HOLISTIC INVESTIGATION OF GROUND-BASED INFRASTRUCTURES FOR ADVANCED AIR MOBILITY: METHODOLOGY AND APPLICATION

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Summary

Advanced Air Mobility (AAM) addresses future transportation challenges by extending networks into the air, helping cities like Hamburg overcome infrastructural limitations. Ground-based infrastructures (GBIs) are crucial for integrating AAM, connecting air and ground transport through subsystems like landing areas, gates, and terminals, tailored to local demands. Our previous work identified necessary GBI subsystems and modeling methods, using scenario techniques to understand influences and constraints in mission planning, topology, maintenance, repair, and energy management. This paper details a simulation-based analysis of GBIs, emphasizing topologies, maintenance, and energy management interactions. AAM is modeled as a complex optimization problem within a simulation environment, using scenario analysis to set parameters and objectives. Network optimization aims to strategically plan local capacities for parking, charging infrastructure, and traffic flows, improving fleet operations. Infrastructure design integrates air and ground systems for VTOL vehicles, with key performance indicators and the Vertiport Design Problem optimizing topology. Maintenance, Repair, and Overhaul (MRO) Ports are designed to be demand-responsive, integrating ground-based infrastructure and mission management systems. Energy management systems consider energy requirements, charging power, range, state of charge, and electrical grid use. MATLAB Simulink models estimate drone energy demand across various scenarios. Subsystem interactions are defined in a workflow for overall system simulation, divided into sub-workflows, exploring synergy effects between parameters.

Keywords: Advanced Air Mobility, AAM, Ground-Based Infrastructure, GBI, Vertiport

1. INTRODUCTION AND STATE OF THE ART

Advanced Air Mobility (AAM) emerges as a pivotal solution to forthcoming transportation challenges, not only within Hamburg but also across major urban centers worldwide [1], [2]. AAM, distinguished by its innovativeness and adaptability to demand, extends the transportation network into the aerial realm, mitigating existing infrastructural constraints. Ground-based infrastructures (GBIs) assume a crucial role in seamlessly integrating AAM, serving as pivotal interfaces between airborne and terrestrial transportation modalities. GBIs encompass diverse subsystem areas (SSA) [3], [4]. These SSAs encompass zones such as landing and departure areas, gates, passenger terminals, and taxiways. The design of GBIs necessitates flexibility to accommodate varied local demands and passenger volumes [5]. In a preceding analysis conducted by our team, we delineated the necessary subsystems for GBIs and elucidated methodologies for their modeling [6]. The employment of scenario techniques and associated methodologies within our study facilitated the objective, comprehensive, and structured elicitation of influences and constraints pertinent to specific technical advancements, including mission planning, topology, maintenance, repair, and energy management. Looking ahead, the potential for empirical evaluation is evident, alongside the integration of the sub-workflow into a holistic AAM framework, enabling systematic identification of additional synergies.

1.1. Methodologies for Simulating AAM

To reduce uncertainties and to improve infrastructure developments in the section of AAM, it is necessary to use methods [1], [7], [8]. These will lead to a transparent design of requirements, conditions and targets functions in the future AAM [6], [9], [10], [11].

1.1.1. Systems of Systems

The AAM can be defined as a System of Systems (SoS) [12]. An SoS consists of multiple subsystems that communicate and exchange system data through interfaces. Each of these subsystems can be completely delineated from the others. These include ground-based infrastructure, propulsion systems, and onboard systems of the Vertical Take-Off and Landing Aircrafts (VTOL). Additionally, the consideration includes energy analyses and the lifecycle of the systems, acceptance studies, and meteorological conditions. Energy management systems are crucial, incorporating data on energy requirements, charging power, range, state of charge, charging duration, and grid utilization. Each of these components plays a critical role in the overall functionality of the system. Including these factors provides a comprehensive understanding of the complex interactions and dependencies within AAM. In Figure 1, AAM is depicted as an SoS. This illustration highlights the totality of subsystems considered in this study. It shows how various subsystems interact through interfaces.

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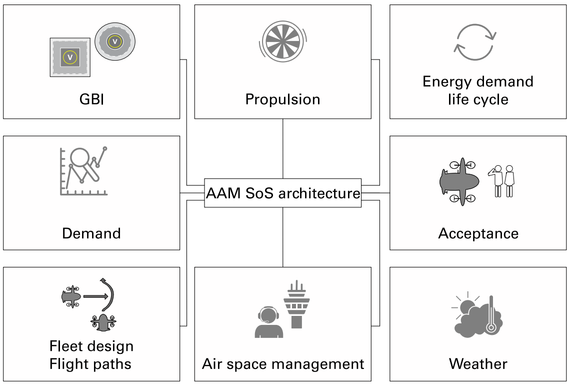

Figure 1: AAM as a SoS

Subsystem interactions are vital for optimizing the overall Ground-Based Infrastructure (GBI) system. These interactions are mapped in a workflow for system simulation in Chapter 3. Ratei et al. and Prakasha et al. emphasize the focus on subsystems within the modeling of ILM and their interface descriptions using the SoS approach [12], [13]. The approach was adopted by Naeem et al., who divided stakeholders into VTOL, BI and airspace management, passengers, ILM as a service, and society including regulations [14]. Conrad et al. developed a simulation platform for managing and optimizing BIs within a multimodal transportation system [15], [16]. This platform uses an agent-based model to represent passenger interactions and the management of terminal, ground, and air operations. It supports the integration of air, ground, rail, and sea transport systems while considering intermodal dependencies, including factors like electric vehicle batteries, flight corridors, and micro-weather conditions.

1.1.2. Modularization of GBI

Modularity in product development is crucial for enabling stakeholders to respond flexibly to changes. The implementation of modular approaches is influenced by factors such as compatibility with existing systems and user-friendliness [17], [18]. By dividing a product into various modules, individual components can be easily replaced or updated without redesigning the entire product. This allows for quick responses to technological advancements by updating only the affected modules. Modularization in product development is key to greater future flexibility. It allows quick and cost-efficient responses to changes, adaptation of products to different needs, and development of innovative solutions. As an extension of the SoS, the GBI and its interfaces can be described using the Feedback-loop Method by Ploetner et al. [19]. Niklaß et al. expand this approach as Cause-Effect Relationships (CER), arranging each subsystem diagonally, allowing for forward and backward iteration loops [20]. This modularizes Ploetner et al.'s approach, enabling expandability and universality within the method application. In GBI, applying CER defines the air and ground interfaces and their influences on the GBI and the module setup within the GBI.

