Building a Holistic ATM Model for Future KPI Trade-Offs

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***Abstract*—We present the model developed within the Vista project, studying the future evolution of trade-offs between Key Performance Indicators. The model has a very broad scope and aims to simulate the changes that business and regulatory forces have at a strategic, pre-tactical and tactical level. The relevant factors that will affect the air transportation system are presented, as well as the scenarios to be simulated. The overall architecture of the model is described and a more detailed presentation of the economic component of the model is given. Some preliminary results of this part of the model illustrate its main mechanisms and capabilities.**

I. Introduction and objectives

The air transportation system is a continuously evolving complex socio-economic entity. In order to monitor its changes, SESAR and other bodies regularly define Key Performance Indicators (KPIs) grouped in Key Performance Areas (KPAs) and the associated targets to drive it in the desired direction [1]. In particular, projects are supposed to estimate the impact of their implementation in the system through the use of these indicators.

However, the impact of a single change in the system, let alone multiple changes, cannot be easily forecast because of the high degree of entanglement of the different components of the system, including the different stakeholders – notably passengers, airlines, ANSPs and airports. The degree to which the indicators depend on each other thus arises directly from the interactions and the complex behaviours of the actors in the system. Possible trade-offs and synergies might arise between indicators, actors, and changes in the system.

This calls for a holistic view of the system rather than the independent assessment of its sub-parts. Hence, the primary objective of Vista is to quantify the current and future (2035, 2050) relationships between a currently non-reconciled set of performance targets in Europe by using an integrated model of the European air transportation system on which 'what-if' scenarios can be tested.

Vista has commenced this task by making a list of future business and regulatory changes and how they may likely impact on the stakeholders. In order to take into account the complex feedback between the actors, a model with three layers has been designed, mimicking the three temporal stages: strategic, pre-tactical and tactical phases. The three layers have a fine granularity in terms of scope, down to the individual passenger for the tactical portion. They also feature complex behaviours from the various stakeholders, whilst bearing in mind the need to keep the model simple enough to be able to calibrate it with real data.

This paper aims at presenting the general ideas behind the model and some more specific details on the economic part, trying to highlight the challenges of building a holistic ATM model with such a broad temporal and spatial scope. It is organised as follows. Section II presents the operational environment modelled in Vista: stakeholders, factors and indicators. This section describes the different stakeholders modelled; how business and regulatory factors, taken into account to predict the evolution of the KPIs, have been selected; and which indicators will be estimated by the model in the future. Section III presents the model itself, first with a general description of its architecture and then with a more detailed description of the economic model at the heart of the strategic layer. Section IV presents some preliminary results obtained with the economic model. Finally, we draw some conclusions in Section V, together with some plans for the future of the model.

II. Operational environment

In this section, we highlight the main operational components of the air transportation system in order to include them in a comprehensive model. Moreover, we look at how they are likely to change in the two time horizons set by Vista – 2035 and 2050 – defining the main drivers of these changes as 'factors'. Finally, we briefly look at the observables in the system, how to measure them what to expect from the model.

A. Stakeholders

Five stakeholders are represented in the model: ANSPs, airports, airlines, passengers, and the environment. It is the ambition of Vista to provide a unique view of each perspective and how these are likely to evolve. We discuss each one in turn.

ANSPs are heavily regulated and have traditionally been providing the full scope of air navigation services, including CNS (communication, navigation, surveillance), AIS (aeronautical information services) and, in some cases, aeronautical meteorology. This monolithic approach is gradually changing.

Next to pressure from the regulatory side on unbundling of services, technological innovations such as virtual centres and remote towers pave the way for different ANSP business models. In some states, competition on, for example, tower services, is enforced by the local regulator, or the ANSP itself may decide to outsource services to increase cost efficiency. In addition, almost all ANSPs have become engaged in one or more strategic alliances and industrial partnerships [2]. For example, an ANSP can at the same time join an operational alliance on free route airspace, establish a joint venture with a training provider and team up with ANSPs that share the same ATM system manufacturer.

For large airports, the current business model heavily relies on non-aeronautical revenues (parking, shopping, etc.) [3]. Most of their other revenues are from airlines using them as hubs. Congestion is a major issue for most and they need to implement different strategies to increase their capacity, including soft management procedures or heavy changes in infrastructure [4]. Small airports rely proportionally more on their aeronautical revenues, and try to attract low-cost, point-to-point traffic. Many of them also play the role of feeders for hubs. The evolution of airports relies heavily on the business models of airlines and the increase in traffic in the future. Capacity extensions and better ATM tools (e.g. extended arrival management) are thus to be expected at several airports. A spectrum of private and public ownership exists, but nearly all are heavily regulated, in particular regarding aeronautical charges [5].

