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Modelling and simulation of urban air mobility: an extendable approach

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Modelling and simulation of urban air mobility: an extendable approach

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Abstract. This paper presents an extendable approach to the modelling and simulation of Urban Air Mobility (UAM), and dissemination criteria for system of systems simulation driven studies. UAM involves a multitude of complexities including the airspace, fleet, demand, and vertidrome management. Simulation is a key enabler for understanding these complexities and the interaction of the different stakeholders within the UAM paradigm. This work builds upon past research of the authors and presents a framework for simulation and modelling which includes the modelling of passenger demand, passenger mode choice, vehicle allocation for heterogenous fleets, route planning, deadheading, vertidrome scheduling, and flight scheduling with stop-overs. The approach presented in this work can be used to model both on-demand and scheduled operations, while the primary focus is placed on the former. Moreover, different methods can be implemented for the detailed modelling of the stakeholders, in addition to parametrically varying aspects such as the fleet size, number of vertidromes, and others. The aims of this paper are two, firstly to offer a framework for the modelling of UAM by breaking down its complexity systematically to simpler blocks, namely the stakeholders, the processes and interaction, through which the emergent behavior of the system of systems simulation may be more easily observed or understood. Secondly, it is to provide a clear method for dissemination of the modelling and simulation with the goal of establishing a common standard, demonstrated through the dissemination of the authors' simulation to the reader.

1. Introduction

Urban Air Mobility (UAM) envisions the use of novel aircraft concepts leveraging advanced technologies for autonomous operations and vertical take-off and landing, to haul passengers and/or cargo at low altitudes across short ranges. The research and commercial interest in this topic have been growing significantly across the many facets enveloped under the umbrella of UAM, such as vertidrome design and operations, unmanned airspace management, vehicle design and operations, and others. As UAM envisions a concept of operations which significantly departs from that of the existing air transportation system, a large amount of uncertainty exists across all levels starting from subsystems such as battery technologies and electric motors, and systems such as the aircraft and vertidrome, to the System of Systems (SoS) level involving interactions and interoperation of the all the constituent systems. Agent-Based Simulations (ABS) of air transportation systems can be a powerful tool to understand complex systems with such a large degree of uncertainty.

ABS are used in a wide variety of fields in the literature from biological systems, financial systems, energy systems, air transportation systems and more [1]. ABS can support the simplification of complex SoS through the modelling of the individual systems as agents and allows for the creation of complex behaviour through simple building blocks.

ABS have been used in aviation research for various different topics such as trajectories, vertidrome airside operations, unmanned aerial systems, aerial wildfire suppression, search and rescue, etc. The research in the literature not only focuses on the aircraft as the system of interest, but also the operational aspects and subsystems. However, despite the growing interest in ABS within aviation, the challenge of comparing different ABS, their conclusions or even their assumptions exist due to a lack of standards in the dissemination of the work. This work seeks to offer an extendible modelling framework of UAM, and more importantly methods for the clear dissemination of the modelling including the assumptions, processes, and dataflow through the stakeholder's perspective. Although the focus is placed on UAM, lessons can be drawn for other air transportation systems and other SoS use cases in general.

2. Modelling and simulation: extensibility and implementation

The authors propose approaching modelling and simulation from the very fundamentals of the SoS to be modelled, and adding complexity step by step until the complete SoS is assembled. As described by Figure 1, this consists of starting with the Stakeholder Identification, followed by identification of the processes and the interaction between the stakeholders, which contribute in the definition of the Concept of Operations, and lastly ending with the clear definition of assumptions. When identifying the processes and interactions of stakeholders, special attention should be paid to the data flow between the stakeholders, and defining clear interfaces between them. The defined concept of operations be as close to reality as possible, or in the case of UAM, as close to the concepts that may develop in the future. Lastly, the assumptions underlying the modelling and simulation should be defined on stakeholder basis to support both the modelling as well as the dissemination of it. The advantage of taking such an approach would be the clear definition of the involved parties, their responsibilities as well as data transfers between the processes at an early stage. As the same functionality can be coded in numerous different ways, of which not all are equal, taking such a systematic approach would ease the process and allow the clear and concise definition of modelling. Furthermore, having a clearly defined processes and interfaces between stakeholders for the modelling would allow the extension/replacement of the stakeholder processes by modules of different fidelity or methodologies, allowing for modularity. Critically, the clear definitions of the stakeholders, processes and interactions would greatly aid in the dissemination of sometimes difficult to grasp System of Systems Simulations and the results generated therein.

