# A Participatory Simulation Framework for Agent-Based Model Validation in Air Traffic Management

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**Abstract.** The European Air Traffic Management (ATM) system is responsible for the safe and timely transportation of more than a billion passengers annually. It is a system that depends heavily on technology and is expected to stay on top of the technological advancements and be an early adopter of technologies. Nevertheless, technological change in ATM has historically developed at a slow pace. As a result, an agent-based model (ABM) of the ATM technology deployment cycle has been developed. This ABM is part of a larger project, which intends to recommend new policy measures for overcoming any barriers associated with technology adoption in ATM. In this paper, a participatory simulation framework validating this ABM is proposed. The aim of the framework is to be able to provide evidences with regards to validation both in an agent as well as in a system level.

**Keywords:** agent-based modelling · validation · participatory simulation · air traffic management.

## 1 Introduction

Air Traffic Management (ATM) is an umbrella term used in aviation for describing all systems that enable an aircraft to depart from an airport, transit the airspace and eventually land at the destination airport. Particularly in EU, ATM as a system was responsible for the safe and timely transportation of more than one billion passengers in 2019. Despite the major disruption due to COVID-19 crisis, this is a figure that is expected to grow and consequently the demands from ATM will also grow. It is therefore an area which despite depending heavily on technology, is still required and expected to stay on top of the technological advancements and be an early adopter of technologies.

Nevertheless, technological change in ATM has historically developed at a slow pace. The reasons are multiple: the very demanding safety requirements, the coordination effort required to harmonise standards around the world, the interdependencies between ground and airborne technologies, the monopolistic nature of air navigation service provision and the relatively small size of the global ATM market compared to other technology markets are among the factors that explain, at least in part, why ATM technological modernisation has traditionally followed a slow, evolutionary path. In recent years, the need to accelerate ATM technological change has become more and more evident: growing traffic demand and new market entrants, such as commercial drone applications, are rapidly pushing the ATM system to its limits, calling for disruptive solutions that are able to boost the performance of ATM operations. Emerging technologies, especially digitisation and automation, have the potential to facilitate this urgently needed technological upgrade. However, technology evolution is a necessary but not sufficient condition; 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. In other words, decisions that affect ATM as a whole are not just influenced by the technical and economical factors, but also by political, legal and social aspects [20].

In order to identify the factors that hinder technology adoption in ATM and be able to tackle them, an agent-based model (ABM) of the ATM technology deployment cycle has been developed [11]. As a modelling method, ABM offers several features that make it particularly interesting for the study of innovation processes, such as the possibility to model agents' heterogeneity, the explicit representation of the agents' interactions, the possibility to endow the agents with non-rational behaviours and behavioural biases (e.g., loss aversion), and the ability to model learning processes, evolutionary behavior and path dependence [21]. The novelty of the model stems from the fact that scarcely any references, and hence relevant work, were identified in the field of ABM in ATM technology diffusion. The organisational point of view, i.e. stakeholders' level, the focus on policy testing and the inclusion of behavioural economics aspects, separately do not represent a new contribution; it is the first time though that such comprehensive approach, combining all these three aspects, is applied to the study of technology adoption.

The ABM is focused on reproducing the mechanisms that drive the adoption and implementation of new ATM technologies. The model includes a representation of all stakeholders identified as relevant for technology adoption in ATM; a non-exhaustive list includes air navigation service providers (ANSPs), airports, airlines, the network manager, aircraft manufacturers and ATM technology providers, labour unions and policy makers. The model represents the long-term evolution of the system (e.g., up to 2050), paying special attention to the coupling between slow and fast dynamics (i.e., how the cumulative effect of the system performance on short timescales ends up triggering long-term decisions, such as the decision to invest in new technologies), building on and extending approaches such as the one proposed by [18].

