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Analysis of airport design for introducing infrastructure for autonomous drones

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Abstract

Purpose – Connecting autonomous drones to ground operations and services is a prerequisite for the adoption of scalable and sustainable drone services in the built environment. Despite the rapid advance in the field of autonomous drones, the development of ground infrastructure has received less attention. Contemporary airport design offers potential solutions for the infrastructure serving autonomous drone services. To that end, this paper aims to construct a framework for connecting air and ground operations for autonomous drone services. Furthermore, the paper defines the minimum facilities needed to support unmanned aerial vehicles for autonomous logistics and the collection of aerial data.

Design/methodology/approach – The paper reviews the state-of-the-art in airport design literature as the basis for analysing the guidelines of manned aviation applicable to the development of ground infrastructure for autonomous drone services. Socio-technical system analysis was used for identifying the service needs of drones.

Findings – The key findings are functional modularity based on the principles of airport design applies to micro-airports and modular service functions can be connected efficiently with an autonomous ground handling system in a sustainable manner addressing the concerns on maintenance, reliability and lifecycle.

Research limitations/implications – As the study was limited to the airport design literature findings, the evolution of solutions may provide features supporting deviating approaches. The role of autonomy and cloud-based service processes are quintessentially different from the conventional airport design and are likely to impact real-life solutions as the area of future research.

Practical implications – The findings of this study provided a framework for establishing the connection between the airside and the landside for the operations of autonomous aerial services. The lack of such framework and ground infrastructure has hindered the large-scale adoption and easy-to-use solutions for sustainable logistics and aerial data collection for decision-making in the built environment.

Social implications – The evolution of future autonomous aerial services should be accessible to all users, "democratising" the use of drones. The data collected by drones should comply with the privacy-preserving use of the data. The proposed ground infrastructure can contribute to offloading, storing and handling aerial data to support drone services' acceptability.

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Originality/value – To the best of the authors' knowledge, the paper describes the first design framework for creating a design concept for a modular and autonomous micro-airport system for unmanned aviation based on the applied functions of full-size conventional airports.

Keywords Design, Framework, Infrastructure

Paper type Research paper

Introduction

The adoption of unmanned aerial vehicles (UAVs) or drones has reached the dawn period of the "industrial revolution in the sky", delivering the technology for logistics and data collection, following the period of hobbyist drone use cases (Nonami, 2018). Yet less focus has been paid to the infrastructure and facilities needed to provide aerial logistics and data collection services in the built environment.

The UAVs gain an increasing role in both data collection and logistics in the built environment. Merkert and Bushell (2020) have shown that the most recognized use cases of drones fall into four categories: (i) monitoring and data collection, (ii) photography, (iii) recreation and (iv) logistics. Another classification is suggested to divide the use cases into civilian, environment and defence (Macrina *et al.*, 2020). The wide adoption of sustainable use cases requires scalability of the services that call for the autonomy of the entire UAV service process instead of the current manual or semi-autonomous drone operations and manual support functions, such as battery swapping and cargo loading. For example, autonomous operations and flights beyond the visual line of sight (BVLOS) hold the potential of offering efficient and nearly zero-carbon services for last-mile deliveries in the urban environment (Lemardelé *et al.*, 2021). Similarly, autonomous drone platforms and wireless sensors deliver long-lasting monitoring systems for data collection (Polonelli *et al.*, 2020). Both examples of use cases depend on both flying the drone autonomously and having all required supporting ground services, in addition to infrastructure in place to serve the stakeholders or customers.

The term *air-ground connection* is used here to describe the infrastructure needed for a functional autonomous UAV ecosystem that connects the stakeholders, services and business processes. This ecosystem consists of physical and digital elements that enable all necessary near-ground procedures such as a safe landing, handling the possible payload, charging and refuelling as well as terminal and hangar functions associated also with airports of manned aviation. The micro-airports refer to the autonomous infrastructure that provides the services needed for the air-ground connection.

Here, it is argued that solutions for an open infrastructure of drones are currently lacking and that these are required for scaling today's primarily manual drone operations. The starting point of this paper is the observation that the design guidelines of full-size airports could potentially be applied as a conceptual design framework for the ground infrastructure of autonomous drones, as an airport serves as the air-ground connection in the field of manned aviation. The successful technological transition in emerging autonomous ground infrastructure for UAVs may lead to a paradigmatic change in the options for last-mile deliveries and data-driven decision-making based on low-altitude aerial data.

The motivation of the study is to search for the minimum framework for the design programme required to establish the air-ground connection.