Figure 1. Modelling and simulation approach for extensibility and clear dissemination.

This chapter details the modelling and simulation of UAM through the definition of its Stakeholders, the Concept of Operations, and the Modelling of the Stakeholder's processes and their interactions, as implemented by the authors and their underlying assumptions.

2.1. *Stakeholders*

The stakeholders involved in the operations of UAM are considered to be the Vehicle Operator, Vertidrome Operator, Unmanned Aircraft System Traffic Management / Air Traffic Management (UTM/ATM), Passenger, Mobility as a Service (MaaS) provider, and the People & Regulators as denoted in Figure 2.

- **Vehicle Operator:** Operates a fleet of air vehicles and seeks to maximize profit through transporting maximum number of passengers at minimal cost.

- **Vertidrome Operator:** Operates a single or multiple vertidromes and seeks to maximize profit through processing as many passengers as possible in the shortest time.
- **UTM/ATM:** Controls the unmanned/manned, urban/conventional airspace and seeks to ensure the highest level of safety while maximizing operational density of the airspace.
- **Customer/Passenger:** Customer of UAM service and wants to get from origin to destination cheaply and quickly.
- **Mobility as a Service provider:** Operates a platform that connects passengers with mobility services, wants to maximize people using the platform through integrated multimodal transport services including UAM and ground transport modes.
- **People & Regulators:** Are the inhabitants, leadership and regulators of the area within which UAM service is provided. Want to ensure a safe living environment and minimize disturbances such as noise and visual pollution.

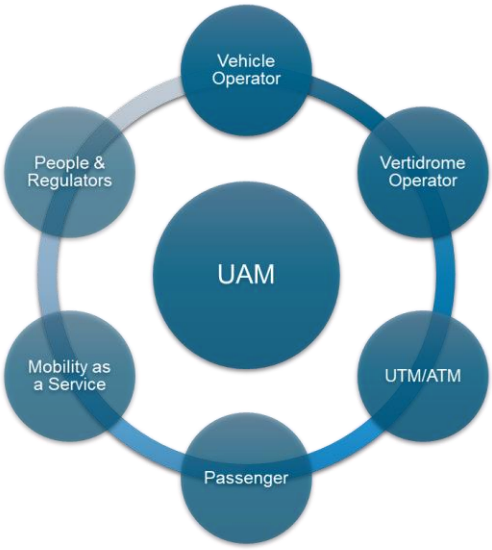

Figure 2. Stakeholders of urban air mobility operations.

2.2. Concept of operations and stakeholder interactions

The concept of operations for booking a UAM trip is as described in Figure 3. In the general concept of operations envisioned for UAM proposes the Customer interfaces with a Mobility as a Service provider who offers integrated travel options connecting ground transport with the air transport options. The integration is critical as one of the main advantages of UAM is the reduction in travel time, and any friction associated with changing from one mode to the other would work to reduce this advantage. Once the customer makes a travel request from the MaaS provider, the request is transmitted to the Vehicle Operator(s) which compiles the suitable travel options for the passenger and requests and reserves departure and arrival slots as well as a 4D trajectory from the UTM and Vertidrome Operator. The Vehicle Operator transmits a ticket price and the flight itinerary to the MaaS provider, which then adds the first and last mile options and price, and provides back to the Customer a list of options including options with only ground transport modes. The Customer can then select a binding offer within a limited period of time, or choose not to use any of the suggested options. If the Customer selects a binding offer, this information is passed onto all the relevant operators so that the travel itinerary can be fixed. Otherwise, the reserved modes are released for others to use. This concept of operations only considers the normal operations and does not account for any disruptions, once the trips are booked they are assumed to operate on time and without fail.