1.2. Building Models for AAM

Jiang et al. developed various simulation tools for ground-based traffic and derived extensions for ground-air traffic for ILM [21]. Besides demand-oriented approaches, solutions can also be defined by geometric boundaries such as administrative zones or national borders. Maget et al. developed a methodology to evaluate potential connections within AAM based on their usability and demand [22]. The state of Bavaria in Germany was used for this purpose, with each municipality provided with an ILM location at its center. Macias et al. created a model for the city of London, England, which includes placement strategies for GBI [23]. This model focuses on administrative boundaries, such as London boroughs, where centralized BI nodes are placed.

1.3. Energy Systems

The energy supply for VTOLs at vertiports presents a complex challenge, requiring sustainable and efficient solutions. Hydrogen supply, battery loading, and battery swapping are the leading technologies being discussed in the literature. Hydrogen is a promising energy carrier, offering high energy density and the potential for long-range flights with relatively quick refueling times compared to batteries [24]. However, the infrastructure for hydrogen production, storage, and distribution is still in the early stages of development, limiting its current feasibility [25]. Battery-powered VTOLs are more suitable for short-distance urban operations, with electric batteries being favored due to their low emissions and the growing availability of renewable energy for charging [26]. Battery loading, is a simpler solution but can result in significant downtime due to charging duration. Battery swapping, in contrast, allows the rapid replacement of empty batteries with fully charged ones, minimizing turnaround time at vertiports [27]. This approach, however, requires standardization of battery designs and storage infrastructure. The realization of the energy systems depends on various framework conditions and parameters at the locations of the vertiport networks and the locations of the individual vertiports. A modular approach to build up an energy supply solution space is also pursued for the energy supply, the basis of which was described in the work of [28], [29].

1.4. Network Planning

In various studies, the optimal positions of vertiports have been analyzed using a hotspot analysis of demand. To achieve a reduction in total travel time through AAM, it is advantageous to position the vertiports in proximity to demand hotspots. In addition to the vertiport locations, it is also essential in network planning to assign quantitative values for each possible vertiport component at all locations. For instance, based on the expected traffic volume per time interval, such as inbound and outbound flights per hour, the number of TLOFs, gates, and taxi lanes must be defined. Simultaneously, numerous questions arise regarding the requirements for charging infrastructure, the necessary capacity for parking stands, or the requirements for local infrastructure to conduct technical checks and maintenance operations. These questions are addressed in the network optimization process, considering assumptions about vertiport locations, vehicle characteristics, and traffic demand. Initial results regarding the capacity design of parking stands and charging infrastructure have been published in [27]. An analysis on maintenance capacity planning is available in [30]. This step consequently transfers the passenger demand between various vertiport locations into site-specific capacity requirements, allowing them to be translated into detailed vertiport topographies in the subsequent steps.

1.5. Vertiport Design Problem

The GBI includes subsystems like ground movements, controls, maintenance planning, and loading. These subsystems combine to form the topology of a GBI. The arrangement of these individual areas is determined by boundary conditions and objective functions. Due to the lack of public data and guidelines for GBI in AAM, the physical and temporal design emerges as a central research question. A topology here is defined as the arrangement of differentiable Sub System Areas (SSA) into a GBI. The literature differentiates between classical topologies and variable approaches. Classical topologies can be categorized into flow-based configurations (FBC), centralized connectivity (CC), and multi-function approaches (MFA) [4], [5], [31]. For the flow-based configuration (FBC), each operation of the VTOL servicing process is assigned a separate area. Additionally, a taxiway is implemented to facilitate the transport of VTOLs between these areas. The installation of differentiated supply and maintenance systems is realized separately from the gates, allowing compliance with required safety distances between FATOs and terminals according to EASA, FAA, and ICAO standards. However, the planning effort for temporally differentiated servicing processes is a disadvantage. Within the flow-based approach, linear, pier, and satellite topologies can be distinguished. Linear topology arranges all required SSA side by side. The pier topology extends the linear arrangement with parallel SSA placement and can include a central taxiway, enhancing capacity with minimal VTOL transport effort. The satellite topology arranges SSA in a curved layout around the FATO area without closing the loop, ensuring obstacle-free flight paths. Overlapping SSA cannot operate simultaneously according to EASA, FAA, and ICAO regulations [32], [32], [33], [34], [35], [36], [37], [38], [39], [40]. Centralized connectivity (CC) involves placing terminals centrally on the BI ground, with FATOs at the edges. The placement of gates is not well-defined in the literature and is shown in examples. Instead of assigning each area a subfunction of the VTOL servicing process, the multi-function approach (MFA) defines a single area that supports multiple functions, such as landing and takeoff within the same space. This eliminates the need for gates and taxiways but prevents simultaneous landings until the serviced VTOL has departed. Classical topologies have fixed, predetermined structures that are mainly manually arranged. They often cannot meet the safety requirements and constraints or the varying demands of the BI due to environmental changes. To address these issues, variable approaches were developed. These methods typically use a grid of defined basic shapes as a basis. The grid positions are initially empty, and each cell is assigned a function from the VTOL servicing process based on optimization criteria. Park et al. developed the Design Optimization Integer Programming (DOIP) for this purpose [3]. In the DOIP method, the available area is divided into basic areas (squares), and the side lengths are determined based on the largest dimension of the largest VTOL in the fleet. This creates a grid structure filled with the functionalities of the SSA, forming the topology of a GBI. Decision variables determine if a subfunction is in a specific cell, maximizing net profit by balancing income from VTOL usage with the lifecycle and operational costs of the BI. The model also includes constraints to ensure connectivity and safety, such as taxiways connecting gates and FATOs and avoiding dead-end taxiways. In summary, classical topologies like FBC, CC, and MFA have fixed structures, while variable topologies use an optimization approach to adapt to varying requirements and constraints, enhancing modularity and modeling quality. Manual design processes for infrastructure are inefficient and error-prone, with low reproducibility. There is a need for a more comprehensive approach that considers the entire handling process, not just partial processes. Park et al.'s DOIP, combined with approaches from Li et al. and Preis et al., offers a strategy to optimize BI topologies [3], [5], [41]. However, it currently lacks areas for inspection, maintenance, repair, and fuel supply for VTOLs, and does not ensure continuous traversability. The use of only square cells limits flexibility, and the DOIP focus on a single objective function does not meet realistic needs [42]. Additionally, there is a lack of scenario consideration and sufficient mathematical boundary conditions, resulting in poor connectivity and potential dead ends. Improving modularity and development quality could enhance adaptability and reduce long-term maintenance costs. In summary, the main deficiencies in ground-based infrastructure development and modeling stem from a lack of robustness and flexibility.

