

Evaluating eVTOL Integration in Intermodal Transport: A Multi-Stakeholder Simulation Study

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The emergence of electric vertical take-off and landing (eVTOL) offers a novel opportunity to address long-standing challenges in intermodal mobility. As cities and transportation planners seek to decarbonize and decentralize mobility systems, understanding the role of new short-range aircraft concepts within the broader intermodal ecosystem becomes crucial in direct comparison with traditional and hybrid travel modes. This study investigates the systemic implications of integrating eVTOL into intermodal mobility networks by comparing multiple modal configurations: (1) fully public transport, (2) hybrid combinations such as eVTOL and public transport. Using a European-scale agent-based system of systems (SoS) simulation framework, the model evaluates performance across different metrics including total travel time, energy consumption, cost, number of transfers, and accessibility. Each passenger agent is assigned personalized utility functions, accounting for time sensitivity, and cost aversion.

The study follows a Product Push Paradigm, where a fixed product is to be deployed into an existing SoS. In this case, the a fixed eVTOL concept is deployed into the existing intermodal transport SoS. A multi-step approach for Product Push Paradigm is extended and demonstrated in this work. In a Product Push Paradigm, a limited decision space, particularly in relation to the eVTOL Operator is open, however within this decision space the operator has to ensure satisfaction of the other stakeholders. IAM can be best described as a Collaborative SoS, as the stakeholders are not subject to a direct authority but work towards the same goal: mobility. As each stakeholder has their best interest at heart by nature of the SoS, this study investigates the impact of multi-stakeholder considerations in decision making.

From the passenger perspective, the study explores how value of time (VoT) profiles affects mode choices and when passengers are most likely to switch from ground based to aerial modes. From the operator perspective, the model investigates how vertiport placement, fleet size and ticket pricing affect vehicle utilization, deadhead ratios and profitability. It evaluates trade-offs between maximizing fleet efficiency and minimizing passenger wait times.

By examining these interactions holistically, this research provides actionable insights for stakeholders aiming to integrate AAM into future mobility systems. The results offer guidance on infrastructure investment, service planning, and regulation, helping to ensure that AAM adoption is equitable, efficient, and environmentally sustainable.

The study evaluates the satisfaction of the different stakeholders involved as quantified by their Value Models capturing their own objectives within the Collaborative SoS. A broad design space exploration is performed and analyzed showing the impact on the stakeholder interests. Furthermore, the study explores the contrasting interests of the Stakeholders and how multi-stakeholder decision making can help find a consensus.

I.Nomenclature

<i>AAM</i>	=	Advanced Air Mobility
<i>ABM</i>	=	Agent-Based Modelling
<i>eVTOL</i>	=	Electric Vertical Take-Off and Landing
<i>IAM</i>	=	Innovative Air Mobility
<i>SoS</i>	=	System of Systems
<i>VoT</i>	=	Value of Time

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II. Introduction and Motivation

Access to remote regions, including islands and coastal areas, is often limited by poor integration between long-distance and local transport modes. Journeys may involve multiple transfers, long waiting times, and separate ticketing schemes. Meanwhile, operators struggle to optimize routes and fleet usage while ensuring affordability and profitability. The recent development of eVTOL concepts presents an opportunity to integrate air travel together with public and long distance transport to enable intermodal door to door operations in both urban, regional and intercity contexts [1]. This paradigm is referred to as Innovative Air Mobility (IAM), or Advanced Air Mobility (AAM) and considering the urban context only: Urban Air Mobility (UAM). This research investigates whether the introduction of new short-range aircraft can improve door to door travel experiences while maintaining overall system efficiency and equitable access.

IAM is a System of Systems, defined as a group of independent systems collaborating to achieve a unique capability otherwise unattainable by a single system [2]. Vehicle Operators, Vertiport Operators, Unmanned Aircraft System Traffic Management (UTM), and Public Transport Operators all need to collaborate together to achieve the core capability of IAM; enabling a seamless connection of air travel over short distances with the existing transport system.

As SoS achieve unique capabilities through the independent collaboration of its constituent systems, the capability is achieved “bottom-up”. The unique capabilities are an emergent behavior of the collaboration of the independent systems. The independent systems may or may not be working toward achieving the emergent behavior, depending on the level of authority involved in the SoS. This “bottom-up” nature of SoS, makes Agent-Based Models suitable for SoS modelling. As in Agent-Based Models, the behavior is prescribed at a system level, where different agents may have different characteristics and behaviors. The Agent-Based Model, then is built up through the independent action of the agents, and can exhibit emergent behaviors.

Our research evaluates the impact of introducing new aircraft concepts as a new transport product; a “product-push” approach; by embedding it into an agent-based intermodal transport simulation covering the Munich–Rijeka–Cres corridor. The “product-push” paradigm, applied to the study, explores how a fixed eVTOL can be integrated into an existing transport system and create value while satisfying stakeholder interests. The overarching question this work aims to answer is:

- 1) *How can other stakeholders be considered in the decision-making of the Product Push Paradigm?*

III. Methodology

The COLOSSUS general methodology for SoS analysis [3] applied to the Product Push Paradigm is depicted in Figure 1. The methodology starts with identification of the problem, where the stakeholders involved in the SoS are identified alongside their needs. A representative set of scenarios are then formulated, with the goal to succinctly capture the variance of conditions the SoS in focus would operate under. Stakeholder value indicators are also identified, to be able to quantify the stakeholder’s satisfaction with a given SoS. With the problem identified, the solution space can be explored. In a product push paradigm, the vehicle concept is known and fixed. Therefore, the SoS architectural space involves the decisions the product owner, in this case the vehicle (eVTOL) operator needs to make to introduce and operate the vehicles in the IAM SoS. The generated architecture concepts are evaluated by an Agent-Based Simulation of the SoS, and further evaluation metrics are computed by specialized domain tools. The results are then to be visualized in a dashboard where interested stakeholders can perform tradeoff analyses and explore the results generated from the SoS analyses. The SoS architecture can be optimized by connecting the analysis modules with an optimization tool, with respect to the objective functions of the SoS, and constraints imposed by stakeholders. The entire analysis chain, is supported by a Transformative Digital Collaborative Framework, directly providing core functionalities such as architecting, requirements analysis, workflow generation, and execution. In this work, the focus is placed on the architecture exploration in the product push paradigm, evaluation in the SoS and specialized domain tools, and results analysis to identify trends. Therefore, focus will be placed on only the relevant aspects of the COLOSSUS Methodology.

