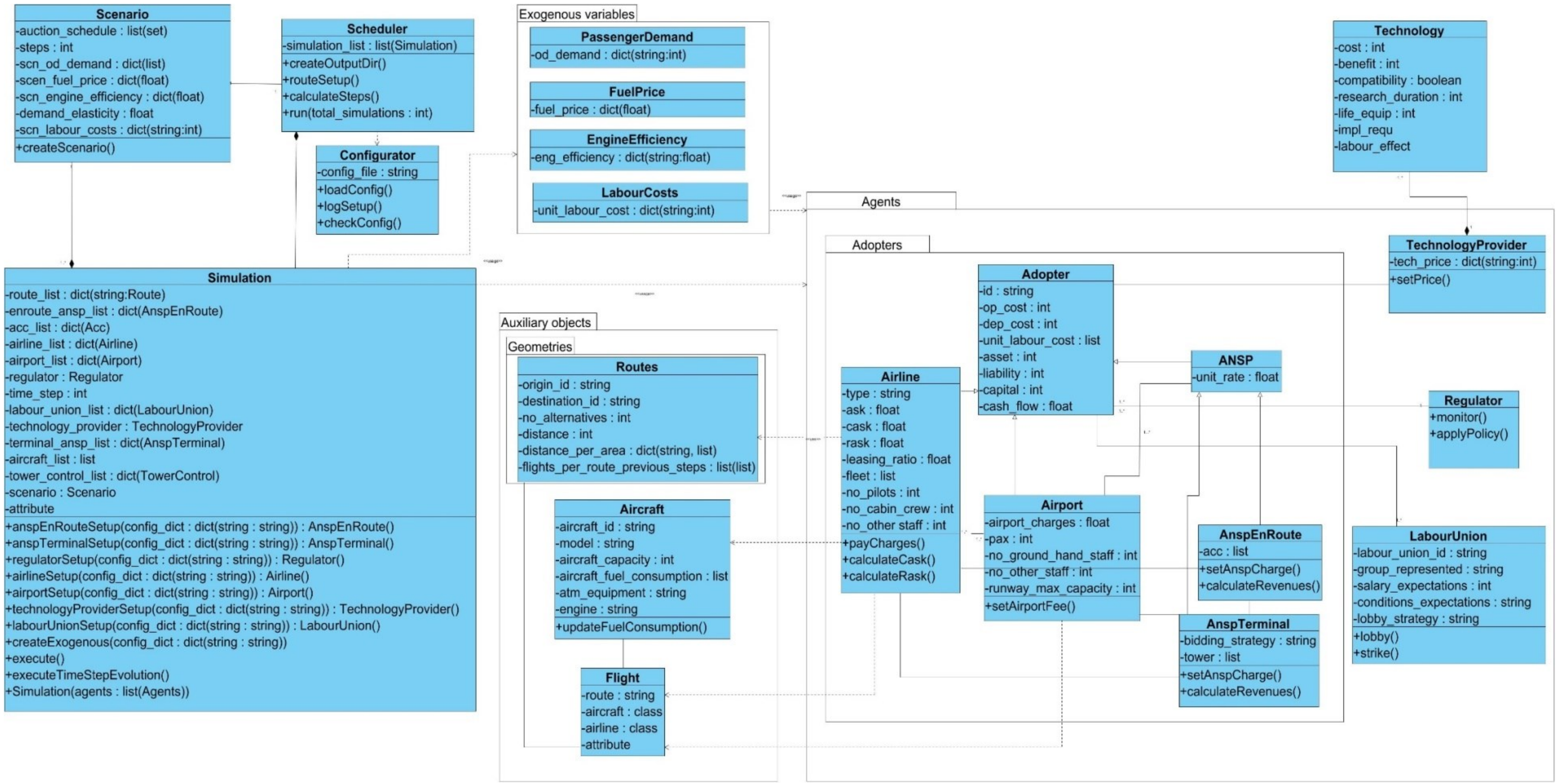

Figure 12: Class diagram