2. METHODOLOGICAL APPROACH

Herein, we will address the aspects and delineate the methodological approach to developing a simulation-based analysis of GBIs. The focus lies on the technical implementation and analysis of energy management for VTOL, network planning of GBI and topologies with a closer examination of the interactions between these subsystems. AAM can be conceptualized as a complex optimization problem, given the multitude of options stemming from diverse stakeholder positions and environments. To model this complexity, it is advisable to construct an AAM model within a tool-assisted simulation environment. Assumptions and constraints for this optimization problem arise from scenario development analysis, with parameters transformed into objective functions and input parameters.

2.1. Modeling Assumptions and Constraints

Herein, it is necessary to select suitable methods from the current state of the art to develop a toolkit for future-proof and flexible development of GBI for AAM. Predefined evaluation criteria are used for this selection. Based on this selection, a collection of methods will be created and modified to meet the requirements of AAM. The focus is on the product planning and development stages of the product lifecycle. The evaluation criteria focus on requirement compliance and quality management, adaptability, and applicability with the inclusion of experience. Requirement compliance and quality management ensure that the method meets specific goals and development requirements, supports effective risk and quality management, and provides comprehensive documentation. Adaptability ensures the method can respond agilely to internal and external changes, integrates feedback directly, and supports iterative and incremental approaches. Applicability emphasizes that the method should be easy to learn and implement, with minimal reliance on special tools or extensive prior knowledge, and encourages stakeholder involvement. The chosen methods are then evaluated against these criteria to form a toolkit that will address the deficiencies of classical topologies. This approach ensures that the development of GBI within AAM is robust, flexible, and future-proof, addressing current deficiencies and optimizing for multiple criteria. The results of the utilization of the methods Dimensions of Uncertainty, Morphological Analysis, Sociovision, Process Design and Delphi-Method are the influence parameter of the domain AAM on the GBI development. These are shown in Table 1.

Table 1: results of the utilization of the methods Dimensions of Uncertainty, Morphological Analysis, Sociovision, Process Design and Delphi-Method are the influence parameter of the domain AAM on the GBI development

Area	Influence tasks on GBI in AAM
Fleet	Composition
External Changes	Technical Changes
Maintenance	Infrastructure
	Duration
Energy	Type of fuel supply
	Supply infrastructure
Regulation	Kind and Scope
Noise	Kind and Amount
	Special Regulation in the Area of GBI
Airspace	Airspace Structure
GBI	Size of Area
	Parking Slots for VTOLs
	Airspace Movements
	Kind and Capacity of fuel supply
	Quantity
Operation	Operation concept and organization
	Kind of transport and reason
	Maximal Take-Off Weight
	Addition into existing transport system
	Individuality
	Turn-Around Time
	Number of Passengers
	Possibilities for emergency landing
VTOLs	Maximal Take-Off Weight
	Energy demand
	Battery Capacity
	Kind of rotor
	Approach and landing procedure

2.2. Cause-Effect Relationships

In GBI, applying CER defines the air and ground interfaces and their influences on the GBI and the module setup within the GBI. These will be presented and integrated into a CER matrix. The temporal dimension of a GBI relates to the turnaround time for processing a VTOL. This time includes all activities necessary to prepare a VTOL for the next flight, which is critical for the overall performance of a GBI, as shorter turnaround times increase the frequency of flight movements, thus enhancing efficiency and throughput. Both airside and groundside interfaces, as well as the various modules of a vertiport, are integrated into this process. The following sections will elaborate on these aspects. Airside interfaces of a GBI include landing and takeoff areas that are sufficiently dimensioned and optimally located to ensure safe flight movements. Navigation aids and communication systems play a central role, providing precise navigation and secure communication between aircraft and ground stations. Weather monitoring systems are essential to provide real-time information on meteorological conditions that can affect flight operations. The airspace structure and management are crucial for smoothly integrating AAM flights into existing air traffic, including planning flight altitude profiles and considering fleet composition. Noise sources must be minimized to ensure public acceptance. Groundside interfaces encompass passenger terminals equipped with waiting areas, check-in counters, and security checks. Seamless integration into the urban transportation network is crucial to ensure door-to-door connectivity, including links to individual and public transport and other mobility forms. Charging infrastructure is necessary to recharge electrically powered VTOLs. Designing the network for GBI requires a flexible and efficient route network to reduce travel time compared to conventional mobility solutions. Strategic placement of GBI locations should maximize demand for urban air mobility and passenger accessibility, considering proximity to urban centers, transport hubs, and key business or residential areas. Interaction between GBI locations and potential demand is a central factor. An effective network design must account for varying traffic flows and peak times to avoid congestion and promote even traffic distribution. Real-time data and predictive models are helpful for accurate demand forecasting and resource planning. Ground movements of a GBI focus on the landing and approach of VTOLs, supported by designated pathways and suitable parking positions. Noise protection is a significant factor, influencing both landing and takeoff procedures and pathway design. Coordinated landing and approach procedures ensure safety and efficiency, requiring specifically marked and equipped landing areas to facilitate aircraft maneuvers. Pathways should allow the shortest and safest routes between landing areas and parking positions, minimizing time spent on pathways. Control systems are essential for the safety and reliability of VTOLs, involving inspections and maintenance programs to ensure proper functioning and safe operations. Regular visual and technical inspections are conducted before each flight, checking for visible damage and testing electronic and mechanical systems. Condition monitoring occurs continuously, with sensors transmitting operational data to a maintenance management system for early issue detection and maintenance action initiation. Maintenance programs include preventive and reactive measures, aiming to ensure the safe operation and longevity of