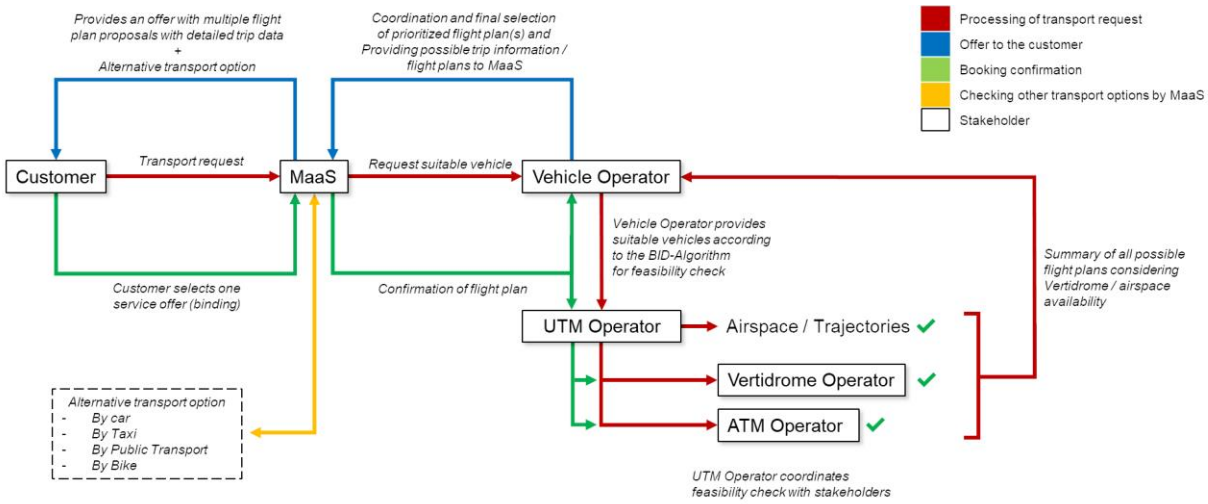

Figure 3. Concept of operations pertaining to booking process [2].

2.3. Agent-based modelling and simulation
This section describes the detailed implementation of agent-based model for UAM as implemented by the authors, describing the processes of each stakeholder and the underlying assumptions. The modelling and simulation described here extends that presented in previous work [3, 4] and is exploited in an accompanying work for the design of a vehicle family for UAM [5]. Interested readers are directed to [6] for the development of the simulation toolkit utilized in this study and to [7, 8] for an aerial wildfire suppression use case developed with the same ABS toolkit.

2.3.1. Customer
The customer modelling is broken down into two aspects, firstly the request made to the MaaS provider and secondly the final decision on the transport mode based on the travel options as follows.

2.3.1.1 Customer request modelling
The passenger requests are generated through a demand model which utilizes parametrically defined outflow and inflow demand curves at each vertidrome to probabilistically create passenger requests. Interested readers are directed to [3] for a detailed explanation of the model. The passenger request is modelled through the origin destination pairs, the desired time of departure and the time of request as denoted in Figure 4. In order to make the model generalized to not only model on-demand but also scheduled operations, a time of request parameter as well as a requested departure time parameter is defined. By this way, a request made hours in advance or minutes in advance can be modelled just as easily. The information of the request is only made available to the MaaS Provider after the time of request has been reached, i.e. when the request is made. Furthermore, in this work only the modelling of the aerial transport is directly considered and it is assumed that the MaaS considers the time required for the passenger to reach from their initial origin to the origin vertidrome, and reflects this in the requested departure time. In future work, the modelling of the ground transport options will be more directly considered.