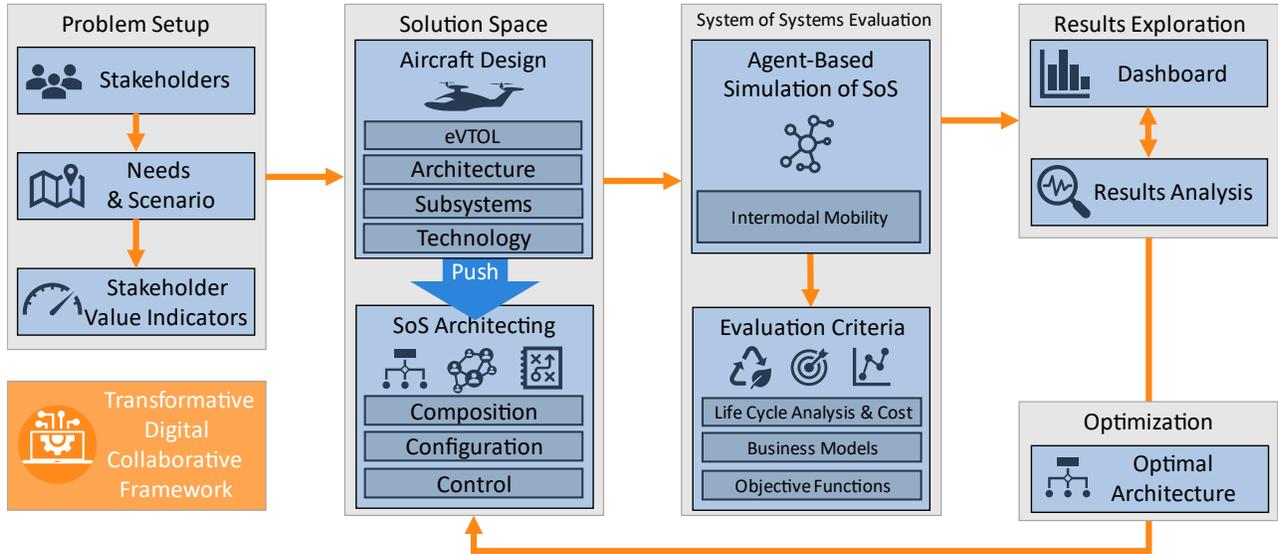


Figure 1 COLOSSUS Methodology for SoS analysis in a Product Push Paradigm

A. Agent-Based Simulation Framework

The study employs a System-of-Systems Agent-Based Simulation modeling passengers, vehicles, and operators as agents. The simulation generates intermodal transportation scenarios between urban and island regions, primarily focusing on the Munich–Rijeka–Cres corridor. The study follows the COLOSSUS framework approach as detailed in [3]. The SoSID toolkit is used as the Agent-Based Modelling and Simulation environment and is described in [4,5] and has been extensively used in different use cases such as [6], [7], [8], [9]

Passengers are initialized with the following attributes:

- 1) Origin and destination GPS coordinates
- 2) Departure time
- 3) Value of time

At each decision point, the passenger selects from multiple dynamically generated route options based on a utility function:

$$Utility\ Function = Travel\ Cost + Value\ of\ Time \cdot Travel\ Time \quad (1)$$

The simulation environment supports both intracity and intercity trips. Ground transport legs use simplified estimation models, while air transport legs follow on-demand or scheduled eVTOL flights with dynamic vehicle availability and air space constraints. Sub-chapter B describes the overall simulation logic particularly pertaining to route generation.

B. Route Generation and Aircraft Integration

The route planning system includes:

- 1) Public transport legs via a simplified mathematical model using regional speed assumptions
- 2) Long distance travel legs with static schedules
- 3) eVTOL/Seaplane legs restricted to trips between predefined vertiports/water aerodromes, incorporating:
 - a. Fleet availability
 - b. Charging requirements
 - c. Scheduled mission

Routes are constructed on demand at the passenger's departure time, ensuring consistency with vehicle availability and airspace capacity constraints. At departure time, each passenger queries the system for all viable intermodal routes. The simulation checks resource availability (aircraft capacity, vertiport slots) and provides the all-feasible options. The algorithm depicted in Figure 2 decomposes a given origin-destination pair, to a series of regional and inter-regional trips, where within a regional area both public transports, and eVTOL options are considered. The

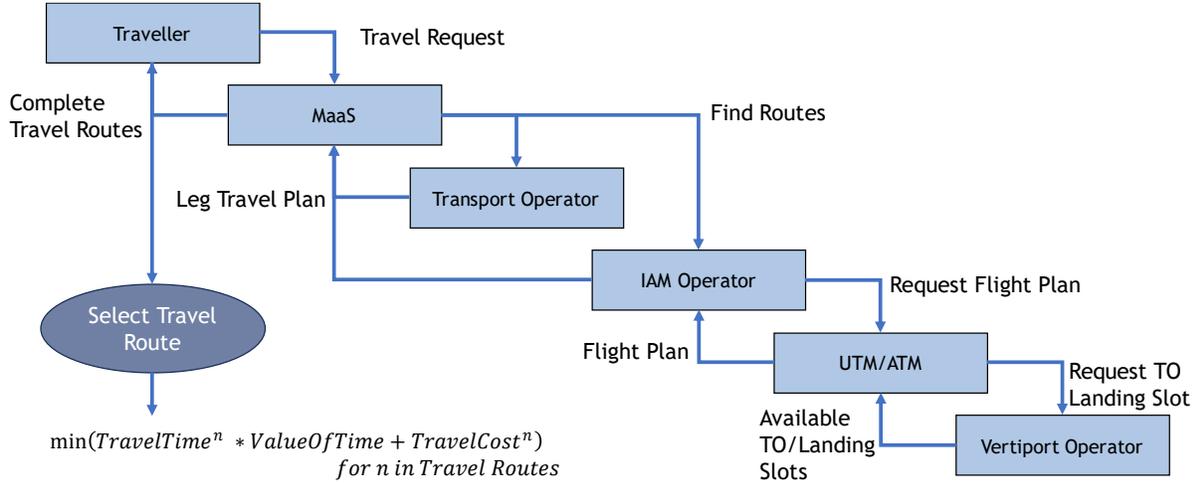


Figure 2 Intermodal Mobility Route Generation Logic

inter-regional trips, are performed by the long-distance transport modes such as bus, airline, or train. For inter-regional trips a recursive Dijkstra algorithm is used to solve a graph composed of the long-distance transport hubs, dispatching the requests for each leg to the appropriate transport provider, and compiling all possible options. The end result is a comprehensive set of route offers for each passenger, both involving and not involving eVTOLs as part of the route. The eVTOL trips, offered as part of a complete route offer, are generated taking into account the airspace and vertiport airspace limitations in addition to the vehicle capacity and fleet limitations. All combinations of available long distance transport options are included in the comprehensive set of route offers. Finally, the passenger selects their preferred route based on Equation (1).

