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A MODULAR DESIGN CONCEPT FOR VERTIPORTS IN URBAN AIR MOBILITY SYSTEMS

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Abstract: *Current technological developments open up the possibility of implementing airborne passenger transport in urban areas. The concepts for urban air transport are mostly based on so-called vertiports and vertical take-off and landing (VTOL) vehicles with rotary wings. Depending on the function of a vertiport in a network, various configurations are required, ranging from vertistops, over flex-vertiports, traffic hubs, up to maintenance hubs. The Vertiport project aims to develop a modular design for such vertiports and to implement the idea of function-oriented modularization in the construction domain. This paper presents the first implementation approach with exemplary application examples.*

Key Words: ***Urban Air Mobility (UAM), Vertiport, Vertistop, Air Taxis, Modular Design, Modularization***

1. INTRODUCTION

The technological developments in the field of electromobility, automatization and batteries provide crucial advances in order to enable airborne passenger transport in urban areas for broad use. While use cases for regional air mobility are usually based on short take-off and landing (STOL) vehicles with fixed wings, the concepts for air transport in intra-urban areas with high population densities are mostly based on vertical take-off and landing (VTOL) vehicles with rotary wings. The latter are supposed to start and land at specifically dedicated facilities that are mostly referred to as vertiports. Depending on the respective function of a vertiport in a network, various configurations are required, reaching from vertistops (a vertiport site with minimal size, functionality and cost), over flex-vertiports (which are flexible and temporary usable), traffic hubs (vertiport locations with high flight frequency and passenger volume), up to maintenance hubs (vertiports with a focus on vehicle MRO). Beyond the task-specific differences of a vertiport, there are additional differences depending on the deployment scenarios (with constraints based on the country, city or urban area). The arising challenges comprise for instance the integration of vertiports into existing, intermodal transport infrastructure, the management of automated vehicle maintenance, the integration of vertiports into the city or the organization of the urban airspace. All these tasks are addressed by the project “Vertiport”, which aims to develop a modular design concept for vertiports and is presented in this study, yielding a first approach of implementation.

In order to realize the vision of urban air mobility, there already exists a wide variety of work and ideas [1]. These contributions are being developed by a large number of companies and research institutions, such as in Hamburg [2] [3], or in research projects of the German Aerospace Center (DLR) [4]. Further work specifically addresses sub-areas of UAM research, such as urban airspace management [5] [6], trajectory and network simulation [7] [8], scheduling and de-conflicting [9] [10], and scientific consideration of potential vehicle designs [11] [12]. In addition, in the field of vehicle development, there is already a number of other projects and prototypes in various stages of development (including City Airbus, Volocopter, Lilium Jet, EHang and others) [13] [14] [15].

Another aspect in UAM systems is the ground-based infrastructure and its requirements as important success factors for sociotechnical integration [16]. Ground-based infrastructure includes communication, navigation, surveillance infrastructure and take-off and landing pads (in the literature also documented as touchdown and lift-off pad) [17]. The spatial integration of landing areas characterised by obstacle environment, restriction areas, traffic networks is a key success factor. It has influence on various technological and societal dimensions and strong impact on urban planning to achieve interconnection with existing mobility networks [18].

In a UAM network, there is a variety of requirements for the functions that a vertiport must fulfill as part of the ground infrastructure. Depending on this, different variants of the individual vertiports in the network are required, ranging from vertiport facilities with minimal size and cost (so-called vertistops) to vertiport facilities with high flight frequency and passenger volume (traffic hubs) to vertiports with a focus on vehicle MRO (maintenance hubs). In order to develop a solution space for these variants, a strategy of modularization is a promising approach [3].

In this paper, we first take a look at related work on the topic of vertiports, modularization in the construction industry, room or space concepts in achitecture and modularization of technical systems and products (section 2). Subsequently, a project is presented that aims to research and develop a modular vertiport (section 3). In section four, the approach and an applied example of the modular vertiport are presented, before a conclusion and an outlook on further work is given in section 5.