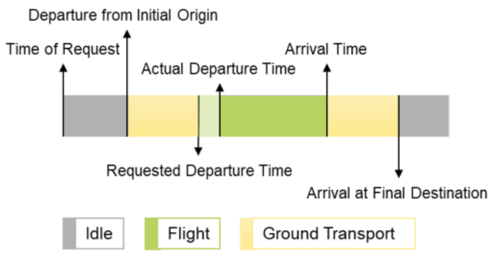

Figure 4. Modelling of passenger request.

2.3.1.2 Customer mode choice modelling

A simple passenger mode choice model is implemented in this study by comparison to the travel time by car. It is assumed that a potential passenger will choose UAM if they are offered a travel time savings through UAM. At this stage, no cost considerations are embedded into the modelling. The travel time estimation by car is done by first estimating the driving distance from the Euclidian distance by the formulas (1) and (2) [9]. The distance is then converted to a time by the driving speed which can take on the values of 30, 50, or 100 km/h depending on the driving distance as defined in Figure 5.

$$\text{Detour ratio} = \beta \frac{1}{\text{Euclidian distance}} + \alpha, \tag{1}$$

where $\beta = 0.213$ and $\alpha = 1.28$ for Hamburg.

$$\text{Driving distance} = \text{Euclidian distance} \times \text{Detour ratio}. \tag{2}$$

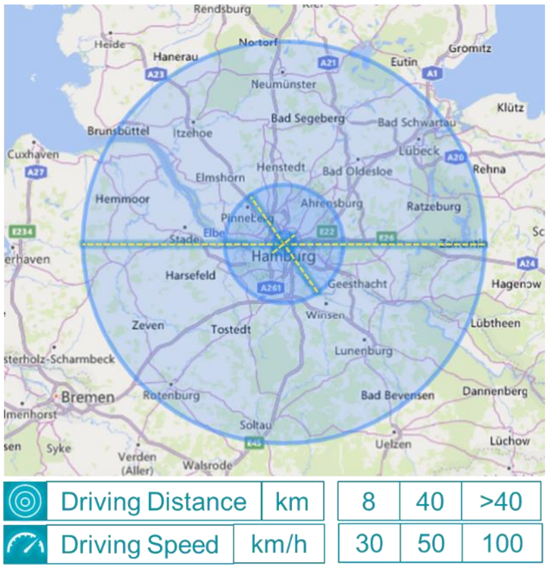

Figure 5. Modelling of alternate transport mode: car, distances and speed assumptions.

2.3.2. MaaS provider

The MaaS provider (considering cases involving an air travel segment) receives the transport request from the passenger, analyses it to account for first mile leg to the vertidrome, and relays the request to the Vehicle Operator(s) with a suitable departure time request. In this regard, it is also considered that the trip can also be broken down into multiple legs by the inclusion of a mid-route stop. It is assumed the MaaS provider would perform this function as it is the integrator of all transport modes, and may also be able to connect flights operated by different Vehicle Operators together. The need for a deadhead flight is accounted for by the Vehicle Operator at the time of the flight request. However, it is considered that the MaaS provider can allocate passengers to existing itineraries, through the Vehicle Operator. In the current implementation, stop-over flights are only considered when the aircraft are unable to perform the direct flight. The ideal stop for the stop-over is found using the Dijkstra Algorithm [10] to find the route with the minimal energy demand.

2.3.3. Vehicle operator

The Vehicle Operator finds the ideal vehicle for the mission considering the availability of the fleet, their positions and other strategic considerations. The vehicle assignment is facilitated by a bidding system where the aircraft agents submit a bid for each mission consisting of the estimated time of completion of the request, the estimation of additional energy needed for the mission, and the suitability of the vehicles passenger carrying capacity and the estimated load factor for the mission. The bid accounts for these three parameters and defined as in equation (3). The first term, prioritizes the time of completion of the mission where any required deadheading, recharging, and limitations imposed by scheduled missions are considered. In the scheduling, deadhead flights are considered not to be fixed, allowing for rescheduling of those legs should it be the best vehicle. Likewise, the second term estimates the additional energy required for the mission, where in the case that a deadhead mission is to be replaced with the prospective mission, the additional energy is considered only to be the difference. The third term is composed of an estimation of the number of passengers that may take the flight, based on the inflow and outflow demand distributions at each vertidrome, without the foreknowledge of the demands that will be created, and mapping the estimated passengers to a suitability value based on the passenger capacity of each aircraft. Figure 6 demonstrates an exemplary case of the mission schedules of two aircraft, where the first aircraft requires a deadhead mission prior to reposition itself, but has no conflicting missions at the time and so can complete the mission sooner. The second aircraft, on the other hand, would not require a deadhead mission however due to a scheduled mission, would only be able to start and complete the mission with a delay. While the first aircraft would complete the mission sooner, it would also require more energy due to the required deadhead mission. Moreover, if we consider the estimated number of passengers that would join this mission, a different aspect of the assignment process would be unveiled.