As with all models, development is just one phase towards having a model that can effectively be used in real-world decision making. Validation is the next phase that gives credibility to the model's results. The aim of this paper is to

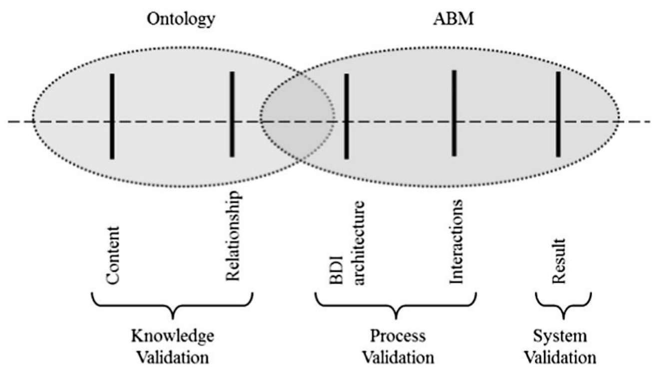


**Fig. 1.** Stages of ABM validation [1]

propose an ABM validation framework, which includes a behavioural analysis of agents and a participatory simulation experiment. The behavioural analysis will examine the behavior of actors in past and future scenarios, whereas the participatory simulations will validate the model in an aggregated/system level and in an individual/agent level.

In Section 2, a literature review in the area of ABM validation in general and with the use of gaming method in particular is conducted. In Section 3, the ABM validation framework is presented. Finally, in Section 4, the future work is illustrated and final remarks are made.

## 2 Background Work

In this section, literature of ABM validation using, but not limited to, participatory methods is presented. ABM validation, as shown in Figure 1, consists of 3 steps as following:

1. Knowledge validation: An ontology is the first step for developing an agent based model [5] and the first thing to study is the agents, their attributes and relationships. Therefore, the validation of ABM starts with the validation of the ontology [2].
2. Process validation: The existing relationships between agents are not enough to define the interactions; the agent behavior attributes and interactions must be modelled separately. At this stage, ABM agents mainly represent two components: behavioural attributes and interaction protocols.
3. System validation: The third stage of the validation follows traditional procedure.The performance indicators of models are validated with hypothesis (in case of synthetic data) or real world measurements of those indicators (in case of real data) [17].

ABM validation is one of those areas that could benefit greatly from participatory methods but in which various quantitative methods can be, and have been, used with success as well.

### 2.1 Quantitative Methods

In general, a quantitative validation means that the results of the ABM are analysed with empirical data, where four aspects should be considered: i. the nature of the object under study (qualitative or quantitative), ii. the goal of the analysis (descriptive, forecasting, policy analysis etc.), iii. the modelling assumptions (e.g., size of the space of representation, time considerations etc.), and iv. the sensitivity of the results to different criteria (initial conditions, micro/macro parameters etc.) [19].

On the one hand, in ABM validation, traditional quantitative validation methods can be used. Some examples are the Temporal Variant - Invariant Analysis (TVIA) [3], the Analytical Hierarchy Process [16], the Mean Square Error and Kappa Index of Agreement [7], as well as traditional statistical techniques [14]. On the other hand, validation frameworks specifically targeted at ABM have been proposed that provide an intuitive and comprehensive validation analysis, like VOMAS [9] and VALFRAM [6].

### 2.2 Participatory Methods

Participatory simulations are an effective, and alternative to the more traditional ones [15], method for gathering information about stakeholders, their interlocking behaviour, and their tacit knowledge [13]. Participants are placed in the dynamic environment of the ABM, so that their decision making is intertwined with each other. By joining an agent-based simulation model with human participants, an environment is created, using formal methods [12], where participants make decisions based on underlying rules that are consistent and coherent [4]. Results from the application of participatory simulations in ABM validation have shown qualitative and quantitative agreement between the decision-making of agents and the players [8, 1].

In order to validate the behavior of agents using participatory simulations, information about the representative participant's behavioural attributes is collected. An agent's decision-making mechanism follows the Belief-Desire-Intent architecture. An agent's belief is defined as the information it perceives about the state of the model's environment. In essence, the belief represents the agent's perception of the current state of the system. The agent's desire is then represented as a motivational state that the agent wants to achieve. Desires are, in fact, priorities for the agent's goals in different situations. Finally, the agent's intention is described as the final act that the agent performs, based on the beliefs and desires at the particular stage of the system [10].