2. RELATED WORK

For the topic considered in this paper, at first a look at the state of the art of vertiports is performed, followed by a view on modularization of technical systems and products and examples for modularization in construction research based on the sientific literature.

2.1. Vertiports

Compared to conventional heliports or airports, future vertiports might have significantly higher numbers of movements per day and hour, particularly at peak times. The design of infrastructure that enables steady and robust operations is a particularly challenging task. The conceptual design of a vertiport requires a general analysis of the system components and procedures in a first step. Another crucial factor in the process is the proper capacity derivation and evaluation of a design. While there are multiple functional components that are capable of limiting the overall throughput of a vertiport, for instance due to limited capacities of ground access to the vertiport or congested airspace, our initial analysis will focus on the so-called airfield capacity. According to an analysis provided in [19], the basic elements that vertiports are composed of can be grouped into touchdown and liftoff pads, gates, taxilanes and parking spaces (here referred to as staging stands, see Fig. 1).

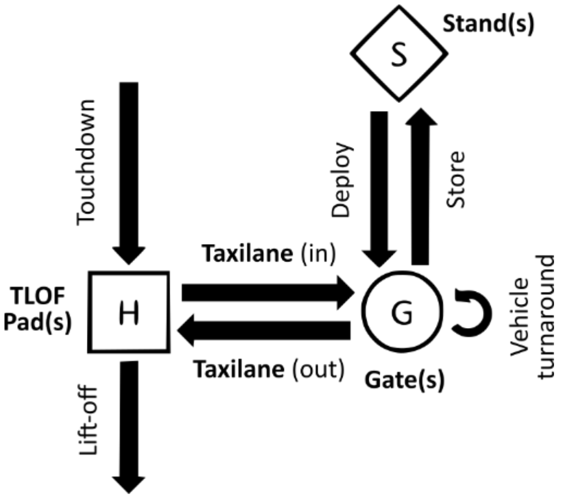

Fig. 1. *Basic elements of a vertiport according to* [19]

A touchdown and lift-off (TLOF) pad is a functional element where a vehicle conducts its approach during the landing procedure and transitions into taxi phase, respectively an element where a vehicle conducts its departure after finalizing the taxi phase. Depending on the vertiport topology, a TLOF pad generally can be deployed for combined or for segregated take-off and landing operations, nevertheless only one vehicle is allowed to occupy a TLOF pad at a time. In order to maintain safety, a TLOF needs sufficient space such that a vehicle during arrival or departure procedure has a certain margin for maneuvering without risking a collision with infrastructure or adjacent vehicles. The dimension of a TLOF pad therefore depends on the operating vehicles and its departure and arrival performance. Furthermore, a TLOF pad requires a flight path free of obstacles for safe operations within a confined urban area. Gates are optional elements on vertiports to which a vehicle may taxi in order to conduct boarding and de-boarding procedures or for charging, respectively refueling. In the same manner as for TLOF pads, gates have spatial minimum requirements to ensure a maneuvering within an obstruction-free area, which depend on the vehicle dimensions.

The taxiing segment between a TLOF pad and a gate is conducted along dedicated taxilanes, either on the ground if the vehicle is equipped with wheels, or in a hovering mode in a small altitude between 1 to 5 feet above the lane. Ground taxiing however provides a higher energetic and spatial efficiency [20], [21] and therefore favors lower spatial footprints.

Parking spaces represent a further optional element, which provides vehicle parking capacities and a certain level of service, for instance battery charging, cleaning or maintenance tasks. Since there are no passenger related activities in a parking space such as boarding and de-boarding, it has a smaller spatial footprint than a gate and therefore provides a space efficient option to hold a local supply of vehicles for missions on short notice. As for taxilanes and gates, the spatial footprint of a parking space depends on the taxiing concept of the operating vehicle, while taxiing in hovering mode requires more space. Based on these elements, there have been investigations on vertiport design regarding capacity, the total spatial footprint, possible topologies and the most significant factors affecting the capacity.