VTOLs. Loading operations at a GBI involve passenger transport and logistical operations, including ticket systems, passenger checks, gates, energy supply, and storage. The passenger loading process involves boarding and disembarking, ensuring all security checks are completed. Logistical loading includes loading freight for VTOL transport, emphasizing quick and safe processes to minimize delays. The ticket system should be user-friendly, with online booking options and automated check-in counters to optimize the process. Security checks include identity verification and screening for prohibited items, balancing efficiency with safety standards. Energy supply encompasses charging stations for VTOLs and energy storage systems to manage peak loads and ensure continuous energy availability. Storage facilities include space for freight and storage for spare parts and maintenance equipment.

3. AAM MODEL AND WORKFLOW

AAM requires a comprehensive model and workflow to integrate seamlessly into existing transportation systems. The goal is to develop strategic planning processes to optimize local capacities such as parking, charging infrastructure, and traffic flows. This enhances fleet operations, minimizes empty flights, and optimizes fleet size, composition, and energy demand. Infrastructure design considers both air and ground systems, particularly for VTOLs. Key performance indicators (KPIs) and the DOIP, treated as a variable topology, are optimized for goal functions, e.g. capacity, through mathematical formulations. Energy management systems are crucial, incorporating data on energy requirements, charging power, range, state of charge, charging duration, and grid utilization. MATLAB models estimate the electric demand of drones across various scenarios. Subsystem interactions are vital for optimizing GBI.

3.1. Subsystem Interactions and Workflow for Overall System Simulation

Mathematical formulations reflecting the interconnections of AAM can be identified to ensure a comprehensive analysis in line with the diverse formulation problem. We outline current insights into network optimization, infrastructure design, and energy management systems, highlighting interactions among them. The goal of network optimization is to develop and apply a strategic planning process to determine minimum local capacities for metrics such as parking spaces, charging infrastructure, and traffic flows per minute. Efforts are directed towards efficient fleet operations to minimize empty flights and optimize fleet size, composition, and energy demand. Infrastructure design must consider interconnected aspects of air and ground infrastructure within the framework of VTOLs. Energy management systems incorporate information such as energy requirements, charging power, range, state of charge, charging duration of individual vehicles, and electrical grid utilization in each area. MATLAB Simulink-based models are developed to estimate the electric demand of drones and drone traffic, considering a wide range of flight scenarios and dynamic start and endpoints. The interaction of subsystems is defined in a workflow for overall system simulation, divided into three serially connected sub-workflows, which are represented in Figure 2. Interactions between subsystems are crucial for optimizing the overall GBI system.

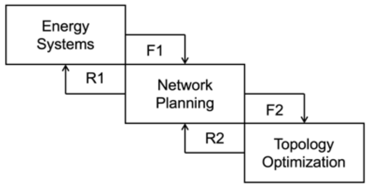

Figure 2: AAM Workflow with connected sub-workflows through application of the CER Methodology

In the following sections the three sub-workflows are described in detail.

3.2. Energy Systems

To do suitable consideration of the variable parameters and uncertainties, a solution space is created for the energy supplies and the different variants of the energy system. This can be used to create individual solutions and versions of the energy system by configuring them according to the requirements of possible different vertiports. The focus is on the areas of hydrogen supply, vehicle charging and battery swap. These variants and their functions are described in individual pool diagrams. To describe the solution space, the processes are recorded with all possible characteristics using BPMN in the form of pools and swim lanes in corresponding diagrams. In this way, all possible functions of each process are documented.

3.2.1. Energy Supplies Modules

The energy supply modules are used as functions to span a solution space. For the structure of the solution space and the modules, the three areas already mentioned are considered and further detailed. In the case of hydrogen supply, for example, an additional distinction is made in the functions as to whether the Vertiport is supplied via a pipeline, i.e. a direct connection, or via tanker trucks and variable storage. Furthermore, possible different working pressures (and the associated tank durations and space requirements) and the resulting modules are included in the solution space. The relevant functions for charging the vehicles and for a possible battery swap are also included. Following the state-of-the-art method of function-based design of solution spaces using BPMN, this is used to create a database that enables the configuration, adaptation and analysis of energy supply functions as well as the processes and documentation directly and adaptably (to other framework parameters). The functions and their dependencies are stored in the database and supplemented with additional parameters. For example, the database also contains estimated space requirements, possible personnel or security levels.

3.2.2. Configuration Model

For the initial implementation of the configurator, the database is transferred to Excel and extended by an interface to the user. By entering possible design parameters, such as the number of refueling processes/charges/battery swaps (per day and per hour to estimate the peak load), different variants can be configured. Exemplary further input parameters are the location of the Vertiport (urban or rural), available space and possible spatial expansion, or the expected type of vehicles operating in the network. The result of the configuration is a comparison of the various energy supply systems and their specifications. This includes the modules of the systems (tank, battery rack or piping systems), their dimensions and the required number. Overview parameters, such as the total space requirement of the respective variants, are also displayed side by side for direct comparison. The linking of the solution spaces described here using the example of energy supply with network planning can take place within the framework of an AAM workflow with connected sub-workflows. This has already been documented for other areas of the Vertiport in existing publications (see also [30]).

3.3. Network Planning

To quantify the local requirements for vertiports within the framework of network optimization, a modeling approach has been developed that takes various datasets into account as input parameters, including vehicle characteristics, traffic scenarios, and vertiport locations. A crucial input of the model is the mission pool, which is derived from the use case-specific demand scenario. The missions are defined by their start and destination coordinates, the number of traveling passengers, and the desired departure time, covering a representative operational day of the AAM network. For simplification, it was assumed that all missions are known in advance and that the entire operation runs without disruptions (such as technical failures, weather phenomena, or similar events). Under these conditions, an integrated step is performed in which optimized operational plans are assigned to potential vehicle candidates. These operational plans consider vehicle characteristics, including speeds in different operational phases, battery capacity, and seating capacity. This ensures that each vehicle is assigned only missions that are feasible within the given time and energy constraints. Empty repositioning flights of vehicles within the network are also considered. Once the potential candidates for the fleet pool are generated, individual vehicles are selected based on their efficiency and added to the fleet, while other candidates with less optimal operational plans are excluded by solving a linear optimization problem. This process is repeated until all missions in the pool have been assigned to a specific vehicle.