Airlines are probably the most market-driven stakeholders. Since it is quite easy for them to reassign – or ground – aircraft, they are able to respond to external stimuli quite quickly. Low-cost carriers (LCCs) generally have lower yields compared with 'traditional' operators. LCC expansion has mainly been based on point-to-point (P2P) strategies, aiming at higher utilisation by using a homogeneous fleet, and lower costs by using secondary airports, in particular [6]. However, more recently, some LCCs have shifted to the 'legacy' model to some extent. For instance, Ryanair has started to operate at primary airports and easyJet has agreements to feed Norwegian and WestJet long-haul flights. The more 'traditional' carriers have been forced to lower costs, sometimes trying to gain market share with an 'in-house LCC'. In future, this apparent convergence will depend,in particular, on the price of fuel.

For the passenger, price, travel time, comfort and convenience constitute some of the factors influencing their choice [7]. The literature often defines archetypal profiles for passengers, usually taking into account socio-economics and travel purpose (often simply 'business' or 'leisure'). Some profiles have been defined during the project DATASET2050 [8], based on several sets of data, and will be loosely adopted in the Vista model, since different types of passenger demonstrate different behaviours when it comes to price, convenience, etc.

The last 'stakeholder' is the environment, ensuring that Vista includes the impact of emissions in the trade-off assessments with other KPIs. Whilst noise is not included in the model, it is planned to include a measure of CO_2 emissions, which are linear with the amount of fuel burned, and an *estimate* of NO_x emissions (although these strictly depend on the background atmospheric conditions, including temperature and humidity, and altitude [9]).

B. Factors

The evolution of the above stakeholders depends on external factors and internal dynamical effects. As a consequence, Vista identified regulatory and business factors and how they will influence the system in the 2035 and 2050 framework. Business factors define economic, technological and operational changes. Regulatory factors encompass regulations and policy instruments that have a direct impact on air transport operations, or that enable the implementation of business factors. A total of 85 references have been reviewed including ICAO, European and national regulations, SESAR documentation and research publications. We have also consulted with stakeholders.

For each factor, possible values and their expected impact on the system have been identified. In some cases, their quantitative impacts are based on literature reviews and goals defined by the SESAR program. In other cases, their impact affects how some operations are carried out. Where possible, a discretisation between a 'low', 'medium' and 'high' effect of the factor is considered. These values are related to the same baseline, for the different timeframes considered in Vista. Indeed, for some of them, we took as reference the late 'time-based operations', 'trajectory-based operations', and 'performance-based operations' targets as they were defined by SESAR in the past [10], [11]. When possible, we mapped them to the possible values of the factors as follows: low is trajectory-based operations; medium is performance-based operations; and, high represents an enhancement of performance-based operations. For example, the impact of development of foreground factor 'traffic synchronisation tools' is based on SESAR defined targets which will represent an increase in airport capacity by 1% in time-based operations and 1.07% for trajectory-based operations, a fuel efficiency of -0.3% in time-based operations and an increase in airspace capacity at TMAs of 5% in time-based operations and 6.74% in trajectory-based operations [12]. For other factors, such as 'passenger provision schemes', the possible values are linked to operational changes (e.g. modification of the threshold of entitlement to compensation in case of delay) and its impact will be modelled by changes on the behaviour of the stakeholders either directly or indirectly (e.g. these changes might represent a higher cost of delay, which might in turn impact the willingness to recover delay). As the value of the factors are related to a baseline which is not linked with the temporal evolution, different values for the factors can be reached in 2035 and 2050 depending on the scenario considered, see below and Table I.

1) Regulatory factors: A total of 22 regulatory factors have been identified. They are grouped into three categories: regulations affecting the gate-to-gate phase of the flight (including

SESAR development and integration, performance-based and ANSP requirements regulations), regulations affecting airport operations (grouped by legislation with impact on airport demand, airport processes and airport access and egress), and regulations affecting other areas in air transport (such as passenger provision schemes, e.g. Regulation 261). As previously mentioned, most of regulatory factors are enablers of operational and technological changes. For example, regulation allowing the operation of UAS is needed for the deployment of these systems, but the regulation itself, without the business development, does not represent an impact on the system. On the contrary, other regulations have a direct effect on the behaviour of stakeholders and the system, this includes, for example, changes to Regulation 261 regarding passenger compensation, or the introduction of new emission trading systems.

2) Business factors: 37 business factors have been classified across categories: factors affecting the gate-to-gate phase of operations (including SESAR operational changes), airport processes and accessibility, and factors affecting demand and other economic variables (such as economic development in Europe and fuel prices).