An approach based on Integer Programming to analytically estimate vertiport capacity envelopes for instance is presented in [19]. Based on a generic ConOps, a total number of 156 different vertiports was examined, each of them assembled from individual combinations regarding their TLOF pads, gates and parking spaces. In addition, relevant operational parameters are varied, such as the required taxi time between the TLOF pad and the gate or the turnaround time, which is required to park the vehicle at the gate and conduct all relevant procedures such as de-boarding, charging and boarding. The variation of further operational parameters results in up to 146 different operational parameter settings, such that 8866 different combinations on vertiport settings and corresponding operational settings were assessed regarding the achievable throughput. As a result of the conducted sensitivity analysis, it is found that the relative ratio of gates to TLOF pads is a crucial vertiport design factor since a too small number of gates can create a bottleneck. Adding more gates, such that the optimal ratio is exceeded on the other hand, will not increase the possible throughput of the vertiport, but increase the operational robustness at the cost of a larger spatial footprint. The addition of parking spaces is mainly found to provide adjustment capacity for unbalanced inflow or outflow of vehicles. This can be relevant for peak hour operations in particular, when commuters mainly arrive at certain vertiports. Furthermore, the availability of multiple TLOF pads has been found to increase the vertiport throughput significantly, as long as these pads enable simultaneous arrival and departure procedures. An Agent-Based Modeling and Simulation framework that takes vehicles and passengers into account at the same time, and implements the vertiport concept of [19], has been presented in [22].

A vertiport scheduling algorithm based on a first-come first-served concept is applied in [23] to compare the capacity for a set of configurations. Therefore, the number of TLOF pads and parking spaces and the resulting capacity tradeoff between these elements is taken into account. However, the model does not take the vertiport layout into consideration and therefore may over- or underestimate the capacity, depending on the topology. Amongst other results, this publication defines a theoretical model that allows for an estimation of vertiport capacity.

A detailed analysis on vertiport topology and its effect on throughput capacity considering the relative spatial footprint is presented in [24]. In this analysis, three generic vertiport topology designs are investigated, each of them with a square shaped surface footprint, in which one TLOF pad is positioned in each corner, while the degree of taxilane interconnectivity between the TLOF pads is varied. The operational capacity of each topology design is evaluated according to the model presented in [23], while the number of parking spaces per TLOF pad is varied between 2 and 8 for each topology. As a result, different vertiport topologies are presented, where the first design focusses on maximizing the parking capacity per TLOF and spatial vertiport footprint at the cost of no connectivity between the TLOF pads. Two further designs provide connectivity between TLOF pads due to taxilane placement around the perimeter, respectively through the center of the vertiport, resulting in better adjustment capabilities of the vertiport operation regarding wind and other weather effects.

In [25], a tool is presented that was mainly developed for architects in order to evaluate vertiport designs. Based on a stochastic Monte Carlo simulation approach, this tool calculates the vehicle throughput capacity and surface area under consideration of safety risk and noise constraints. This analysis methodology is applied to evaluate three different vertiport designs, in two cases with one combined TLOF pad, and in one case with two single pads, spatially dividing the functional areas into starting and landing pad. For a set of operational boundary conditions, the conducted analysis finally quantifies the correlation between the required vertiport surface area and the throughput capacity.

Crucial factors affecting the vertiport capacity were investigated in [26]. Therefore, a Discrete Event Simulation model is applied to determine the capacity of vertiports with 1, 2 and 3 TLOF pads, respectively. A key finding of that investigation includes the quantification of required repositioning flights resulting from imbalanced inflow or outflow. This study found that the requirement for repositioning flights depends on trip purposes and can be reduced by scenario modification, for instance by adding trips for airport access or shopping. Furthermore, a sensitivity analysis on vertiport capacity was conducted and found significant dependencies on service times at TLOF pads and parking spaces, as well as on required time to fulfil a repositioning request. However, the battery charging rate and the number of pre-staged vehicles at the vertiport did not show a significant impact on the capacity.