Infrastructure for autonomous unmanned aerial vehicles and technological transition

The rationale for the air-ground connection is to make the autonomous UAV services accessible to the users in a similar fashion as airports connect the cargo and passengers to airplanes. The development of airports has evolved through a transition from the early airfields to contemporary high-capacity airports (Eames, 1958). Similarly, UAV solutions and services can be viewed as a technological transition from manual flight operations to autonomous and low-carbon drones-as-a-service operations based on the transition theory (Geels, 2012). The success of the transition depends on multiple and multi-level societal, technical and economic variables. For example, the legislation and authorities, such as the EU, hold the position to catalyse the transition through harmonisation, standards and common airspace management (U-space or unmanned aircraft system traffic management UTM). The regulation is a vast topic that affects both the airside and the landside of drone aviation, for example, the acceptability of the landing locations or siting of micro-airports. This paper focuses on one key component of the technological transition, the framework for a physical air-ground connection, in other words, the infrastructure and facilities needed for autonomous UAV services. In turn, the successful air-ground connection contributes to the transition by realising the strategic policy objectives of the EU in support of its sustainable and smart mobility strategy, Drone strategy 2.0, changing the technological landscape (European Commission, 2021).

At the early stages of the transition, before the regulation matures, the dedication of the infrastructures to specific use cases may drive the transition first in restricted areas, such as logistics and data collection at seaports, construction sites or industrial areas. However, the design and development of infrastructure should be implemented in a way that supports the provision of infrastructure services across industries and user groups, as it is in the case of full-sized airports. It is worth pointing out that the scale and size of the micro-airport infrastructure do not necessarily need to be heavy at the beginning to allow the evolution of the solutions and the adoption of the first autonomous services. Digital, mobile or transportable solutions could serve the need as relocatable infrastructures launching the transition and the wider societal impact. To that end, the development of the needed infrastructure should consider the application of digital solutions, as those are an essential part of manned aviation also. As potential hinder to the transition, a survey of the European Union Aviation Safety Agency identified as the main concerns of the people on the UAVs safety, noise and security, whereas 83% of the respondents of the survey had a positive or a rather positive attitude towards the urban air mobility (McKinsey, 2021).

A successful framework for air-ground connection can mitigate all the above concerns. However, this calls for a holistic approach connecting the air and ground operations instead of focusing on a few selected technical manoeuvres of UAVs. Next, the paper looks at the state-of-the-art of air-ground connections for drones.

State-of-the-art of physical air-ground connections for drones

The body of literature on the air-ground connections for autonomous UAVs is at the early stage. Most of the UAV literature covers topics such as drone delivery, path planning, privacy and regulation (Merkert and Bushell, 2020). However, some research concerning the design of fixed air-ground infrastructure for autonomous UAVs has been done in the last few years, but proposals for dense urban areas are lacking (Kellermann *et al.*, 2020). Proposed solutions include e.g. mobile carriers for UAVs (Polonelli *et al.*, 2020) or separate storage depots and recharging solutions (Boukoberine *et al.*, 2019a). The need for more detailed design instructions on drone infrastructure has been identified (Otto *et al.*, 2018).

Despite technology being ready for detailed design, a holistic approach to integration of all required technologies is still missing (van Hoof, 2022).

The drone delivery industry has proposed solutions both for fixed-wing and multi-rotor drones. Alphabet's wing provides business-to-consumer services based on a manually operated field with charging pads and QR codes assisting the localisation of the drones (Wing, 2023). Weather conditions, scalability, payload capacities and automatization pose challenges to the application, but the solution serves the aims of customer research and experimentation. Amazon has envisioned and patented the HIVE, a large-scale urban delivery hub (Curlander *et al.*, 2022). The concept remains on a conceptual level as a future alternative to large logistics hubs. Zipline has experimented with a sling type of launch system combined with a net catching the fixed-wing drone (Zipline, 2023). The proposed sling solution first used in rural Africa may pose challenges in operating heavier point-to-point deliveries in the dense urban fabric.

The state-of-the-art literature on air-ground connections for drones focuses mainly on the “drone-in-a-box” solutions with partial solutions on charging and payload handling for single drones (Galimov *et al.*, 2020). For example, DJI offers a solution containing six batteries (DJI, 2023), whereas other companies such as Airobotics rely on charging pads (Airobotics, 2023). As part of the drone-in-a-box solution, the essence of the air-ground connection has been in the touch-down process, that is, aligning the drone in a desired position for storage or charging. Galimov *et al.* (2020) classify the drone landing platforms into systems with no positioning and with positioning. Furthermore, the systems with positioning can be either active, passive, combined or other non-standard systems. In all classifications of the platforms, the precise position of the drone is the starting point of the system and the main objective of controlling the landing or docking process.