3) Scenarios: A scenario in Vista is modelled by combining a temporal frame (current, 2035 or 2050) and individual values for the regulatory and business factors. The high number of factors and their possible values needs careful management at the analysis stage. For some factors, their individual impact will be assessed. For others, either a small impact on the indicators measured in Vista or a high consensus on their evolution is defined or their coupling with other factors is very high, thus not allowing the modification of their values independently in the model. The factors that will be analysed in more detail are classified as foreground factors, the rest as background factors.

Background factors are grouped in a meaningful manner to create background scenarios to which different options for the foreground factors can be applied. Table I shows the different background scenarios defined. These scenarios are created to model 2035 and 2050 timeframes with and without high economic growth in Europe and considering whether technology is developed to accommodate the economic evolution. This should allow us to analyse the impact of a shortfall of technological development along with the individual impact of foreground factors. The values ‘low’ and ‘high’ for economy and technology then need to be mapped to the ‘low’, ‘medium’, and ‘high’ values of each of the background factor. This has been already been done in Vista and some examples of values for each scenarios are given in Table I.

A total of 14 foreground factors are identified, e.g. changes to regulations defining passenger provision schemes. These foreground factors are grouped into four higher-level categories: environmental and mitigation policies, regional infrastructure development, passenger focus and Single European Sky evolution.

TABLE I
BACKGROUND SCENARIO DEFINITION. THE LAST COLUMN INCLUDES TWO EXAMPLES OF THE VALUES OF FACTORS IN EACH SCENARIO. ‘BED1’ REPRESENTS THE GLOBAL ECONOMIC DEVELOPMENT OF THE EU-EFTA ZONE, WHILE ‘BTS4’ IS THE POSSIBILITY TO HAVE ENHANCED ROUTE STRUCTURES.

Period	**Name**		**Example of factor values**	
Current	Current		Current values	
2035	L35:	Low economic	BED1:	Low
		Low technology	BTS4:	Low
	M35:	High economic	BED1:	Medium
		Low technology	BTS4:	Low
	H35:	High economic	BED1:	Medium
		High technology	BTS4:	Medium
2050	L50:	Low economic	BED1:	Medium
		Low technology	BTS4:	Medium
	M50:	High economic	BED1:	High
		Low technology	BTS4:	Medium
	H50:	High economic	BED1:	High
		High technology	BTS4:	High

C. Key performance indicators and trade-offs

Different indicators have been identified for each stakeholder. They are selected considering their relevance to stakeholders and the possibility of capture them in the model with the degree of reliability and precision required. Specific consultation with stakeholders has been conducted and will be expanded on further activities to ensure that the most relevant metrics are considered. The metrics currently considered focus on the on time (gate-to-gate and door-to-door times, delays experienced or generated per stakeholder, missed connections), economic (delay hard/soft costs, value of time, revenue and costs) and environmental performance (CO_2, NO_x).

The high uncertainty on the modelling of 2035 and 2050 timeframes means that the objective of Vista is not to precisely compute the value of the indicators on a specific scenario, but to understand the main tendencies and the trade-offs between them under the different scenarios, timeframes and factors. In this manner Vista will provide insight on the relationship between indicators and factors. The trade-off methods that will be used and results will be reported in future publications.

III. MODEL

A. General architecture

Since the breadth of the project is large, the model in Vista is composed of different layers with timeframes aligned with key aspects of future target setting (2035 and 2050). This is depicted in Figure 1.

Overseeing the other layers, the ‘environment’ is designed to be the host of all the static variables feeding the other parts of the model. It comprises the values taken by all the factors, but also historical data to feed to model. It communicates data to each layer.

The first operational layer, the ‘strategic layer’, is designed to capture high-level, long-term decisions by the stakeholders. These decisions are based on a changing environment, comprising socio-economic variables (e.g. demand, fuel prices)