C. Vehicle Operator Design Space

The vehicle operator is responsible for operation of the eVTOL. The Vehicle Operator decisions include:

- 1) The fleet size and distribution
- 2) Ticket pricing scheme
- 3) Vehicle allocation strategy
- 4) Traveler request lead time
- 5) Operating route network

Through the aforementioned decisions, the operator can achieve higher profitability, utilization or other. The study varies the different levers in the hands of the vehicle operator and performs a sensitivity study evaluating the impact not only on the operator but also on the other stakeholders and the overall SoS.

D. Vertiport Placement

This part of the methodology focuses on how the physical placement and operational management of vertiports affect the performance of the intermodal transport system. According to [10], AAM profitability is significantly affected by the vertiport network planning. The purpose of the study to determine how vertiports are critical infrastructure for eVTOL operations. Their location, number, and scheduling logic determine:

- 1) How accessible eVTOLs are to passengers (spatial reach)
- 2) How efficiently the eVTOL fleet is used (utilization vs. idle time)
- 3) How long passengers wait before boarding (service level)

The vertiport placement used in the study considers three major aspects:

1. Centralized (at main stations and airports)

Vertiports are located at major existing transport hubs such as train stations, ferry terminals and airports. This reflects a hub-and-spoke model and simplifies multimodal transfers. A similar approach can be observed in [11].

2. Decentralized (population based)

Vertiports are distributed across the region based on factors like population density, suburban spread and residential clusters. This model favors accessibility and inclusiveness but may lead to inefficiencies in fleet usage.

3. Remote (popularity based)

Vertiports are placed at remote-areas with tourist attractions, where people frequent but are poorly connected by existing transport options. This model improves connectivity in areas where infrastructure is costly to build, and targets high-value of time passengers.

All three aspects are considered in the vertiport placement used in this work, and the vertiport network is depicted in Figure 4. Identifying the optimal vertiport placement requires careful and methodical analysis, as it directly impacts the accessibility of eVTOLs to and from other modes. However, in this work the focus is not placed on the vertiport placement and a fixed vertiport network is considered.

E. Product Push Methodology

The “Product Push” Paradigm asks the question: “How can a product be integrated into an existing System of Systems, to create value, and satisfy stakeholder requirements?” The “Product Pull” paradigm conversely is related to designing a dedicated product to be integrated into an SoS to solve a problem. The difference between the two, being whether or not the product itself is known and fixed. Indeed, as both paradigms are applied to the SoS, the design space involves operational parameters as well. By nature of an SoS problems, the design space even when the product itself is excluded from it, is large. Therefore, a systematic approach for the product push paradigm proposed in a preceding work [6] is continued in this work. The systematic approach is composed of the following steps:

- 1) Understand Ideal Value
 - a) Under ideal conditions, what is the value created from the introduction of the product into the SoS? The definition of what “value” is in this context, relates to the objective of the SoS.
- 2) Understand the Market
 - a) Who is the customer or user of the product?
 - b) Where is the product most needed? Are there characteristics of those regions?
 - c) What enabling systems are needed for the product?
- 3) Capture the Market
 - a) How do we utilize the product to capture as much of the Market?
 - b) What are the choices at the hands of the Operator, that impact Market capture?
- 4) Tradeoff stakeholder interests
 - a) The active stakeholder interests should be satisfied for the SoS to be realized
 - b) Therefore, a tradeoff analysis on the product operator and other active stakeholders should be performed to ensure requirements are satisfied

In this work, primary focus is placed on the final point in the Product Push Approach, where the stakeholder interests will be traded off. In a previous work, the preceding points were explored systematically [6].

F. Stakeholder Considerations

IAM involves many active stakeholders that deliver core capabilities required for its realization. These include the vehicle operator, vertiport operator, and UTM/ATM as examples. Air travel using novel eVTOL concepts not only needs the vehicles themselves, but also vertiports for safe take-off and landing, as well as UTM/ATM to manage a safe airspace. In addition, the manufacturers of the vehicle and vertiports are also key, however these may or may not be different from the operators. An excerpt of the IAM stakeholders is given in Figure 3. While the figure does not provide an extensive list of all stakeholders, it highlights an excerpt of the important stakeholders. Some of

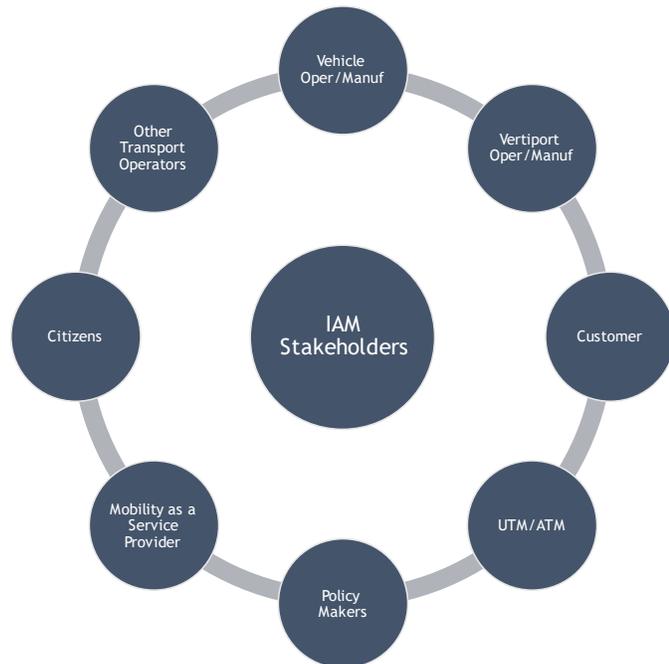


Figure 3 Excerpt of IAM Stakeholders

these stakeholders, will be directly considered in this study in the multi-stakeholder decision-making.

To assess the impact of integrating AAM into intermodal transportation systems, a set of quantitative evaluation metrics are defined. These metrics span multiple stakeholder perspectives including passengers, operators, planners, and environmental regulators and are used to compare various modal configurations (fully public transport, and hybrid combinations).