3.3.1. Strategic Planning and Local Capacities

Based on the resulting operational plans for the entire fleet, local analyses of vertiport utilization can finally be conducted. In this step, the vertiports are analyzed throughout the entire operational day in terms of their load profiles. For example, to determine the local demand for parking positions, it can be assessed at what times and how many vehicles are parked at or require energy supply from a specific vertiport. The peak value of the respective load profile can then be used to determine the necessary capacity for the metric under investigation. By using the subsequent model for topology analysis, the number of incoming and outgoing traffic movements can also be translated into the required number of TLOFs, taxi lanes, and gates, allowing the topology and the necessary area of a vertiport to be determined.

3.3.2. Maintenance Capacity Planning

To determine the need for maintenance facilities as an additional vertiport component, this workflow has been expanded with further steps. First, analyses of the expected maintenance intervals were carried out to quantify the vehicle-specific requirements in terms of the duration and frequency of various checks [29], [43]. Based on these results, a maintenance status is randomly assigned to each vehicle in the determined fleet. Subsequently, a fourth constraint is introduced to the vehicles' operational plans, stating that the plan must also be feasible in terms of maintenance status. If a check is required during the missions throughout the operational day, the mission sequence is adjusted so that the vehicle visits a maintenance station before falling below a defined threshold of remaining operational hours. If maintenance can be completed before the end of the operational day, the vehicle resumes its remaining missions in the operational plan accordingly.

3.4. Topology Optimization

The development of adaptive, modular, and variable GBI concepts involves understanding processes and translating requirements into solution concepts. This includes ground movements, controls, loading, boundary conditions of subsystem areas for topological modeling, interface considerations, and handling strategies. For ground movements, controls, and loading, the focus is on understanding the specific requirements and integrating them into the overall system. The boundary conditions for subsystem areas are crucial for accurate topological modeling, ensuring that all elements function cohesively. Interface considerations ensure seamless integration between different subsystems, while handling strategies optimize operational efficiency. The modeling of the entire ground-based infrastructure system begins with the basic model, defining input parameters, and selecting an optimization algorithm.

3.4.1. Mathematical Formulations and Interconnections

The GBI will be modeled in a comprehensive system simulation. Initially, the system structure of the basic model, its input parameters, objective functions, and the relationships between the SSA will be outlined. Finally, a modeling environment and an optimization algorithm will be selected for the system simulation. The basic model of the GBI consists of a series of identical shapes called cells. Both the cell shape and size are crucial, and each cell is assigned an SSA. The EASA recommends square or round basic shapes for GBI, but not all SSA can be placed within a round shape [40]. For squares, there are no undefined areas due to overlaps or gaps, and the edges of the GBI can be clearly defined, which simplifies neighbor definitions and reduces implementation effort. The cell size should at least match the largest SSA of the GBI to represent all types of area. Each cell is assigned only one type of area, and dummy cells are implemented to apply boundary and connectivity conditions to the outer cells of the GBI. Input parameters for the simulation are determined based on existing method tool kit, aiming to keep the number of parameters as low as possible. These parameters will be used in the MATLAB environment. To perform topology optimization, an appropriate modeling environment, such as MATLAB, is selected due to its Optimization Toolbox and Global Optimization Toolbox. This environment supports reproducible results and integrates third-party applications, ensuring consistent boundary conditions and libraries. The

Optimization Toolbox provides solvers for various mathematical problems, while the Global Optimization Toolbox solves multi-objective optimization problems. The optimization algorithm is selected based on criteria like program usability, result reproducibility, and the ability to handle numerous constraints using integer values. The solver intlinprog from MATLAB's Optimization Toolbox is chosen for its ability to solve deterministic and discrete optimization problems. The implementation of the optimization algorithm in MATLAB involves defining variables and constraints, converting binary representations back to SSA, and using symbolic representation for constraints and objective functions. This approach ensures a streamlined and efficient optimization process. Objective functions are defined based on external conditions such as location or mission assignment within a GBI network. These functions are analyzed for their presence in the literature and necessity for the handling process. Capacity and throughput, noise reduction, maximizing usable area, minimizing turnaround time, maximizing control and parking areas and safety are critical factors considered in the optimization. Each objective function is represented in the MATLAB environment.

3.4.2. MATLAB-Based Model

Driveability includes connecting every VTOL-SSA with a TW and avoiding dead ends. It ensures that all necessary SSA are accessible from a FATO. Control areas are considered drivable SSA. While Park et al. provide mathematical formulations, their implementation in a modeling environment is missing [3]. Wang et al. and Rehfeldt et al. have addressed connectivity in IP, but subgraph polytopes and optimization of connected subgraphs are not applicable to this problem [44], [45]. Therefore, driveability must be examined, divided into preventing dead ends and connecting TW to FATOs. Unlike Park et al., dead ends are prevented by constraints. The first input possibility is connecting at least one TW with another TW cell or a FATO cell. In certain cases, the implementation of the FATO-Taxiway relationship needs iterative adjustments within the modeling environment. Although the presented relationship offers design freedom, it may be fulfilled even when multiple taxiway cells are connected without a real connection to a FATO. Therefore, the following two relationships are integrated and called iteratively. In the second iteration step, the constraint is adjusted if two or more taxiway cells are connected without a link to a FATO. The third input possibility allows connecting all FATOs and taxiways to each other. To achieve this, blocking is prevented, as the connection works only if no parallel taxiways are possible. All taxiway cells should have two other taxiway cells as neighbors, except those at the beginning and end of a taxiway. Safety on a BI is defined by overflight prohibitions for SSA with passenger or staff presence and defining neighbor cells without such presence around a FATO. Only taxiway and TV areas should be near a FATO to minimize security risks. The safety conditions are specified by the restrictions of the neighboring areas of FATOs. Noise conditions are not analyzed here concerning the number, thickness, or height of noise barriers. The noise emission minimization objective function introduces additional constraints, like restricting area arrangements. Verification through checking boundary conditions involves conditions that must be met for every BI verified automatically in MATLAB after input by the user. The program sequence in the modeling environment is divided into a main script and sub-scripts. The main script frames the program and acts as the executable for users, while sub-scripts function as integrated functions called during execution. Global variables or parameter passing via structure arrays are used, with parameter passing preferred to avoid variable overwriting. Input parameters include VTOL and BI dimensions, objective functions, area selection, and TW connection. These inputs generate requirements. An optional matrix design can be inputted, checked against boundary conditions, and used as a reference. Finally, the number and positions of FATOs are optionally entered. Topology optimization begins with parameter passing and problem definition. Optimization and helper variables are integrated, constraints applied, consistent matrices generated, and area selections implemented. Optimization options are set, and topological optimization executed. If results are obtained, a plot of the BI matrix is created. The optimized topology is then checked for driveability and general constraints. If checks fail, optimization is repeated after adjusting constraints. If successful, KPIs are calculated and displayed.