At least two gaps from the ground facilities’ point of view can be identified in the solutions of the above classification describing the current situation in the air-ground connections of autonomous drones. Firstly, it falls short of addressing the end-to-end service process from the user and customer points of view. Now, the categories identified as “standard” define much of the state-of-the-art with a limited capacity to address the end-to-end service process that needs the ground infrastructure and facilities. For example, current definitions miss a category introducing solutions to how the payloads are loaded and off-loaded in an autonomous ground system or how the ground infrastructure could support the off-loading of UAV sensor data instead of using only cloud services.

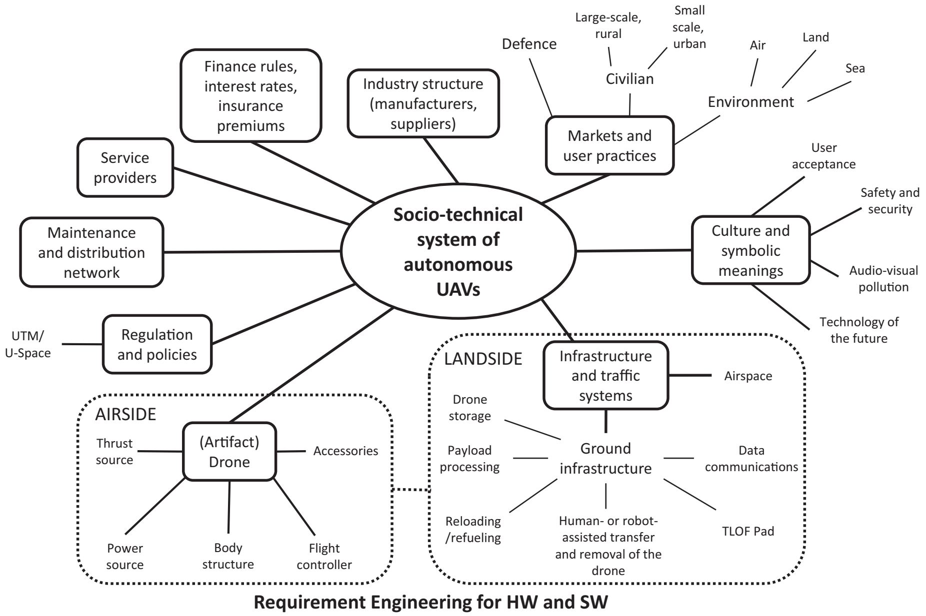
Secondly, the current solutions on air-ground connections for drones focus merely on the accuracy of the landing or repositioning of the drone itself on the platform based on either GNSS or local multimodal sensors such as cameras (Janousek and Marcon, 2018). As in the case of airports for manned aviation, the means for servicing the aircraft are more versatile, including ground vehicles moving the aircraft as well as performing services around the aircraft independent from its precise position. Similarly, autonomous ground robots could service drones without a need for complex repositioning with high accuracy and poor tolerance for errors. To that end, the detailed technical and system solutions for servicing the drones should be looked beyond the drone and its position in the landing area, connecting the drone to a ground-based service ecosystem in a similar fashion as aircraft in the airports.

Another classification of the ground docking system has been presented based on the mobility of the docking solution. The division based on mobility consists of fixed and mobile solutions. Fixed solutions can be divided into solutions that are fixed to the ground and applications that are transportable or relocatable. The mobile solutions, in turn, are categorised as UAVs landing on an unmanned ground vehicle, an unmanned surface vessel, another UAV or on a moving vehicle. Furthermore, the classification is based on the method for precise positioning of the UAV in air consisting of visual, wireless, geomagnetic and system based on sound waves (Grlj *et al.*, 2022). The above classification supports this paper for defining the minimum framework for air-ground connections applicable to both fixed and mobile solutions for establishing the air-ground connection.

Grlj *et al.* (2022) conclude that precision landing and algorithms as the main direction of research on UAV landing systems during the past decade. Furthermore, they state as the objective of future research enhancing the vision and algorithm-based solutions to reduce the number of pushers or other devices as landing aids and reduce passive positioning using shapes or gravity. However, the focus on precision landing provides little guidance on what happens *after* the landing to service the drone, e.g. battery swapping or cargo handling. To that end, the focus on the precise landing location may provide a limited perspective hindering solutions capable of promoting the technological transition. In conventional airports for manned aviation, for example, the landings are never fully replicable, and the service infrastructure and ecosystem can make the air-ground connection work.