1. Vehicle Operator Perspective

The Vehicle Operator is arguably the most important stakeholder in the IAM SoS as it provides an integral capability to IAM: a new mode of air travel. The Vehicle Operator seeks to offer a service to its potential customers by offering on-demand and quick travel between vertiports. The Vehicle Operator, as a business entity seeks profit in exchange for its services. Therefore, we can capture the Vehicle Operator's perspectives directly through their Profit, or implicitly through the parameters that impact profit such as the deadhead ratio, vehicle utilization rate, and number of flights. In this work, the direct representation of the Vehicle Operator's perspective is used, i.e. the profit. The revenue is computed based on the number of passengers taking eVTOL flights in the simulation, and the total operating cost is computed based on specialized eVTOL cost models [12].

- **Profit [EUR/Day]**
Profit attained over the course of a typical operational day considering the revenue from tickets, and the total operating cost.

4. Vertiport Operator Perspective

The Vertiport Operator seeks to maximize the utilization of their vertiports, as a profit-seeking operation. The Vertiport Operator gains revenue from the number of landings and takeoffs from the Vertiport. This may also be complemented by parking fees, sales of products and additional services to the passenger, and ad revenue. For a simple representation of the vertiport operators' interest, the number of landings is selected to represent their interests while implicitly capturing the other factors impacting their satisfaction.

- **Movements at all Vertiports**
Sum of all departures and landings across all vertiports in the study area. Represents vertiport usage as a stand-in for Vertiport Operator revenue.

5. Citizens and Regulators Perspective

As IAM involves operations in urban/sub-urban areas, the perspective of the people living in those areas need to be considered. The utmost concern when considering over/near flights of urban areas is security. Safety and security, is a requirement and non-negotiable for IAM to be realized, as it is with all existing aviation. As such safety and security are not considered in this multi-stakeholder study for trade-off analysis. Beyond safety and security, when considering the Public Acceptance of the citizenry, noise pollution is identified to be one of, if not the most important aspects. In addition, visual pollution, and privacy concerns are often also highlighted [13]. In this work, the noise levels from the eVTOL operations over the area of study is considered to represent the citizens perspective.

- **Overflight Max Noise Indicator (Day-evening-night level - Lden)**
Noise level based on energy equivalent noise level (Leq) over a whole day with a penalty of 10 dB(A) for night time noise (23.00-7.00) and an additional penalty of 5 dB(A) for evening noise (i.e. 19.00-23.00) [14]. Represents the noise disturbance to the citizens in the study area in forward flight phase.

IV.Scenario

A case study considering the Greater Munich area and a region in Croatia is considered for this study. The scenario was chosen based on the following considerations:

- Intercity travelers (Business or Tourist) have a higher Value of Time and therefore may be more inclined towards the time savings offered by IAM
- Munich Airport (MUC) is a major airport hub with a large catchment area, and therefore presents an opportunity for eVTOLs operating as feeders from regional areas to the airport and back
- The coastal areas of Croatia are popular tourist destinations, but offers lower ground transport speeds due to its geography. Direct flights by eVTOLs connecting regions in the area may provide time savings making eVTOLs more attractive

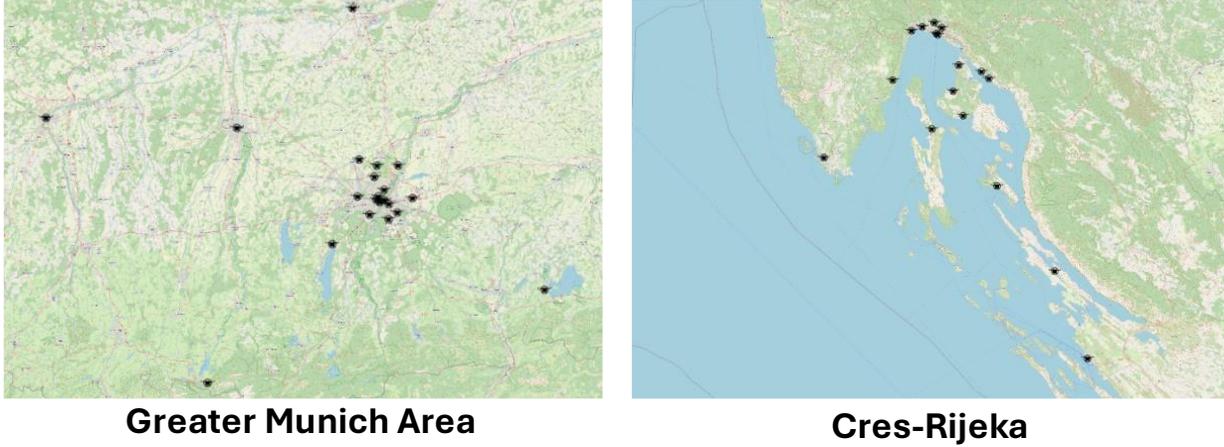


Figure 4 Vertiport Placement in the Study Area

The ground transport is modelled by average speeds of the transport network in different regions, where Munich center, Munich metropolitan area, Rijeka-Cres were modelled with different speeds. The values are attuned to the typical transport speeds achievable in the respective areas. The long-distance transport models are modelled using schedules, where the time, cost, and distance of the modes are represented largely based on what is available today. However, an exact one-to-one match with the schedules were not attempted, as the focus of the study is to quantify the relative difference in improvement after introduction of eVTOLs rather than absolutes. The following assumptions were used for the study are detailed in Table 1.

Table 1 Average transport speeds assumed in study area by region

Parameter	Munich-City	Cres-Rijeka	Munich Region	Remote Areas
Avg. transport speed	10 km/h	10 km/h	100 km/h	60 km/h

A fixed eVTOL concept is used for the analysis, also integrating acoustic models to capture noise impact of operations throughout the day [15]. A tiltrotor concept with 4 passenger payload capacity for a future scenario of 2050, and battery swap capabilities of 10 minutes is considered as the target of the Product Push. The eVTOL operations are modelled as described in Chapter III with capacity and fleet limitations accounted for.

An exemplary demand of ~27000 door-to-door travelers is considered in the study, composed of intercity, regional and intracity travelers with a Value of Time of 60 EUR/hour. The vertiport placements considered for the study is shown in Figure 4.

V. Results

The results are generated by executing a Design of Experiments of the Vehicle Operator’s design space on the Agent-Based Simulation of the IAM SoS as described in Chapter III. This work employs the Product Push Paradigm and therefore focuses on the impact of the Vehicle Operator’s decisions on the overall SoS. A special focus in this work is placed on quantifying the impact of the Vehicle Operator’s decisions on other stakeholders. The chapter first investigates the preferences of the Vehicle Operator when the design space is varied, and proceeds with the impact on the other stakeholders. Finally, a combined MoE is evaluated presenting a traded off design space considering all stakeholders of interest of this study and their importance. The design space considered in this study consists of 5 different variables, with 4 perspectives to be considered. Therefore, to ease comprehension, the two most impactful variables are selected after a predictor screening and are presented in 2D contour maps representing each stakeholders’ interests. The two variables identified by the predictor screening are fleet size, and ticket price per km. These serve as representative variables for the methodology, and can be easily extended to other variables.