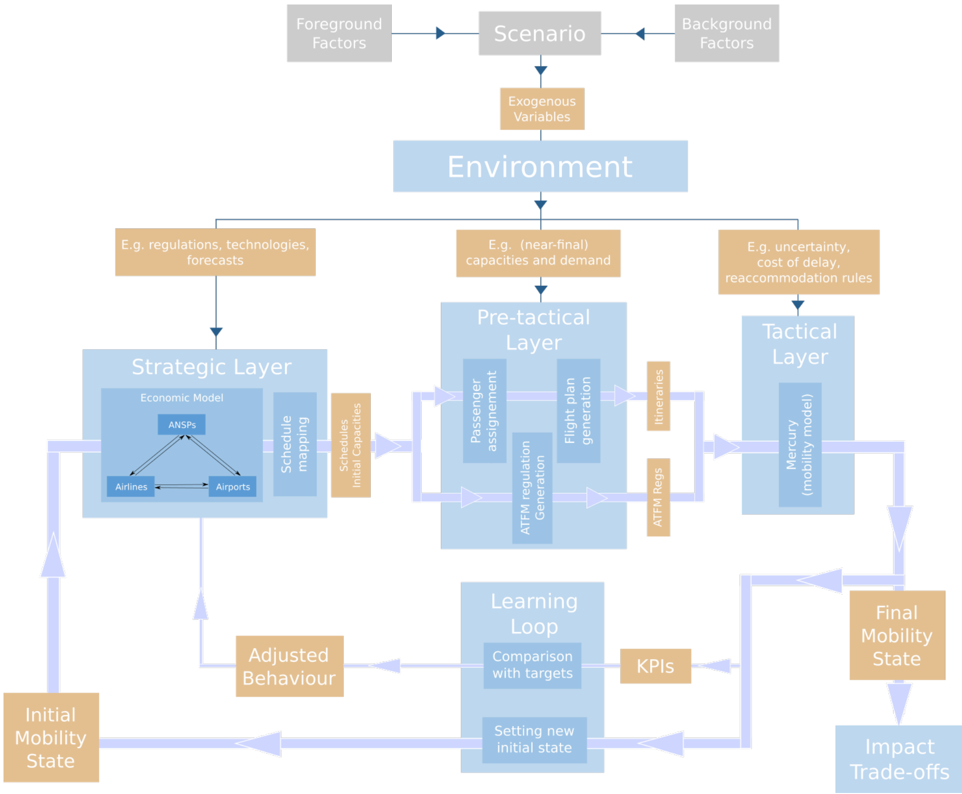

Figure 1. Architecture of the Vista model. Each layer is independent and feeds the downstream blocks.

and taking into account simple economic feedback. The strategic layer has the objective of providing outputs from the main flows between cities, down to the microscopic level of individual schedules and passenger flows. The main features of the economic model are described in the next section.

The 'pre-tactical' layer aims at transforming the consequences of the strategic decisions (the schedules, passengers flows and capacities) into realistic day-to-day operations. As explained previously, there are different archetypes of passengers in Vista, each of them having different characteristics which translate into probabilities of making specific itineraries. This layer is thus tasked with converting the schedules and passengers flows produced by the strategic layer and converting them into passenger itineraries. It also produces flight plans that could be used for the actual flight during the tactical phase, as well as other possible flight plans available during disruption, based on historical data and traffic patterns. The pre-tactical layer will also estimate ATFM regulations and delays.

The third layer is the 'tactical' layer, which is designed to simulate a day of operations. As input, it takes the passenger itineraries produced by the pre-tactical layer, as well as the flight plans and possible airspace disruptions. It simulates the entire day of operations by tracking, microscopically, each passenger and each flight. It generates ad hoc delays and disturbances, based on the information provided by the pre-tactical layer. The model is not strongly agent-driven and only minimal decisions are taken by the airlines during this phase. This matches the idea that on the day of operation the options are very much reduced for them. The tactical layer is based on the mobility model called 'Mercury' and developed during previous projects, including POEM, ComplexityCosts, and DATASET2050.

Finally, the last layer displayed in Figure 1 is the learning loop. Since the Vista model is actually a succession of models, each of them feeding the one downstream, some discrepancies could appear between the layers. For instance, the evaluation of the cost of one minute of delay for the airline during the strategic phase could be wrong and turn out to be significantly different during the tactical phase. In fact, these discrepancies are **desirable**, to some extent, because they exist in the real system. The network operations centre – which takes tactical decisions – is typically distinct from the marketing department – which takes some strategic decisions – in most airlines. Of course, there is some communication between them, but this is imperfect. This is an important feature of this complex socio-economic system[1] that the actors are not hyper-rational with perfect information but have rather a bounded rationality with imperfect information. However, it is also important that the information within the strategic layer is consistent with the tactical one, to avoid unrealistic discrepancies leading to unrealistic decisions as they will be adjusted in the mid-term.

[1]Of any socio-economic system in fact.

One possibility to achieve this is to check the output of the tactical run and compare it with the expectations that the agents formed during the strategic phase. This is the idea behind the learning loop, which should be able to compute different KPIs important to the stakeholders and thus adjust their behaviours.

B. Economic model

In this section, we describe the economic model already developed in Vista, for which the results are shown in Section IV. We briefly show its functionality and the principles behind its design. As shown in Figure 1, the economic model in Vista is part of the strategic layer and constitutes its main component. It is the first block of a chain of models and thus provides information to all the blocks downstream. It should reflect the main, high-level changes occurring in the ATM system in the future. Its objective is essentially to take into account the macro-economic factors to forecast the main changes of flows in Europe. As a consequence, its output should include the:

- main traffic flows in Europe;
- typical market shares of different airline types;
- capacities of ANSPs and airports;
- average prices for passenger itineraries.