In summary, these results show that there are multiple factors, such as the ratio of components or the topology that can have a significant effect on the capacity and the efficiency of a vertiport. Furthermore, additional metrics such as the spatial footprint or the capability of a vertiport to handle imbalanced traffic play an important role in vertiport design. Since multiple of the relevant factors are still unknown today, such as vehicle size or taxiing speed, the target to design modular vertiports seems a challenging, but reasonable approach.

2.2. Modularization of technical systems and products

Modularity is a gradual property of the product structure. Modules comprise components with certain common features, which can thus be treated as a logical unit. Modularity is targeted at the requirements of all product life phases. Modules are connected via interfaces, they are an area of interaction between two (sub-) systems. The interaction can be a positioning, a power flow or the exchange of energy, material or information. The main measures for the realization of modularization is interface standardization and function binding [27]. For the latter, modules perform exactly one function or a specified set of functions [28], [29].

The functional structure of technical systems and products comprises their functional units and the interdependencies between them. On the one hand, the functional structures can be represented in a process-oriented manner in order to show the material, energy and information flows within the product (for example, by the general or special functional structure according to Roth [30]) and, on the other hand, functional structures can be strictly hierarchical in order to decompose the function of a product into its individual partial and auxiliary functions [31].

In contrary to the functional structure, the product structure serves to represent the relationship between the product and its components [32]. It describes the physical, hierarchical composition of a product from its components (such as assemblies and other individual parts and (sub)assemblies) and summarizes them at a lower level [27]. These two views of the product are mapped to each other in the product architecture [33] (see Fig. 2).

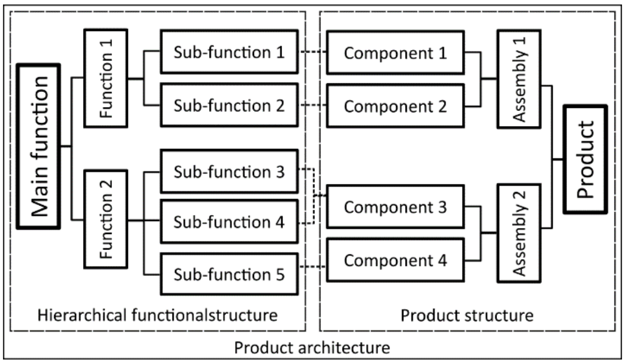

Fig. 2. *Product architecture based on* [33]

2.3. Examples for modularization in construction research

In the construction industry, complex and mostly individual products are manufactured in which many disciplines and planners are involved. In the scientific literature, modularization is described as an attractive approach for improving efficiency, flow and quality. In this context, the modular construction method is described as a construction method with prefabricated room-sized volumetric units, which are usually completely equipped in production and installed on site as load-bearing "building blocks". The advantages here are economies of scale in manufacturing multiple repeating units, speed of on-site installation, and improved quality and accuracy in fabrication. Also, modular buildings can potentially be disassembled and reused. The most common application of this modular construction method affects cellular buildings, such as hotels, dormitories, etc. where module size is compatible with manufacturing and transportation requirements [34].

In their paper, Peltokorpi et al. [35] describe various modularization strategies and derive the following classification of production systems from the literature into the following four categories (depending on the degree of product standardization and off-site production). (1) Modular buildings: here, pre-assembled volumetric units alone or in conjunction with each other form the actual building (e.g. houses, prison blocks, motels). This is associated with the highest degree of offsite production and standardization. (2) Volumetric pre-assembly: specific building components are pre-produced and assembled on-site in an independent structural framework (e.g., plumbing fixtures, toilet stalls, shower rooms). (3) Non-volumetric pre-assembly: units are pre-assembled that do not create usable space (e.g., heat generators, structural frames, wall panels). (4) Component fabrication and subassembly: this item covers the traditional approach to construction. Raw materials and components such as bricks and mortar are used for onsite construction, indicating a high degree of customization and the lowest degree of offsite production.