G. Vehicle Operator Perspective

As highlighted in the preceding section, the Vehicle Operator perspective is modelled by their profit in this work. The Vehicle Operator seeks to maximize their profit, by exploring the available design space. The results will be demonstrated on two variables, namely the fleet size and the ticket price per km for IAM and is shown in Figure 5. The figure shows that an increasing fleet size can generally increase Profit for the operator as it increases the number of travelers taking IAM (demonstrated in Figure 6). An increase in flight ticket price shows an increase up to a point beyond which profit diminishes. As the ticket price increases, the number of travelers taking IAM decreases as demonstrated in Figure 6. Despite increasing ticket price reducing the number of travelers taking IAM, up to a price of 2.5 EUR/km the profit increases. The reduction in IAM passengers are compensated for by the increase in ticket price up to that point. Any further increases reduce profit as the loss of passenger demand is more than is compensated for by the higher revenue from each person. Figure 5 thus shows that there is an profit maximizing region for the Vehicle Operator, and for the settings used for this scenario analysis, it occurs at a fleet size of 60 eVTOLs operating across Munich and Croatia with a ticket price of 2.5 EUR/km.

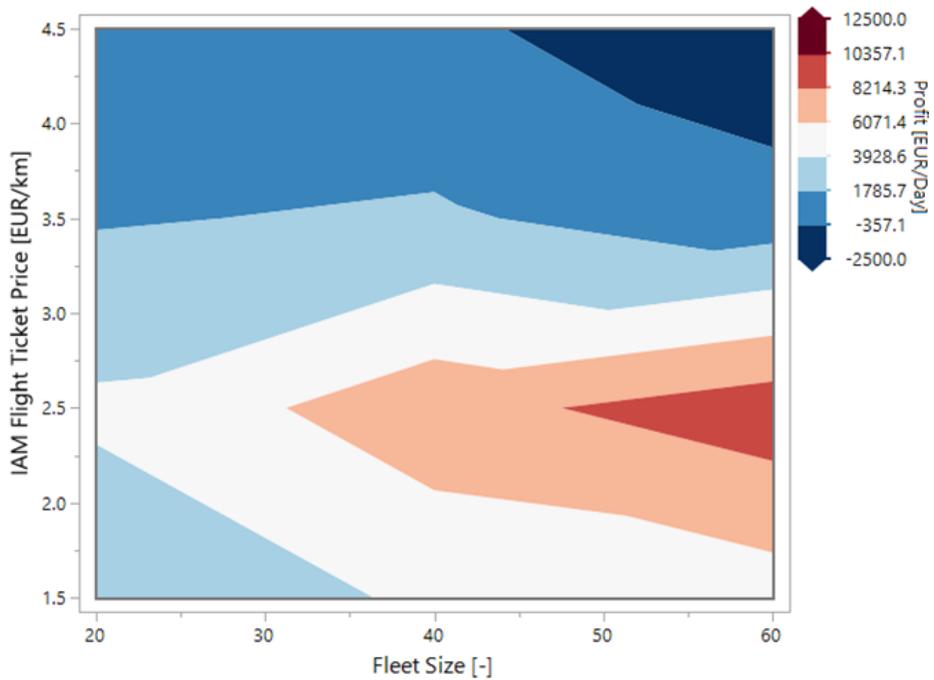


Figure 5 Contour Plot of Vehicle Operator Profit against IAM Flight Ticket Price and Fleet Size

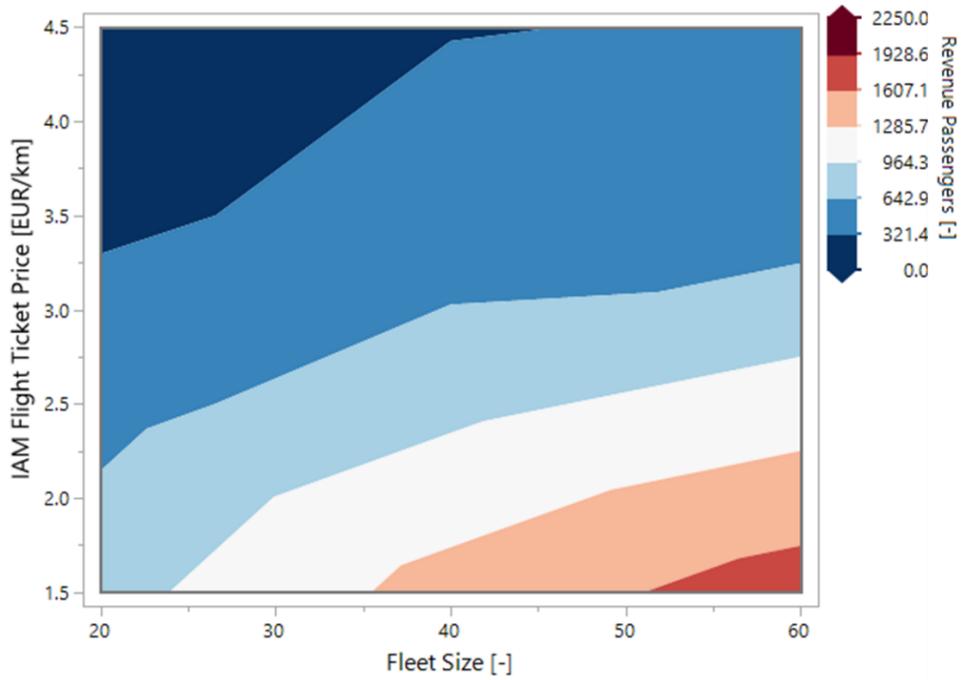


Figure 6 Contour Plot of Revenue Passengers taking IAM against IAM Flight Ticket Price and Fleet Size