In order to do that, the model should simulate various mechanisms within the system and take into account the inputs from the environment. In particular, it should take into account or reflect the:

- main changes in demand, in terms of:
  - volume;
  - passenger heterogeneity (types).
- major business changes:
  - point-to-point vs hub-based operations (airlines);
  - competition vs cooperation (ANSP);
  - privatisation vs nationalisation (ANSP and airports);
  - etc.
- capacity restrictions and congestion, in particular:
  - congestion at airports;
  - ATCO resource constraints.
- major changes in costs/prices of commodities:
  - fuel;
  - airspace/airport charges;
  - new technology developments.

All these mechanisms are directly or indirectly influenced by several business or regulatory factors, and a list of the factors influencing the economic model has been made to ensure that no important ones have been omitted. In order to take all this into account, and because of the heterogeneity of the system in terms of flows and types of actors, it has been decided to use a deterministic agent-based model embedded in the network in order to find the economic equilibrium between the different actors and how it is impacted by the changes in the environment.

1) General flow of the ABM: The agent-based model currently features three types of agents, the:

- airport (one agent per airport);
- airline (one agent per airline);
- passengers (one agent per OD pair, including all the possible itineraries).

Each agent has its own objective, with a specific cost function. The simulation is turn-based, and during a turn all the agents form expectations and decide to act accordingly in order to reach their objectives. A turn proceeds as follows:

- airlines estimate the prices of each itinerary, based on past prices;
- airlines estimate the delays at airports, based on past delays;
- airlines choose their operated capacity for each airport pair based on their cost function, the estimated delays, and the estimated prices;
- airports estimate their traffic;
- airports decide whether to expand their capacity, based on expected traffic and their own cost function;
- passengers choose between the different itineraries available for a given OD pair;
- the price of each itinerary is updated based on the discrepancy between demand and supply;
- delays are updated based on real traffic;
- airports and airlines compute their final profit.

The airports also have a lag in the construction of their capacity, contrary to the airlines. Indeed, there are several turns between the decision to expand their capacities and the step in which the capacity is available to airlines.

2) Cost functions: The agents have different objectives and different expectations. First, the airlines estimate the price for each itinerary for a given turn. This is done by using an exponentially-weighted average of the past changes in prices. The same technique is used with the delay generated by the airports. Once the airline ‘knows’ the price and the delay, it computes the optimal (seat) capacity to provide for each airport pair, based on the following cost function, for a given airport pair:

$$\begin{aligned} c_a &= c_0 + c_1 S + c_2 S^\alpha \\ &= c_0 + (c_1^0 + \chi \Delta\delta t_O + \chi \Delta\delta t_D) S + c_2 S^\alpha . \end{aligned} \quad (1)$$

The cost structure of the airline has been chosen to reflect the long-term choices that the airlines (are supposed to) make in the strategic layer. Apart from the constant term, it includes a linear term which is the cost of operating a capacity S (for instance in number of passengers). This term can be slightly non-linear with the capacity due to inefficiencies but we keep it linear in the model. The coefficient c_1 includes the cost of crew, cost of fuel, cost of delay, etc. The latter is modelled as a linear law, following the findings of [13], in which the cost of delay is found to follow a quadratic law for airlines, with a relatively weak quadratic term for lower delays[2]. Hence, χ represents the cost of one minute of delay for the airline, $\Delta\delta t_O$ and $\Delta\delta t_D$ being the additional delay generated by the origin and destination airports, with respect to the initial (calibrated) situation.

The second term is related to the cost of capital, which is non-linear with the capacity produced. Indeed, it is important to realise that in the model the airlines do not address the question of the optimal capacity given the capital (goods), but rather the optimal level of capital given the expected costs and revenues. As a consequence, the airline adjusts its capacity S based in fact on the underlying choice of the capital (goods) 'K', here representing in particular the aircraft. The exact cost of (additional) capital is certainly a complex function, which depends on the size of the airline, its financial situation, the state of the finance system, the state of the aircraft production/leasing sector, etc. However, this function needs to be monotonically increasing and concave in order to have diminishing returns, which is why $\alpha > 1$.

The profit of the airline for one airport pair is simply $r_a = pS - c_a$, where p is the price of the ticket for the airport pair AB. The optimal capacity is thus simply given by $S = ((p - c_1)/c_2)^{\frac{1}{\alpha}}$. To set the capacity provided on an airport pair in this turn, the airline uses the estimations of p and c that it performed previously and uses this equation. Note that c_1 in the future will include other terms, for instance ANSP charges.