Furthermore, the authors describe nine real-world cases that also essentially follow the strategy of assembling prefabricated modules already named [35].

Other authors in the scientific literature (such as [36] [37] [38]) also focus their work on the approaches to assemble prefabricated blocks on construction sites and thus to enable structured modular building in building construction with common parts.

The first three categories described by Peltokorpi et al. [35] allow for a distinction based on the hierarchical bundling of functions embedded in a single component. In modular buildings, the packaging of functions [28] is the most comprehensive, while non-volumetric pre-assembly follows more strictly the idea of one-to-one correspondence between functions and components [35].

In order to enable the aesthetic design of the form and appearance of a sophisticated system such as a vertiport, on the one hand, and to take into account the technical complexity and, on the other hand, to create a solution space in order to be able to react to the different external requirements and characteristics of a vertiport, the strategy of modularization must be aimed at on a functional level that has a suitable degree of abstraction. A good starting point here is the room or space concept of the building.

3. THE PROJECT MODULAR VERTIPORT

The project Vertiport started in November 2021 and has a runtime of two years. It receives funding from the City of Hamburg and involves 11 partners: (AERTEC Solutions, AIR TECCON, Altran Deutschland, APSYS Risk Engineering GmbH, CT Ingenieure, DLR – Air Transportation Systems, Drone Industry Insights, igr Aerodrome Engineering GmbH, Sogeti Deutschland GmbH, TUHH – Institute of Air Transportation Systems, Ylipson GmbH)

The consortium includes engineers from the aviation and construction sector, software and IT specialists, drone experts, airport infrastructure planners and designers. The interdisciplinary nature fosters a truly collaborative approach that combines the expertise to create a holistic and future-oriented project. The research will comprise the following working packages:

WP 0: Project lead
WP 1: Analysis and regulation
WP 2: Operations of vertiports
WP 3: Layout & Design of Vertiports
WP 4: Sustainability and social acceptance
WP 5: Marketing

WP 1 contains the market and requirement analyses and answers the following questions: What is the status quo regarding vehicles and what are estimated passenger numbers of UAM? Additionally, the regulatory framework is assessed, and suitable locations are suggested.

Vertiport operations are examined in the second WP, which is divided into the following topics: Security, maintenance and automation concepts deals with the technical operations perspective. Business models are developed and calculated in the other part of the task.

WP 3 Layout & Design of Vertiports, representing the core of the project, gathers information from all work packages and derives the requirements. As the name implies, the Layout and Design is developed and linked to the urban connection.

Sustainability concepts and public acceptance are integrated into the concept development in WP 4. Among other things, suitability aspects such as the cradle-to-cradle concept are analyzed.

The fifth WP deals with marketing. On the one hand, a marketing concept is developed to visualize the infrastructure and to present the outcome. On the other hand, partnerships and possible investors are needed to integrate more stakeholders into the project.

4. THE APPROACH MODULAR VERTIPORT

The project presented and the approach documented below shows the function-oriented description of a vertiport. For this purpose, the relevant functions of a vertiport are shown based on the information from the scientific literature (see Section 2.1) and the analysis of the experts of the research consortium. Then, the approach of the modular vertiport and the idea of a spatial plan level configuration is described.