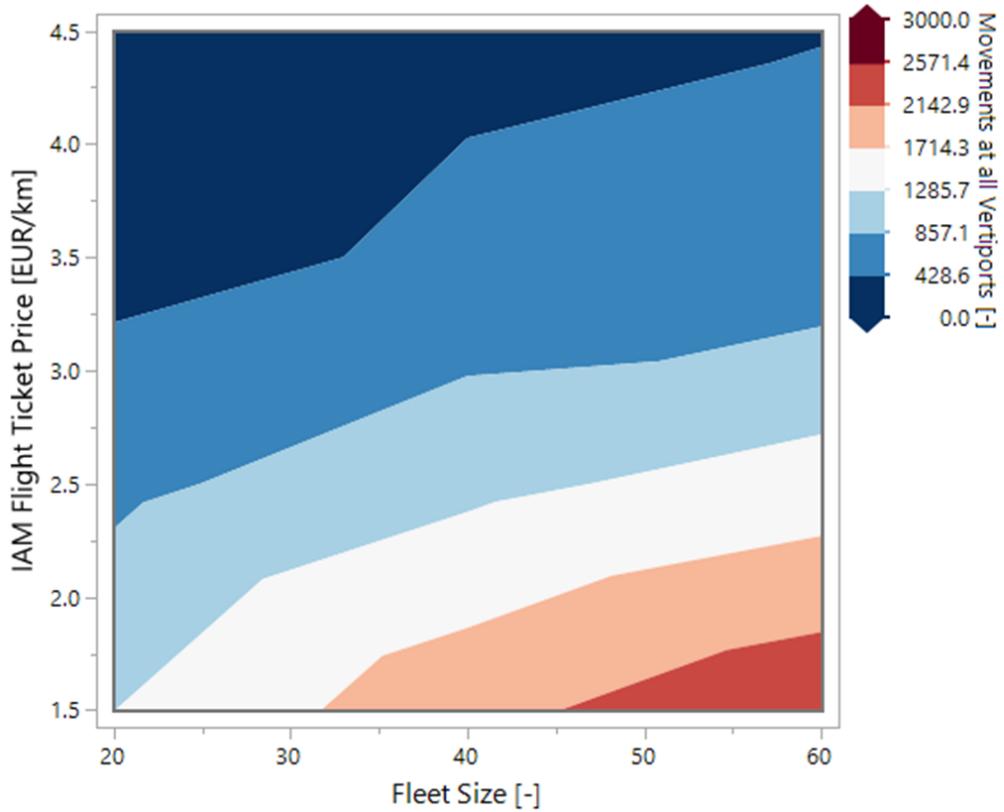


Figure 7 Contour Plot of Movements (Take-offs and Landings) at all Vertiports against IAM Flight Ticket Price and Fleet Size

H. Vertiport Operator Perspective

The impact of the two chosen Vehicle Operator decisions on the Vertiport Operator's perspective, represented by the total number of movements at all vertiports are shown in Figure 7. The Vertiport Operator, seeking to maximize the movements at all vertiports are benefited by an increase in number of flights. As the number of passengers taking IAM are strongly correlated to the number of flights, the same trend can be observed in Figure 6 and Figure 7. The Vertiport Operator, is benefited most when there is a low-ticket price on the IAM flights, and a high fleet size in operation. The Vertiport Operator is highly impacted by the decisions of the Vehicle Operator(s). In this study, a single Vehicle Operator is considered, which exacerbates this reliance. If multiple Vehicle Operators were in operation, then the decisions of one enterprise may be dampened by the impact of the others. However, it is worth note that the chosen metric to represent the Vertiport Operator is a simplification of what would be their primary interest; Profit. As highlighted before, the Vertiport may attain profit in other manners than just the landings and takeoffs from the Vertiports. These may be from parking fees, charging fees, or even advertisement. A Vertiport Operator may also choose to not operate the extensive vertiport network considered in this study, but rather only consider the most advantageous locations from their perspective. As such, the decisions of the Vertiport Operator would also significantly impact the Vehicle Operator.

I. Citizens and Regulators Perspective

Figure 8 shows the maximum noise indicator (Lden) due to the eVTOL operations in the Munich Central Region. This smaller area was chosen for the analysis, as it is the most densely populated area and thus would show the highest noise impact. To minimize the computational effort the analysis area for the noise indicator was focused on this smaller area. The results indicate a high correlation with the number of passengers taking IAM (comparing against Figure 6). This is as expected, as the number of passengers is correlated with the number of flights, and an increase of flights will correspond with the noise levels experienced for a given vertiport network. The citizens and regulators preferences on the design variables are directly in conflict with those of the Vertiport Operator and Vehicle Operator. The analysis would be further complemented by varying the vertiport network, as vertiport placement and density will have a significant impact on noise due to overlapping flight paths and approach and takeoffs around vertiports. The vertiport network variation will be evaluated in a future work.

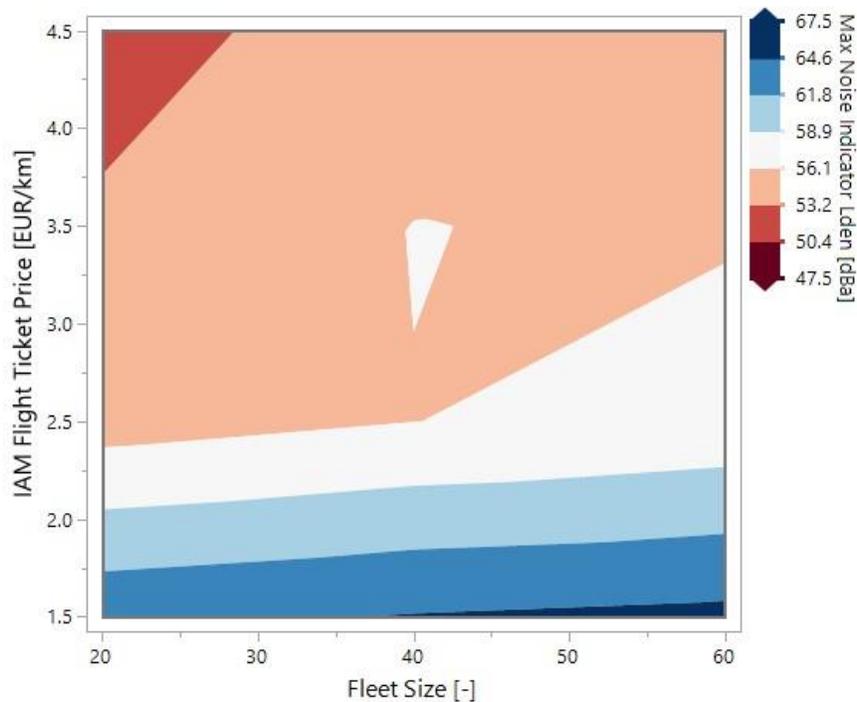


Figure 8 Contour Plot of Overflight Max Noise Indicator (Lden) against IAM Flight Ticket Price and Fleet Size

J. Stakeholder Tradeoff Study

In order to perform a tradeoff of stakeholder interests, a combined MoE is formulated. Firstly each stakeholder MoE is normalized using the Equation (1)

$$Normalized\ MoE = \sum_j \frac{Stakeholder\ MoE_j - \min(Stakeholder\ MoE_j)}{\max(Stakeholder\ MoE_j) - \min(Stakeholder\ MoE_j)} \quad (1)$$

Where j indicates component metric of the Stakeholder MoE

The normalized MoE of each stakeholder, bound between 0 and 1, is then weighted and combined using Equation (2)

$$Combined\ MoE = \sum_i Stakeholder\ Weight_i * Normalized\ MoE_i \quad (2)$$

Where i indicates each Stakeholder, and the sum of stakeholder weights are equal to 1.