The airport is currently essentially a delay manager. Given traffic T, the airport produces some delay because of congestion, following the equation:

$$\delta t = \delta t_0 + \frac{T}{\mathcal{C}}, \quad (2)$$

where δt_0 is a constant and $\mathcal{C}$ is defined as the capacity of the airport. This linear phenomenological equation is often used in the literature [15], [16], albeit usually without a constant term. It is justifiable with queuing theory, assuming a maximum number of movements per unit of time and a random queue for the flights [17]. Note that other functional forms are sometimes used in the literature, for instance with a divergence when reaching the capacity [18]. In practice, exponential and linear laws both fit well the data [14]. When a linear law is fitted with data, the intercept is found to be significant for nearly every big airport in Europe, and is sometimes negative.

Note that here we include every flight operated at this airport in the generation of delay, either departing or arriving. It does not preclude other types of delays to be added to the delay of the flight, and thus represents only the part of delay purely due to congestion at the airport (terminal and runway). The delay generated by the airport is dependent on the traffic at this airport, but this traffic is in turn dependent on the delay because airlines are sensitive to it, as shown in equation 1. This is a typical example of (negative) economic feedback, which is resolved in the model by a convergence of the expected levels of traffic and delays with the actual ones.

Just as the airline tries to predict the delay at the airport, the airport tries to estimate the traffic, since it does not have direct access to the supply function of the airlines' agents. Once the traffic is estimated, the airport computes its expected profit in two hypothetical cases, its capacity:

1) remains the same, or,
2) is increased by a fixed increment.

To do this, we use for its **operating** cost a linear law with respect to its capacity. A similar law has been used in [14]. Additional data would be required to compute the actual production function of the airport and test this linearity. Once the airport knows the two values of the profit in cases 1 and 2, the airport decides to build additional capacity if the profit in case 2 is higher than a given threshold with respect to case 1. The airport then spends a fixed number of steps with the current capacity, after which the capacity is increased suddenly by a given amount.

Note that airports do not yet change their charges, as it is currently implemented in the model. Since airports have very diverse regulations, some react sharply to markets and others are slower to react. As a consequence, this version of the model considers that all airports have constant charges per passenger. We also considered that the revenues of the airport were linear with the traffic (in fact, the number of passengers). In reality, there is an aeronautical component, proportional to the number of flights (and to the number of passengers also for some airports), and a non-aeronautical component. The latter is more complex, and comprises parking charges, concession rents, etc. Most of these are directly proportional to the number of passengers or can be safely assumed to be so in the long run (for concessions, for instance).

Finally, the passengers are represented by agents which are quite passive. They do not forecast any value and they have an implicit utility function which drives them to choose one itinerary over the other. Their choice is driven by different variables, some of them depending on other agents (such as prices), others depending on the model environment (such as passenger income levels). Given an OD pair, the demand on a particular itinerary k operated is given by:

$$D_k = D_k^0(1 - \alpha\Delta p_k + \beta\Delta i_k)\mathcal{C}(p_k, \{p_l\}_{l\neq i}). \quad (3)$$

This equation is composed of two terms. The first is a 'volume' term, sensitive to the difference in price Δp_k of the itinerary with respect to a baseline (the initial situation) and the difference in income Δi_k of the passengers on this itinerary with respect to the same baseline. α and β represent, respectively, the price elasticity and the income elasticity of the passengers. There is a huge literature (see for instance [19]–[21]) dedicated to the computation of these two types of elasticities, which we will use during the calibration phase of the model. The second term $\mathcal{C}(p_k, \{p_l\}_{l\neq i})$ is a term of competition, which is a function of the prices of all the itineraries possible for this OD pair. It is directly inspired by choice models where, given

[2]But the full cost of delay is to be included in the model, including the statistical effects studied in [14]

a discrete choice with different advantages and disadvantages, passengers have a given probability to choose one option or the other. This function of choice needs to be decreasing in its first argument (the price of itinerary k) and increasing in its other arguments (the prices of the itineraries $l \neq k$). There are several choices possible for this function, among which the multinomial logit function is popular, see for instance [22]. For numerical reasons, the logit function is sometimes problematic, so we choose instead a linear function:

$$\mathcal{C}(p_k, \{p_l\}_{l \neq i}) = 1 - \frac{1}{s}\left(\Delta p_k - \sum_{l=1, l \neq k}^{n} \frac{\Delta p_l}{n-1}\right), \qquad (4)$$

with the additional constraints $0 \leq \mathcal{C} \leq 1$. Hence the competition is sensitive to the difference between the price of itinerary k and the average price of the other itineraries. The parameter s is the (inverse of the) intensity of choice. When it is large, the passengers are not very sensitive to the difference of prices between different itineraries (and in particular between airlines serving the same OD pair). In the limit where $s \rightarrow 0$, passengers all choose the less costly solution, hence having perfect competition between itineraries (and thus airlines).