4. RESULTS AND DISCUSSION

4.1. Energy Systems

The extended Swimlane diagram approach to building a solution space maps all potentially possible functions of the vertiport's energy supply and enriches them with additional information and parameters. It thus creates a comprehensive database and a system solution space. In addition to the functions themselves, this database also contains information on the space requirements resulting from the functions, which materials and devices are required to implement the functions, which personnel resources, which time resources (duration of the function sequence) and possible automation variants. This information can be used to configure the processes (functional sequences) at the site based on the given boundary conditions and requirements for the individual site. In addition, the technical requirements and specifications of the vertiport and its equipment can be derived (configuration of products and hardware). This information can be passed on to other areas such as network planning and topology optimization.

4.2. Network Planning

In the conducted investigations, fleets were created and analyzed for various traffic scenarios, along with the resulting capacity requirements for parking positions, charging infrastructure, and maintenance stations. For a fleet of 275 vehicles, an estimated 422 parking positions and a peak charging load of 11.1 MW were needed. It was shown that the concept of fixed batteries versus battery swap significantly impacts fleet size (275 vs. 225 vehicles) and charging demand. While battery swapping can reduce fleet size, it may lead to a significant increase in peak charging loads. Maintenance needs were found to be relatively low, with a fleet of 338 vehicles requiring a maximum of 11 maintenance checks per day. As a result, empty repositioning flights due to maintenance had little impact, suggesting that for similar fleet sizes, a centralized maintenance facility is preferable to a decentralized approach.

4.3. Topology Optimization

Based on predefined goals, the optimization quality is assessed using general and specific metrics. The goals include generating optimized topologies, optimization duration, reproducibility, sensitivity to input parameters, objective function influence, KPI analysis, scenario representation, and advantages over classical and variable topologies. Optimization parameters, boundary conditions, and objective functions must be correctly implemented with the optimization algorithm to generate optimized topologies. Reproducibility must be 100% for result comparability. Input parameters for optimization control will be implemented in the modeling environment, with sensitivity analysis being a key factor. Users can select and weight objective functions to influence them directly. Various scenarios regarding BI size, area number, area variation, and objective functions can be created, with recommendations derived from optimization. Optimized topologies will be compared to classical and variable topologies from the literature, highlighting their benefits. Necessary input parameters depend on implemented boundary conditions and objective functions, entered through MATLAB input fields. There are mandatory and optional inputs. If no input is given, a predefined value is used. Parameters related to the area size and maximum VTOL diameter are mandatory, along with selecting a primary and secondary objective function. Optional selections include control and parking areas, and FATO connection types. FATO numbers and positions can be fixed, excluding these cells from optimization variables. FATO positioning also depends on surrounding infrastructure, as buildings may limit flight paths. Decisions on parallel taxiways are also required. An initial topology can be optionally entered for comparison with the optimized one.

5. CONCLUSION

To address future traffic infrastructure challenges, integrating a new mobility form that deviates from conventional, overloaded routes is crucial for expanding capacity. AAM offers such an expansion by incorporating airspace into urban traffic infrastructure. VTOLs provide demand-driven, air-based passenger transport, serving as a mobility alternative through a ground interface connected to conventional infrastructure. This interface, realized through GBI, is essential for AAM integration, facilitating all operational aspects of VTOLs and passenger handling. Vertiports offer a customizable ground infrastructure variant that meets AAM requirements.

5.1. Summary of Findings

The state of the art was reviewed, defining air-based mobility. GBI were explained. Existing models and topologies, including classic and variable ones, were examined. MATLAB was chosen for modeling due to its Optimization Toolbox, with intlinprog selected for integer optimization to ensure reproducible and precise results. Developing a consistent model specific to Vertiport requirements yet adaptable by the user is essential. The scope regarding area types and VTOLs was defined, and input parameters were specified. Different objective functions were detailed, along with essential aspects of boundary conditions.

5.2. Future Research Directions

Future work should include detailed examinations of inputs and dimensions, including higher cell numbers and more input combinations. The cell concept should be explored for potential advantages. Another objective function integration concept could allow implementing mathematical equations as objectives, increasing goal diversity. Boundary condition implementation should be specified for specific cell numbers. Algorithm analysis suggests exploring other modeling environments with more integer optimization algorithms. Choosing a solver that integrates non-linear boundary conditions and separate objective functions could broaden applications. Using heuristics and cut generation with intlinprog should be analyzed for their impact on optimization and integrated if beneficial.

REFERENCES

[1] R. Bridgelall, “Locating Electrified Aircraft Service to Reduce Urban Congestion,” *Information*, vol. 15, no. 4, Art. no. 4, Apr. 2024, doi: 10.3390/info15040186.

[2] R. Goyal, C. Reiche, C. Fernando, and A. Cohen, “Advanced Air Mobility: Demand Analysis and Market Potential of the Airport Shuttle and Air Taxi Markets,” *Sustainability*, vol. 13, no. 13, Art. no. 13, Jan. 2021, doi: 10.3390/su13137421.