The stakeholder weighting is considered to be allow prioritization of certain stakeholders over the others. Certain stakeholders in the SoS, may have a larger role than the others, in such cases it is important to be able to consider the entire breadth of interests while prioritizing the more important stakeholders. In addition, enforcing stakeholder requirements can also be explored. As an example, certain noise threshold requirements may be enforced on IAM operations, and in such cases enforcing this as a requirement onto the solution space can ensure the requirement is met while still exploring the best tradeoffs for the other stakeholders. In this work, no requirements are enforced and will be explored in future work.

The combined MoE of the stakeholders using the normalization procedure and combination procedure represented by Equations (1) and (2) is represented in Figure 9 with respect to the two chosen variables of the Vehicle Operator. It is important to note that since noise is to be minimized, the difference of the normalized value with 1 is used in the combined MoE. The weightings chosen for the combination are 0.6 for the Vehicle Operator, 0.3 for the Vertiport Operator and 0.1 for the Citizens and Regulators. The resultant combination, largely represents the interests of the Vehicle Operator, but has the influence of the Vertiport Operator in that the high-fleet size and low-ticket price combination becomes more prominent. This influence is mitigated by the MoE of the citizens and regulators, as it has an opposing push. The combined considerations considering the two highest value bands, present a solution space where the Vehicle Operator is still largely within their ideal profit generating values, the Vertiport Operator is expecting 1200-3000 movements at their vertiports, and a max noise impact ranging from 58.9 to 67.5 dBA due to the IAM operations.

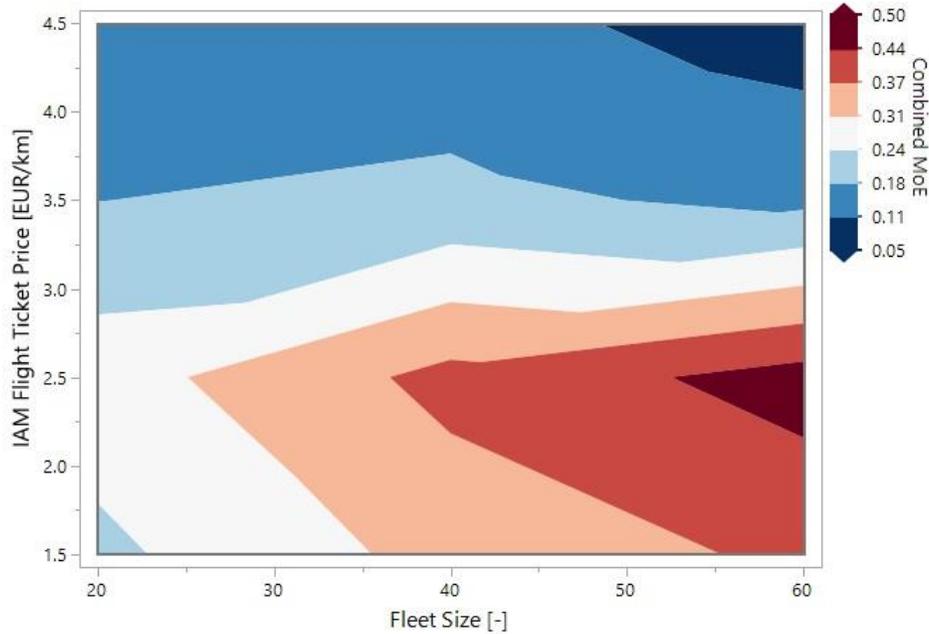


Figure 9 Contour Plot of Combined MoE of Stakeholders against IAM Flight Ticket Price and Fleet Size with weights (0.6, 0.3, 0.1 for Vehicle Operator, Vertiport Operator and Citizens and Regulators)

However, as noted before, the Vehicle and Vertiport Operators are highly interdependent on each other. If we consider a scenario where the Vehicle Operator is less dominant in the weightings, and are equally weighted, the result would be as in Figure 10. The strongest band, between 0.44 and 0.5 MoE disappears and in its place a broad range where MoE is in the range 0.37-0.44 is found. The strongest band, expands to smaller fleet sizes and is extended downward to lower ticket prices. In this band, the Vehicle Operator remains profitable but has compromised with the Vertiport Operator in favor of higher volume of operations at a lower ticket price.

Lastly, lets consider the case where the citizens and regulators are highly dominant in the decision-making, and wants to mitigate the additional noise pollution from the IAM operations. Figure 11 shows the combined MoE with weightings (0.3, 0.2 and 0.5 for the Vehicle Operator, Vertiport Operator, and Citizens and Regulators). The strongest band has a broad spread, across fleet sizes which stems from the impact of the higher prioritization of the Citizens and Regulator’s MoE. While the Vehicle Operator has a strong preference for the larger fleet size, the Citizens and Regulators MoE shows the opposite trend, thereby the combination of the two create a large area with similar MoE. The region highlighted by the strongest band, still ensures the Vehicle Operator makes profit, and noise levels are in the range of 53 to 58 dbA.

The exemplary weightings chosen in this Chapter were to demonstrate the impact of combining at times conflicting interests into a tradeoff space, enabling better decision making that satisfies the stakeholders. The proposed approach of representing stakeholders directly with MoEs, and combining the MoEs into a singular MoE for the SoS can be leveraged to swiftly narrow down the design space and make decisions.