$$\text{Bid} = -w_1 \times \Delta\text{time} + w_2 \times \Delta\text{energy} + w_3 \times \text{load factor value} \tag{3}$$

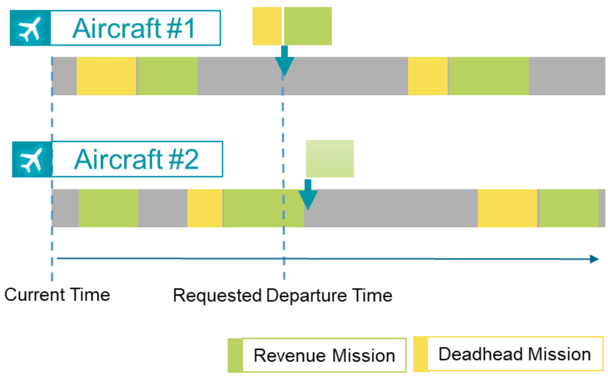

Figure 6. Exemplary mission schedule of two aircraft to demonstrate vehicle allocation process.

2.3.4. Vertidrome operator

A simplified model of the Vertidrome Operator is considered in this work. The Vertidrome Operator ensures a conflict free use of the take-off and landing pads through enforcing a time delay between subsequent uses of the pads. Two pads are assumed in this study for mixed-use of departures and arrival. In this work, a parking capacity limit is not enforced and the simplifying assumption of sufficient parking capacity is taken. Furthermore, congestion or limited use of the gates, taxiways or any layout related impacts are not considered.

2.3.5. UTM/ATM operator

The UTM/ATM Operator finds suitable 4D trajectories and ensures a conflict free and safe airspace. In this work, a simple model is taken for the UTM/ATM operator which will later be replaced by a higher fidelity model. A direct vertidrome to vertidrome trajectory is considered for each flight where deconfliction efforts are not considered and the airspace is assumed to not have any occupancy limits. A trajectory consisting of vertical, transitional and horizontal flight phases is modelled and flown. Furthermore, no fly-zones are assumed not to exist and disruptions to scheduled service are not considered.

2.3.6. People and regulators

The People and Regulators are not directly modelled in the current study and it is assumed that no restrictions are imposed due to this stakeholder. This assumption is meant to simplify the simulation, 24/7 operations are considered and no restricted airspace is considered. Noise or visual disturbance limits are assumed not to exist. Lastly, it is assumed that the vehicles achieve high enough safety criteria to allow overflight of residential areas.

2.4. Dissemination of modelling and simulation

The interest in SoS simulation driven research, either through ABS or discrete-event simulations has been growing in literature. The focus of research varies from vehicle design, network analysis, subsystems, and others. Across the literature, various simulations have been utilized for these studies which have been developed on different software, and disseminated with a focus on different aspects of the modelling. There is currently very little consistency between the dissemination of the modelling across researchers, including assumptions, the interactions between the stakeholders or the concept of operations. As a result, it makes it difficult to understand the results of the work or understand whether key conclusions from one could be applied to the other. The most critical aspect of this is the clear dissemination of assumptions, which often vary significantly across works. In attempt to alleviate this problem, the authors propose dissemination through an adapted XDSM diagram to concisely describe SoS simulations as in Figure 7. It modifies the tools to describe the stakeholders, and introduces processes boxes to describe the processes carried out by each stakeholder, the interconnections model the flow of information as well as describing the data that is transmitted and finally the yellow boxes at the top describe the assumptions under which each stakeholder is modelled. By this way, the authors hope a clear description of the SoS simulation can be achieved and aid in the dissemination and uptake of the research.