4.1. Function structure of vertiports

To implement the approach of a modular vertiport, the functional structure known from product development and presented in the prior art (see Section 2.2) is first built up. This functional structure is shown as an example in Fig. 3. To build the functional structure, the possible main functions of a vertiport are first defined. The “vehicle handling” function is always part of a vertiport, likewise the “passenger handling” function is usually part of a vertiport. An exception would be a pure MRO hub, where no passenger boarding or disembarking is possible. The other main functions are MRO and energy supply. In which form or with which sub-functions these main functions are realized, if at all, depends on the vertiport variant (vertistop, flex-vertiports, traffic hub or maintenance hub) and its design (e.g. targeted maximum passenger throughput or targeted MRO capacities).

Further sub-functions are described in the function structure; this is done in the context of the project described here up to the level of abstraction at which the equivalent to the architectural space concept is achieved. These functions are used to define the modules relevant for the vertiport.

The “vehicle handling” function is divided into four sub-functions: “enable take-off and landing”, “storing vehicles”, “moving vehicles” and “fill and empty vehicles”. For the “passenger handling” function, the sub-functions “boarding and leaving”, “enable waiting” and “offer shopping opportunities” are relevant at the room program level. The function “take care of vehicles” can be subdivided into “provide cleaning”, “enable pre-flight checks” and “enable C-/D-checks”. The function of energy supply “provide energy” is divided into the two subfunctions “provide electricity” and “provide hydrogen”, since these two energy sources are the most relevant in the field of UAM research.

Subsequently, solutions can be generated from the solution space (corresponding to the module construction kit) by different characteristics of the individual function solutions (of the individual modules), as well as by the combination of different modules.

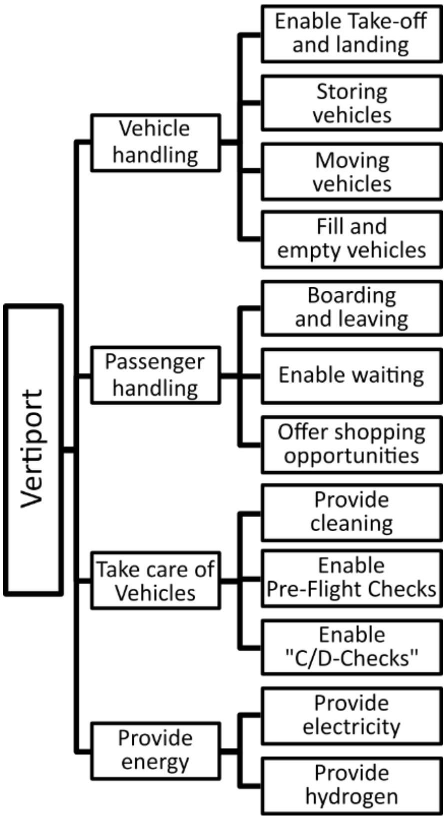

Fig. 3. *Functionstructure of a vertiport*

In the elaboration of the individual modules, a further detailing of the functions can take place. Here, too, the strategy of modularization can be applied. This then moves away from the approach of the configurable and reconfigurable space concept to the modularization strategies of the classification of Peltokorpi et al. [35], which are well-known and common in the construction industry.

4.2. Application example of vertiport modules

In order to determine the corresponding product structure based on the previously described functions and the functional structure of the Vertiport, the individual functions are considered and the respective modules defined. First, the modules of the sub-functions of the “vehicle handling” function are taken up. These have already been described in the state of the art, as they are often part of the scientific consideration of vertiports in terms of their airside organization and their design with respect to their potential capacity. The four sub-functions can be realized by the modules “pad” (landing and take-off, or touchdown and lift-off pad), “stand” (parking space, or staging stand), “lane” (taxiing segment between a pad and a gate) and “gate”. Since the “vehicle handling” function of a vertiport is the interface to the airside of a UAM system, it is considered separately from the other modules at the room concept level. This airside area (or the “airside assembly of modules”) of the vertiport depends on the available plot (or property) area and is usually the bottleneck in terms of vertiport capacity. For the design of this area, the four modules “pad”, “stand”, “lane” and “gate” are selected depending on the available plot (or property) area, their shape and the targeted vertiport capacity. The number of modules and the topology (arrangement of the modules in relation to each other) can vary depending on the underlying constraints and can be configured differently (displayed in Fig. 4 as the multiple selectable modules at the top right of the figure).