Note that in reality other factors should enter the composition of the competition term. In particular, it is known that the passengers are sensitive to the quality of service. This is, however, difficult to calibrate, as there are no available, substantial data on this. Another parameter is the total travel time, since passengers are usually more attracted by shorter travel times, e.g. selecting a direct option rather than a flight with a connection. This is related to the complex issue of the value of time of passengers, for which there is a substantial literature. We thus plan to include this factor in the next version of the model.

IV. First Strategic (Economic) Results

In this section we explore the possibilities of the Vista model, and more particularly its strategic component. The results shown below have been obtained on a very simplified setting in order to show the main mechanisms within the model and how the interaction between the agents leads to some non-trivial behaviours. The set-up is illustrated in Figure 2. We define four airports – labelled from 0 to 3 – and two airlines – A and B. One airline, A, is notionally a P2P low-cost carrier, whereas the other, B, is a traditional, hub-based airline. Company A operates two airport pairs: from 1 to 3 – branch δ – and from 2 to 3 – branch ϵ. Company B operates three airport pairs: 1 to 0, 2 to 0, and 0 to 3, respectively branches α, β, and γ. Each branch represent notionally a certain number of flights operating during a given period, e.g. a day.

Passengers travelling from 1 to 3 thus have two possibilities: taking a direct flight with company A, or making a connection at 0 with company B. The same applies for itineraries from 2 to 3. Other passengers begin their journey at 1 and finish at 0, as well as from 2 to 0 and 0 to 3, for which they have to take a flight with company B. We calibrate the model so

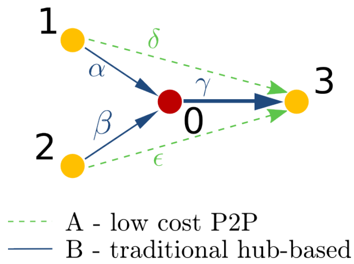

Figure 2. Representation of the configuration used to produce the results.

that company A has a lower cost than company B, but the branches α, β, δ, and ϵ have a relatively low demand with respect to the branch γ. In other words, company B generates most of its revenue from one high-yield branch, with the two others feeding it, whereas A competes with direct flights from 1 to 3 and 0 to 3.

We wish to observe three effects in this system. Firstly, how the increase of demand on one branch affects the other branches. Secondly, how airlines respond to an increase in the fuel price. Lastly, how a capacity increase somewhere in the system affects the whole system. In order to do this, we run a single simulation. During steps 5-15, we increase slowly the demand on branch γ. Then around step 90, airport 3 increases its capacity. Finally, we simulate the increase of fuel price by increasing the parameter c_0^1 by 20% in step 170. Note that in reality, an increase in fuel price would have a smaller impact on the operational cost of company B compared to company A. However, even with the same increase, both companies already react differently, as we see in the following.

We show in Figure 3 the evolution of the traffic on the different branches (top panel) and the evolution of the profit of the airports (bottom panel). Focusing first on the top panel and dismissing the transient effects, one can see different effects. Firstly, the increase of demand on the branch γ during the first 15 steps impacts all the airlines. More specifically, the traffic on this branch increases, whereas the traffic on branches α and β, belonging to the same company, **decreases**, and the traffic on branches δ and ϵ **increases**. This is triggered by a simple effect: since the demand on γ increases, the price on this branch increases. Hence, passengers willing to go from 1 to 3 with company B now have a higher total price for their ticket because of this branch. As a consequence, some of them switch to the competition, i.e. to the direct flights on branches δ and ϵ.

Around step 90, airport 3 increases its capacity. The direct consequence for companies having flights landing at 3 is that their cost is decreased, because the delay at this airport decreases. One could naively think that all will benefit from this increase of capacity, or at least not lose anything. However, this is not what happens, since both branches of company A indeed have higher traffic, whereas all branches from company B see traffic **decrease**. Since company A is cost-driven, the increase of capacity allows it to decrease its prices from 0 to 3 and 1 to 3 to a greater extent than company B, and thus