[3] B. T. Park and S. H. Kim, “Vertiport Design Optimization using Integer Programming,” *2022 IEEEAIAA 41st Digit. Avion. Syst. Conf. DASC*, pp. 1–6, Jan. 2022, doi: 10.1109/DASC55683.2022.9925809.

[4] M. Taylor, A. Saldanli, and A. Park, “Design of a Vertiport Design Tool,” *2020 Integr. Commun. Navig. Surveill. Conf. ICNS*, pp. 2A2-1-2A2-12, Sep. 2020, doi: 10.1109/ICNS50378.2020.9222989.

[5] L. Preis, “Estimating vertiport passenger throughput capacity for prominent eVTOL designs,” *CEAS Aeronaut. J.*, vol. 14, no. 2, pp. 353–368, Mar. 2023, doi: 10.1007/s13272-023-00650-5.

[6] J. Eltgen, T. Fraske, G. Mavraj, M. Swaid, D. Kloock-Schreiber, and Roentgen, O., Schüppstuhl, T., “Methodik zur ganzheitlichen Analyse bodengebundener Infrastruktur für die Urban Air Mobility,” *Proc. DLRK Dtsch. Luft- Raumfahrtkongress 2023*, vol. 2023, Jan. 2023.

[7] F. A. Abbasi, R. H. Ngouna, M. A. Memon, M. S. Al Reshan, A. Sulaiman, and A. Shaikh, “Fostering UAM implementation: from bibliometric analysis to insightful knowledge on the demand,” *Soc. Netw. Anal. Min.*, vol. 14, no. 1, p. 80, Apr. 2024, doi: 10.1007/s13278-024-01210-3.

[8] P. Bishop, A. Hines, and T. Collins, “The current state of scenario development: an overview of techniques,” *Foresight*, vol. 9, no. 1, pp. 5–25, Feb. 2007, doi: 10.1108/14636680710727516.

[9] G. Mavraj *et al.*, “A Systematic Review of Ground-Based Infrastructure for the Innovative Urban Air Mobility,” *Trans. Aerosp. Res.*, vol. 2022, no. 4, pp. 1–17, Dec. 2022, doi: 10.2478/tar-2022-0019.

[10] A. Straubinger, R. Rothfeld, M. Shamiyeh, K. Büchter, J. Kauser, and K. O. Plötner, “An overview of current research and developments in urban air mobility - Setting the scene for UAM introduction,” *J. Air Transp. Manag. 87*, Jan. 2020, doi: 10.1016/j.jairtraman.2020.101852.

[11] J. Michelmann, A. Straubinger, A. Becker, C. A. Haddad, K. O. Plötner, and M. Hornung, “URBAN AIR MOBILITY 2030+: PATHWAYS FOR UAM – A SCENARIO- BASED ANALYSIS”.

[12] P. S. Prakasha *et al.*, “Urban Air Mobility Vehicle and Fleet-level Life-Cycle Assessment Using a System-of-Systems Approach,” in *AIAA AVIATION 2021 FORUM*, VIRTUAL EVENT: American Institute of Aeronautics and Astronautics, Aug. 2021. doi: 10.2514/6.2021-2457.