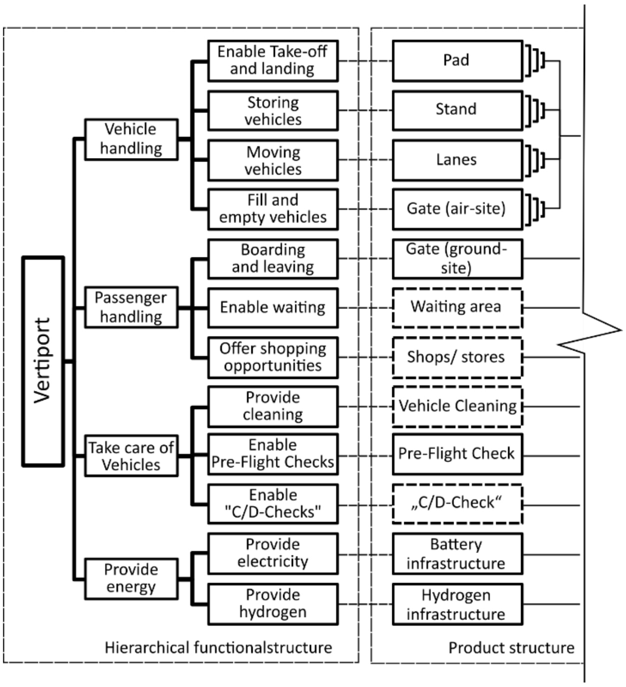

Fig. 4. *Part of the product architecture of a vertiport*

The other modules of the Vertiport refer to the building, its room plan and the equipment of the individual rooms and parts of the building. To achieve modularization here, module boundaries are defined for the individual modules and their interfaces. On the room level, this means for the vertiport that the dimensions of the rooms, their area and side edges, as well as the room heights are relevant. Openings and possible cutouts are also documented. Thus, depending on the requirements, different equipment (which can be standardized for the respective modules) can be accommodated in the rooms. In this way, several modules can be combined in the core of the vertiport (depending on demand or predicted passenger numbers), but on the outside, design freedom is still maintained and adaptation to the respective environment is made possible.

The use of modules at the space plan level means that when a UAM system or network analysis or utilization analysis of individual vertiports is performed, the corresponding modules can be exchanged and adapted. For example, the modules shown in Fig. 4 with dashed lines; here, if the utilization of the waiting areas is low, these can be reduced by one module, thus creating further space for a “shop/store” module, or the service part of the vertiport is expanded and a new “vehicle cleaning” module is integrated.

5. CONLUSION AND OUTLOOK

This paper first took a look at the current state of the art with regard to the functions of Vertiports their relevant parts and configurations regarding a capacity analysis, functional structures and modularization of technical products the idea of product architectures, and modularization in the construction industry.

Subsequently, the methodology of the project to develop a modular Vertiport was presented. First, the relevant functions and sub-functions of a Vertiport were defined. Here, the currently documented state of science was used, which was supplemented by the extensive expertise available in the project. After the functional structure was established, the first modules and modularization strategies were described. A distinction must be made between the airside and the groundside areas of the vertiport. On the air side, the modules “pad”, “stand”, “lane” and “gate” are combined and selected. On the ground side, the approach of a modularization on the level of the spatial plan is pursued and was presented as an example on a high abstraction level.

As the Vertiport project started this year, the presented results are still on conceptual level and will be further elaborated in following work. In particular, the combination of airside and groundside modularization and their interfaces offer exciting research gaps and justify the chosen holistic approach. A modular Vertiport also offers exciting starting points with regard to reconfiguration in the event of changing demand scenarios or the adaptation of the UAM network.

6. ACKNOWLEDGMENTS

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