Materials and methods

The study applies a mixed methods approach including the needs assessment for micro-airport and the qualitative analysis of the literature on airport design as potential solutions for the identified needs. Firstly, the framework of the socio-technical system for the evolution of car-based transportation by Geels (2005) was applied to identify the elements needed in the UAV infrastructure ecosystem (elements in Figure 1), and secondly, based on the airport design literature, a qualitative analysis was implemented on the service functions of airports and how the functions are separated (summary of results in Figure 2). Furthermore, the service functions were analysed in what ways they support the UAV infrastructure (detailed results in Figure 3). Finally, exploratory research by design was applied in support of the discussion part to illustrate potential first infrastructure and drone platform solutions based on the discovered framework (Figure 4).



Source: Adapted from Geels (2005)

Figure 1. The identification of the design requirements using socio-technical systems and requirement engineering

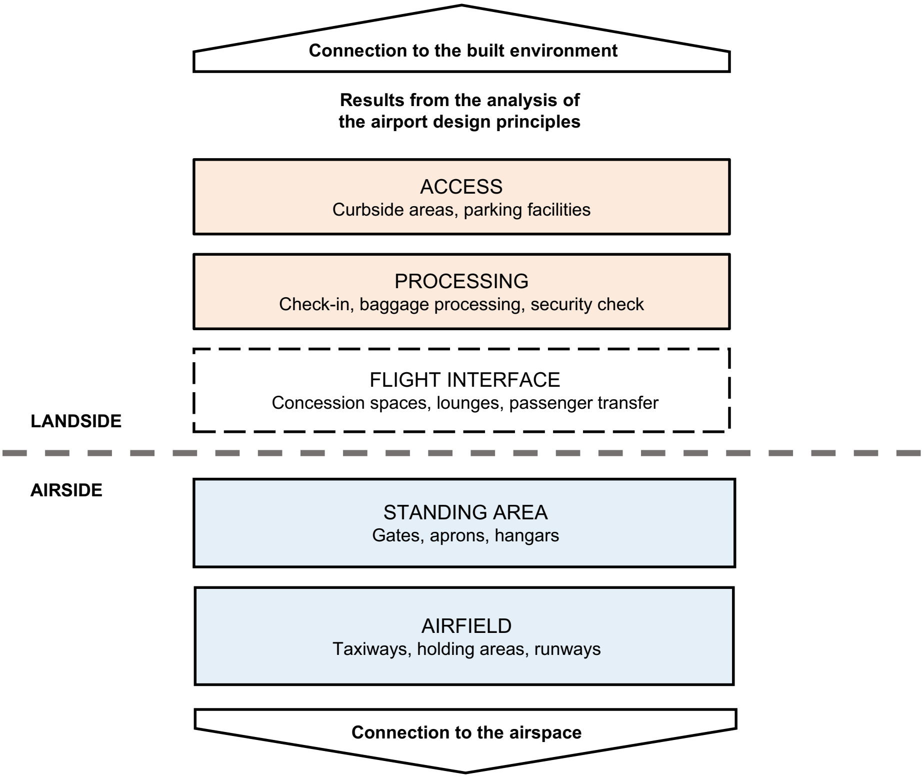


Figure 2.
A summary of the findings from the analysis of airport processes and functions