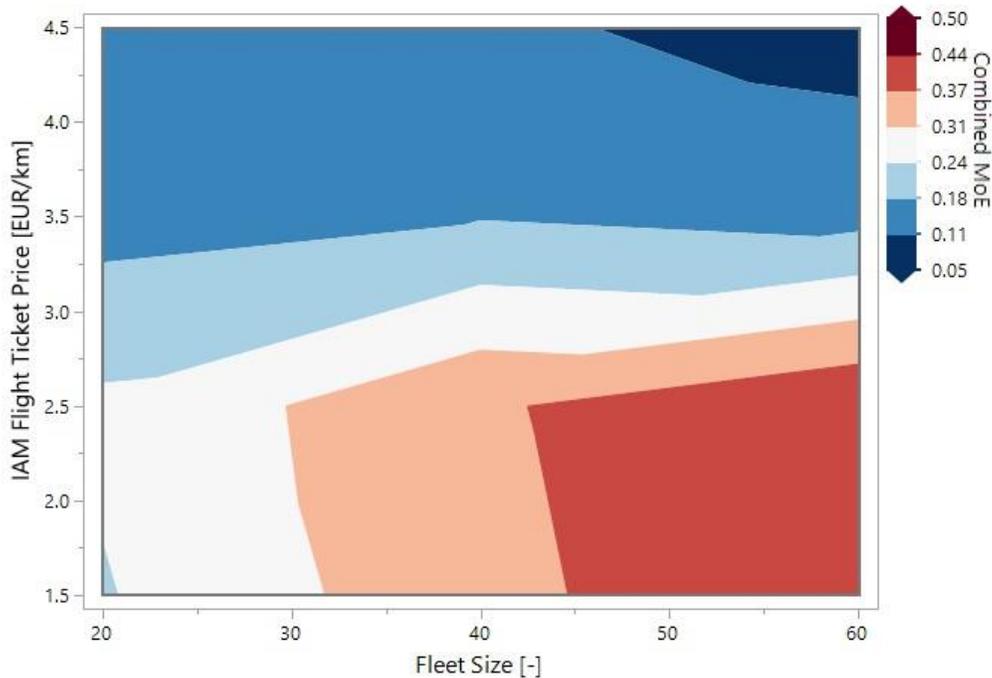


Figure 10 Contour Plot of Combined MoE of Stakeholders against IAM Flight Ticket Price and Fleet Size with weights (0.45 0.45, 0.1 for Vehicle Operator, Vertiport Operator and Citizens and Regulators)

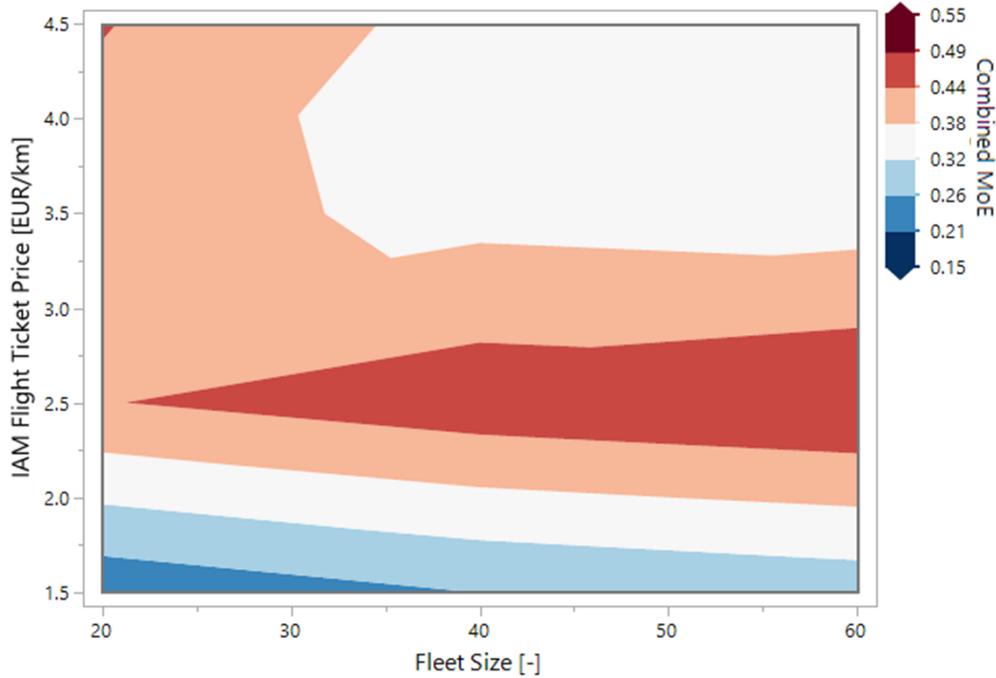


Figure 11 Contour Plot of Combined MoE of Stakeholders against IAM Flight Ticket Price and Fleet Size with weights (0.3, 0.2, 0.5 for Vehicle Operator, Vertiport Operator and Citizens and Regulators)

VI. Conclusions and Future Work

This study presents a comprehensive SoS simulation framework to evaluate the integration of eVTOLs into intermodal transportation systems, with a specific focus on the Munich–Rijeka–Cres corridor. Through agent-based modeling and dynamic route generation based on individual passenger utility functions, we can explore the potential of Advanced Air Mobility to reshape regional mobility dynamics.

The extension of the Product Push Paradigm into the multi-stakeholder tradeoff step is performed in this work. The approach presented in this work allows the different stakeholder interests to be captured in a singular view, while also considering their significance in the SoS. Different weighting parameters lead to different ideal ranges for the decision variables in consideration. The results demonstrate the degree of interdependence among IAM stakeholders, that the decisions of one stakeholder, can significantly impact the others, and a compromised solution would be needed.

The analysis presented in this work is with the purpose of highlighting trends, and relative differences between results. The exact numbers of IAM demand, and number of flights are highly dependent on the assumptions made in the analysis, and therefore should not be the takeaway from this work. While the assumptions are based on available data wherever possible, further validation of them are needed before any conclusions on the exact numbers can be taken.

Future work includes the exploration of the other variables of the Vehicle Operator in the Product Push Paradigm, such as the vehicle allocation strategy, traveler request lead time, operational route network, and further extensions of the ticket pricing strategies. In addition, other stakeholders such as EU Policy makers will be considered through the impact of eVTOL on emissions and travel times within the region. UTM/ATM, Vehicle Manufacturer, are among the stakeholders that can also be considered in multi-stakeholder tradeoff analysis.

The extension of the Product Push Paradigm for the integration of Seaplanes is part of ongoing work by the authors, and will be further evaluated in the future.

Ultimately, this work provides a modular, extensible framework to guide operators and decision-makers in evaluating the operational, environmental, and socio-economic implications of AAM adoption. By modelling not only the Vehicle Operator, it can capture the impact of stakeholder decisions on other stakeholders as demonstrated in this work. The framework is not only limited to the product push paradigm, but is also flexible in achieving the product pull paradigm where a product is to be designed for a given problem.

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