[13] P. Ratei, N. Naeem, P. S. Prakasha, and B. Nagel, "Sensitivity analysis of urban air mobility aircraft design and operations including battery charging and swapping," *CEAS Aeronaut. J.*, Apr. 2024, doi: 10.1007/s13272-024-00725-x.
[14] N. Naeem, P. Ratei, and P. S. Prakasha, "Modelling and simulation of urban air mobility: an extendable approach," *J. Phys. Conf. Ser.*, vol. 2526, no. 1, p. 012104, Jun. 2023, doi: 10.1088/1742-6596/2526/1/012104.
[15] C. Conrad, Y. Xu, D. Panda, and A. Tsourdos, "Intelligent Vertiport Traffic Flow Management for Scalable Advanced Air Mobility Operations," in *2023 IEEE/AIAA 42nd Digital Avionics Systems Conference (DASC)*, Barcelona, Spain: IEEE, Oct. 2023, pp. 1–10. doi: 10.1109/DASC58513.2023.10311299.
[16] C. Conrad, Y. Xu, D. Panda, and A. Tsourdos, "Simulating Enhanced Vertiport Management in a Multimodal Transportation Ecosystem," in *2024 IEEE Aerospace Conference*, Big Sky, MT, USA: IEEE, Mar. 2024, pp. 1–14. doi: 10.1109/AERO58975.2024.10521373.
[17] J. Eltgen and T. Schüppstuhl, "MROPort for Airworthiness Checks of VTOLs in a Future-Proof Environment," *Proc. AIAA Aviat. 2023 Forum*, vol. 2023, Jan. 2023, doi: 10.2514/6.2023-3576.
[18] J. Eltgen and T. Schüppstuhl, "Technical concepts for inspecting UAVs for damage," *Proc. 33th Congr. Int. Counc. Aeronaut. Sci.*, vol. 2022, Jan. 2022, doi: 10.15480/882.4760.
[19] K. O. Ploetner *et al.*, "Long-term application potential of urban air mobility complementing public transport: an upper Bavaria example," *CEAS Aeronaut. J.*, vol. 11, no. 4, pp. 991–1007, Jan. 2020, doi: 10.1007/s13272-020-00468-5.
[20] M. Niklaß *et al.*, "A Collaborative Approach for an Integrated Modeling of Urban Air Transportation Systems," *Aerospace*, vol. 7, no. 5, Jan. 2020, doi: 10.3390/aerospace7050050.
[21] X. Jiang *et al.*, "Simulating the Integration of Urban Air Mobility into Existing Transportation Systems: A Survey," May 2023, doi: 10.48550/arXiv.2301.12901.
[22] C. Maget, S. Gutmann, and K. Bogenberger, "Where Should We Fly? A Metric to Determine Possible Connections for Advanced Air Mobility," Jan. 2023.
[23] J. Escribano Macias, C. Khalife, J. Slim, and P. Angeloudis, "An integrated vertiport placement model considering vehicle sizing and queuing: A case study in London," *J. Air Transp. Manag.*, vol. 113, p. 102486, Oct. 2023, doi: 10.1016/j.jairtraman.2023.102486.
[24] T. Yusaf *et al.*, "Sustainable hydrogen energy in aviation – A narrative review," *Int. J. Hydrog. Energy*, vol. 52, pp. 1026–1045, Jan. 2024, doi: 10.1016/j.ijhydene.2023.02.086.
[25] M. Yue, H. Lambert, E. Pahon, R. Roche, S. Jemei, and D. Hissel, "Hydrogen energy systems: A critical review of technologies, applications, trends and challenges," *Renew. Sustain. Energy Rev.*, vol. 146, p. 111180, Aug. 2021, doi: 10.1016/j.rser.2021.111180.
[26] L. A. Garrow, B. J. German, and C. E. Leonard, "Urban air mobility: A comprehensive review and comparative analysis with autonomous and electric ground transportation for informing future research," *Transp. Res. Part C Emerg. Technol.*, vol. 132, p. 103377, Nov. 2021, doi: 10.1016/j.trc.2021.103377.
[27] M. Swaid, J. Pertz, M. Niklaß, and F. Linke, "Optimized capacity allocation in a UAM vertiport network utilizing efficient ride matching," *AIAA Aviat. 2023 Forum*, Jun. 2023, doi: 10.2514/6.2023-3577.
[28] S. Papakonstantinou, D. Kloock-Schreiber, T. Kocks, U. Wieczorek, and V. Gollnick, "Vertiports Task Areas and Functional Sequences for Basic Operations in Urban Space," in *2023 IEEE/AIAA 42nd Digital Avionics Systems Conference (DASC)*, Barcelona, Spain: IEEE, Oct. 2023, pp. 1–10. doi: 10.1109/DASC58513.2023.10311150.
[29] S. Papakonstantinou *et al.*, "MRO for VTOLS in a Functional Sequence Solution Space," in *Proc. 34th Congr. Int. Counc. Aeronaut. Sci.*, in Vol. 2024. Sep. 2024.
[30] M. Swaid, S. Papakonstantinou, D. Kloock-Schreiber, and V. Gollnick, "Design of a UAM Ground Infrastructure Network with Respect to Maintenance Capacity Requirements," in *Proc. 34th Congr. Int. Counc. Aeronaut. Sci.*, in Vol. 2024. Sep. 2024.
[31] S. Zelinski, "Operational Analysis of Vertiport Surface Topology," *2020 AIAAIEEE 39th Digit. Avion. Syst. Conf. DASC*, Nov. 2020, doi: 10.1109/DASC50938.2020.9256794.
[32] Federal Aviation Administration, "Annex 16 - Environmental Protection - Volume I - Aircraft Noise," ICAO. Accessed: Jul. 03, 2024. [Online]. Available: https://store.icao.int/en/annex-16-environmental-protection-volume-i-aircraft-noise
[33] U.S. Department, of Transportation, Federal Aviation, and Administration, "Heliport Design 150/5390-2C," Apr. 2012.
[34] Federal Aviation Administration, "VERTIPORT DESIGN 150/5390-3," May 1991, [Online]. Available: https://www.faa.gov/documentLibrary/media/advisory_circular/150-5390-3/150_5390_3.pdf
[35] International Civil Aviation Organization (ICAO), "Annex 14 - Aerodromes - Volume II - Heliports," *ICAO*, Accessed: Jan. 30, 2024. [Online]. Available: https://store.icao.int/en/annex-14-aerodromes-volume-ii-heliports
[36] European Aviation Safety Agency (EASA), "VTOL designs for Urban Air Mobility," VTOL designs for Urban Air Mobility. Accessed: Feb. 08, 2024. [Online]. Available: https://www.easa.europa.eu/en/light/topics/vtol-designs-urban-air-mobility
[37] European Aviation Safety Agency (EASA), "Special Condition for small-category VTOL aircraft," vol. 1, no. SC-VTOL-01, Jul. 2019, Accessed: May 06, 2024. [Online]. Available: https://www.easa.europa.eu/sites/default/files/dfu/SC-VTOL-01.pdf
[38] European Aviation Safety Agency (EASA), "Certification Specifications and Guidance Material for the design of surface-level VFR heliports located at aerodromes that fall under the scope of Regulation (EU) 2018/1139 (CS-HPT-DSN)," no. 1, May 2019.
[39] European Union Aviation Safety Agency, "Regulation (EU) 2018/1139," *EASA*, Aug. 2018, Accessed: Jan. 30, 2024. [Online]. Available: https://www.easa.europa.eu/en/document-library/regulations/regulation-eu-20181139
[40] European Union Aviation Safety Agency (EASA), "Vertiports Prototype Technical Specifications for the Design of VFR Vertiports for Operation with Manned VTOL-Capable Aircraft Certified in the Enhanced Category (PTS-VPT-DSN)," Mar. 2022.
[41] X. Li, "Repurposing Existing Infrastructure for Urban Air Mobility: A Scenario Analysis in Southern California," *Drones*, vol. 7, Jan. 2023, doi: 10.3390/drones7010037.
[42] J. Eltgen, A. Viebrock, and T. Schüppstuhl, "Use of Integer Programming for Topology Optimization of Ground-Based Infrastruc-tures for VTOLs in Advanced Air Mobility," in *Deutscher Luft- und Raumfahrtkongress 2024*, Hamburg: Deutscher Luft- und Raumfahrtkongress 2024, 2024.
[43] S. Papakonstantinou, D. Kloock-Schreiber, T. Kocks, U. Wieczorek, and V. Gollnick, "Vertiports Task Areas and Functional Sequences for Basic Operations in Urban Space," pp. 1–10, doi: 10.1109/DASC58513.2023.10311150.
[44] Y. Wang, A. Buchanan, and S. Butenko, "On imposing connectivity constraints in integer programs," *Math. Program.*, vol. 166, no. 1, pp. 241–271, Nov. 2017, doi: 10.1007/s10107-017-1117-8.
[45] D. Rehfeldt, H. Franz, and T. Koch, "Optimal connected subgraphs: Integer programming formulations and polyhedra," *Networks*, vol. 80, no. 3, pp. 314–332, 2022, doi: 10.1002/net.22101.

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