Figure 2 depicts a schema for ABM validation using a participatory simulation. The left side represents the typical process for developing the agent's behavior in the ABM. The right side shows the process for collecting decision-making attributes from a participant using a participatory simulation [1].

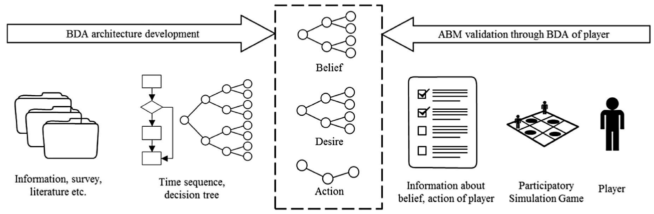


**Fig. 2.** ABM validation using participatory simulations [1]

## 3 ABM Validation Framework

In this section, a participatory simulation framework is proposed for the validation of ABM. The framework consists of i. a behavioural analysis, which cover the knowledge validation and partially the process validation, as those are described in Section 2, and ii. participatory simulations, which complement the behavioural analysis by covering the remaining part of the process validation and the system validation.

The validation of an ABM model occurs in two levels, which also coincides with the two parts of the framework, i.e. the behavioural analysis and the participatory simulations. The first level is the validation of the conceptual model and the second is the validation of the operational model. In turn the behavioural analysis will validate the conceptual model whereas the participatory simulations the operational one.

### 3.1 Behavioural Analysis

The aim of the behavioural analysis is to validate the conceptual model, meaning the assumptions made by the modellers while building the ABM and the behavioural aspects embedded in the ABM. In order to gather data for conducting the behavioural analysis, interviews with experts in the field of air traffic management will be conducted. The questionnaire used in the interview and in turn the interview itself has 4 different parts:

1. Experts check the list of assumptions and in a semi-structured short discussion, they clarify whether they agree or not with them and why. Then, they are informed on the proposals with the new potential technologies to adopt in the ATM system.
2. Experts indicate their role and the agent they represent. Then, through a series of questions they answer on whether they would adopt each of the technologies proposed as well as answer questions related to the behavioural aspects of the ABM.
3. Experts are asked to rank the new technologies based on their probability to be accepted by other agents. The objective of this part is to capture the perspective that agents have about the rest of agents, and if the assumptions

that have been considered about them match the vision that the people involved in ATM have.
4. Experts are asked whether they would change their answers knowing the answers of the rest of stakeholders, aiming at getting greater insight into the social dimension.

### 3.2 Participatory Simulations

The participatory simulations (PS) are going to be used to validate the operational model, or in other words the executable ABM. The PS's aim is to enable the validation of the ABM in an individual/agent level and in an aggregated/system level, using both formal and informal methods.

**Formal and Informal Validation Methods:** The combination of formal and informal validation methods allows for a more holistic approach to validation since the shortcomings of the former can be mitigated by the advantages of the latter and vice versa. Specifically, formal methods have the major advantage that their results are data-driven, hard evidences, but they also come with two significant disadvantages. On the other hand, informal methods, which by many are considered equally powerful as formal ones, are human-driven, i.e. rely almost exclusively on experts' opinion.

With regards to the disadvantages of formal methods, the first one is that validation can only be performed synchronously, which means that for validating the model or a component of the model, the model or the component should first be built, then all the necessary data should be gathered in order to run all the tests. This sequential process is time and resource intense and could cause unforeseen delays and expenses. This is where informal methods complement formal ones by allowing for both synchronous and asynchronous validation. An informal method can be applied before, during and after the design and implementation of the model or the component of the model, enabling an iterative process where improvements can be identified and implemented in a timely efficient manner.

The second disadvantage is that formal methods can only validate what is already known. The application of a formal method for validation requires specific criteria that need to be defined beforehand, which in turn means that if certain aspects of the model are not known during the design of the validation study, then a formal method would not be able to capture it. Again, this is where informal methods can be very handy because of their human-driven nature, which enables them to be able to capture relationships that had not been identified and account for them almost immediately. In other words, informal methods enable the validation of models beyond the defined KPIs.