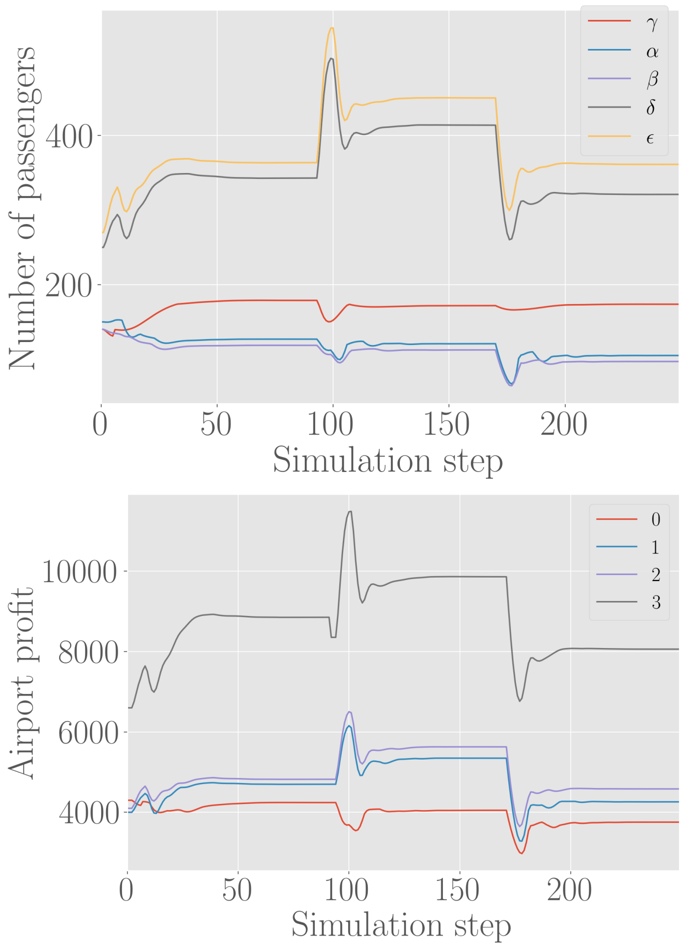

Figure 3. Evolution of the traffic per branch (top panel) and the profit per airport (bottom panel) during a simulation. The simulation increases the demand on branch γ between step 5 and step 15, airport 3 increases its capacity around step 90, and the cost of all airlines are increased at step 170 by 20%.

capture all of the additional traffic, **and more**. This mechanism also has an impact on the airports. If airports 1 and 2 see their profit increase because the traffic on branches δ and ϵ increase, airport 0 ends up with a slightly **smaller profit**. Whereas one could have expected a higher profit for any airport connected with another airport undergoing a capacity extension, the hub of company B actually suffers from this situation.

Finally, around step 170, the operational costs of the airlines are increased as described above. As seen in Figure 3, the different branches react differently to this increase. The most affected are branches δ and ϵ, which lose a sizeable share of their traffic. Branches α and β are also affected, but γ, on the other hand, sees its traffic **increase**. This happens for the same reasons as previously outlined during the capacity increase. Indeed, since this branch is notably less cost-driven than the others (because of its high-yield market), it captures some of the lost traffic on the other branches, where the prices have risen significantly.

The model is thus able to capture complex economic feedback in the system, due to the adaptation of the agents to changing conditions. This non-trivial feedback is triggered by the heterogeneity of the agents, which have different roles and different objectives, and powerful network effects.

V. Conclusions and Future Work

In this paper, we have presented the main foundations on which the Vista model is being built and its objectives. We have highlighted the need for a holistic approach because of the entanglement of the different sub-parts of the system, taking into account the heterogeneity of agents, their numerous interactions, and the influence of external factors. We have segregated these into background and foreground factors. These categories help Vista to focus on a few scenarios instead of having to test each factor independently. We have explained the sequential architecture of the full model, featuring three layers mappable on the strategic, pre-tactical, and tactical phases of ATM. The layers are independent simulations and may be used in other simulation engines in future. The tactical layer is already implemented and has been used in several other projects, in which it has demonstrated its capabilities.

More recently developed is the strategic layer, including the economic model that we have described in more detail. Required to be computationally light but including economic feedback, it has been designed as a network-based deterministic agent-based model in order to take into account heterogeneous behaviours in the system and network feedback. The first results from this model have been presented. Although run on a non-calibrated and highly simplified scenario, it demonstrated its capability to produce complex behaviours arising from the competing, heterogeneous agents in the system. In particular, the sensitivity to cost for airlines combined with the competition with other airlines triggers non-trivial responses when the system is disturbed.

Future work includes the full integration of the different layers into one single engine, which can produce a typical day of (future) operations, taking into account all the factors influencing these layers. We also need to improve the model by adding certain features, such as including some pro-active (instead of essentially passive) ANSPs. We are entering the final stages of stakeholder consultation, through a series of presentations and workshops. Finally, the model needs to be properly calibrated, both on the current situation and for the future scenarios. This requires some data mining to train the model properly, and further calibration against published traffic and passenger forecasts. This will then allow us to move to the ultimate objective of examining the trade-offs between the stakeholder KPIs, demonstrating whether future alignment improves or deteriorates, and the underlining drivers of such behaviour.

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