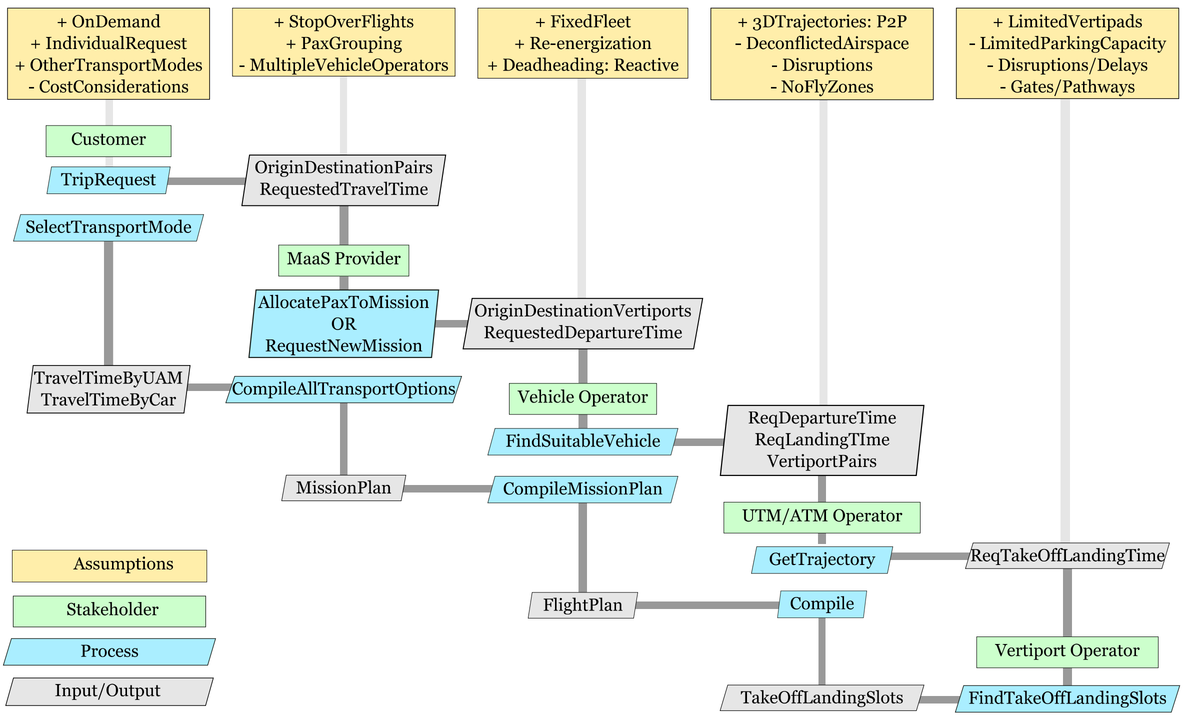

Figure 7. System of systems simulations design structure matrix S3DSM: adapted XDSM diagram for system of systems simulations.

3. Conclusion

This work aimed to present a systematic approach for the extendible modelling and simulation of UAM, and importantly the dissemination of the modelling and simulation along with all the assumptions and interactions considered. The work seeks to establish a common ground upon which the modelling and simulation of SoS use cases, such as air transportation systems, can be built and disseminated. It also detailed the implementation of the modelling and simulation of UAM as done by the authors and used for the design of a vehicle family concept through the derivation of top-level aircraft requirements in the accompanying work. The future work entails the embedding of higher fidelity modules within the simulation such as demand estimation, mode choice including cost, vertidrome operations, conflict free trajectories, and maintenance considerations.

Acknowledgements

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