**2 Levels of Validation:** The PS is implemented in such a way as to allow for the validation to occur in two different levels, in an individual/agent level and in an aggregated/system level. In order to accomplish that, participants are able to play in two different ways:

- *Playing in the model:* Participants assume the role of agents in the model. This gameplay enables participants to actually play the role of an agent, who is relevant to their experience, thus allowing for the validation of the agents' behavior (individual/agent level).
- *Playing with the model:* Participants tweak the parameters of the model. This gameplay enables participants to play around with the model changing parameters not necessarily directly related to their expertise, thus allowing for the validation of the model as a whole (aggregated/system level).

In both gameplays, it is important for designers and decision makers to have two questions in mind:

1. What are the questions we need to answer now?
2. What are the decisions that need to be made?

Keeping track of these questions would enable to always know what is needed from any game session.

**2 Modes of Play:** The PS which is in the form of a game is developed online with the capability of interacting with the ABM. The game has two modes of play both of which can accommodate the validation of the ABM in both levels, i.e. agent and system as described above. The two modes of play are single player and multi player.

*Playing in the model* in the single player mode allows a single participant to take over an agent, while the remaining agents are run by the model itself. *Playing with the model* in the single player mode allows a single participant to tweak the parameters of the model in order to see how the model reacts.

*Playing in the model* in the multi player mode allows multiple participants to take over several or even all agents; if not all agents are taken over by a participant, the remaining agents are run by the model itself. *Playing with the model* in the multi player mode allows multiple participants to tweak parameters in the model at the same time, although this is a very challenging as it is explained below.

While it seems more realistic and intuitive to have only a multi player mode, since the ABM has multiple agents, it comes with certain challenges that the single player mode can overcome. The challenges of having all agents, or even several of them, played by human participants at the same time are the following:

1. It is a logistical nightmare to coordinate 10+ very busy professionals to participate at the same time. The single player mode allows them to play at their own time, when it is convenient for them.
2. Given that it is very difficult to coordinate multiple participants at the same time, in that occasion, the best case scenario will be to conduct 2 or maybe 3 game sessions with each having 5 or 6 variations. These would result in maximum 20 distinct exercises, which although not entirely bad, it still is weak with regards to establishing statistical significance.

3. Particularly when *playing with the model*, having multiple players tweaking more than a few parameters at the same time would most probably yield results very difficult to analyse. It would be very challenging to interpret the effects of tweaking a certain parameter when 10 or even more other parameters were tweaked at the same time. The concept of tweaking a single parameter in order to observe its effects to the whole is known in economics as ceteris paribus and the single player mode could in several occasions accomplish it.
4. From the design and implementation point of view, it is much more complicated and time consuming to build an interface for a multi player game. When a player tweaks one parameter or takes any action within the game, the change of state should be immediately communicated to the other players; this is one of the most challenging tasks with regards to software development. By all means, this would not be a problem in a board game or any non-digital game.

## 4 Conclusion & Future Work

In this paper, a participatory simulation framework was defined for the validation of an agent-based model (ABM) in air traffic management (ATM). The framework consists of two parts; the first part is the behavioural analysis of agents and the second part a participatory simulation experiment. The behavioural analysis examines the behavior of actors in past and future scenarios, whereas the participatory simulations validate the ABM in an aggregated/system level and in an individual/agent level. In order to accomplish that, the participatory simulations, which are in the form of a game, have two options, *playing in the model* and *playing with the model*. The game can be played in both single and multi player mode, with an emphasis on the former due to the several advantages presented in this paper.

The work presented in this paper is just the first step towards a comprehensive participatory simulation framework for ABM validation not just in ATM but in various other fields as well. At the time of writing, the first part of the framework, i.e. behavioural analysis, is under way, meaning that interviews with experts in ATM are conducted, whereas the second part is at its last stages of implementation and will be ready for participants to interact with it the next couple of months.

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