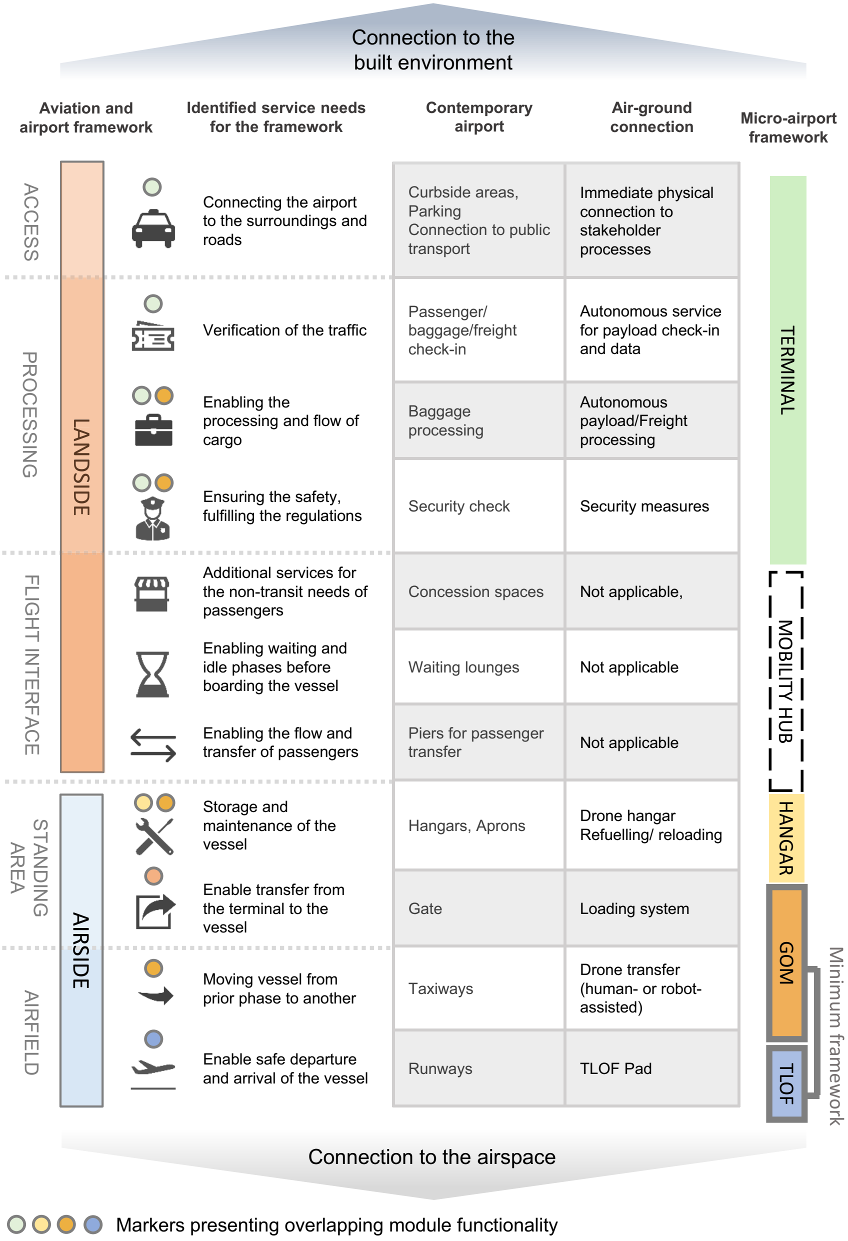
Source : Created by Edelman, H. and Stenroos, J.

Literature materials on airport design principles were searched using electronic databases EBSCO, ProQuest, Springer and AccessEngineering. The scope of the search was limited to books and academic journals that were published after the year 2000. The search was carried out using Boolean operators with title keywords: “designing airports” (number of total hits: 29), “airport* AND design” (265), “airport* AND planning” (171), “airport functions” (21), “airport service AND design” (31), “airport operations AND design” (88) and “airport facilities” (80). Out of these publications, eight sources in total were identified as seminal books covering widely adopted design principles in a holistic fashion.

Identifying the elements of the autonomous aerial system

The needed development of the infrastructure for UAV services is a gradual process involving several changes in society. The transition theory based on evolutionary economics argues that multiple smaller steps must be taken through technological adoption before such a scenario becomes a prevailing regime instead of early niche trials (Geels, 2002).

For the needs of this paper, the emerging and potentially novel technologies of UAVs are investigated as socio-technical systems fulfilling the earlier identified needs for the *air-ground connection*. The elements outside the scope of the infrastructure, such as funding,



Aviation and airport framework	Identified service needs for the framework	Contemporary airport	Air-ground connection	Micro-airport framework
ACCESS LANDSIDE	Connecting the airport to the surroundings and roads	Curbside areas, Parking Connection to public transport	Immediate physical connection to stakeholder processes	TERMINAL
PROCESSING	Verification of the traffic	Passenger/ baggage/freight check-in	Autonomous service for payload check-in and data	
	Enabling the processing and flow of cargo	Baggage processing	Autonomous payload/Freight processing	
	Ensuring the safety, fulfilling the regulations	Security check	Security measures	
FLIGHT INTERFACE	Additional services for the non-transit needs of passengers	Concession spaces	Not applicable,	MOBILITY HUB
	Enabling waiting and idle phases before boarding the vessel	Waiting lounges	Not applicable	
	Enabling the flow and transfer of passengers	Piers for passenger transfer	Not applicable	
STANDING AREA AIRSIDE	Storage and maintenance of the vessel	Hangars, Aprons	Drone hangar Refuelling/ reloading	HANGAR
	Enable transfer from the terminal to the vessel	Gate	Loading system	GOM
AIRFIELD	Moving vessel from prior phase to another	Taxiways	Drone transfer (human- or robot-assisted)	
	Enable safe departure and arrival of the vessel	Runways	TLOF Pad	TLOF

Source: Created by Edelman, H. and Stenroos, J.

Figure 3.
Application of the analysed functions of manned aviation for creating the framework for the air-ground connection

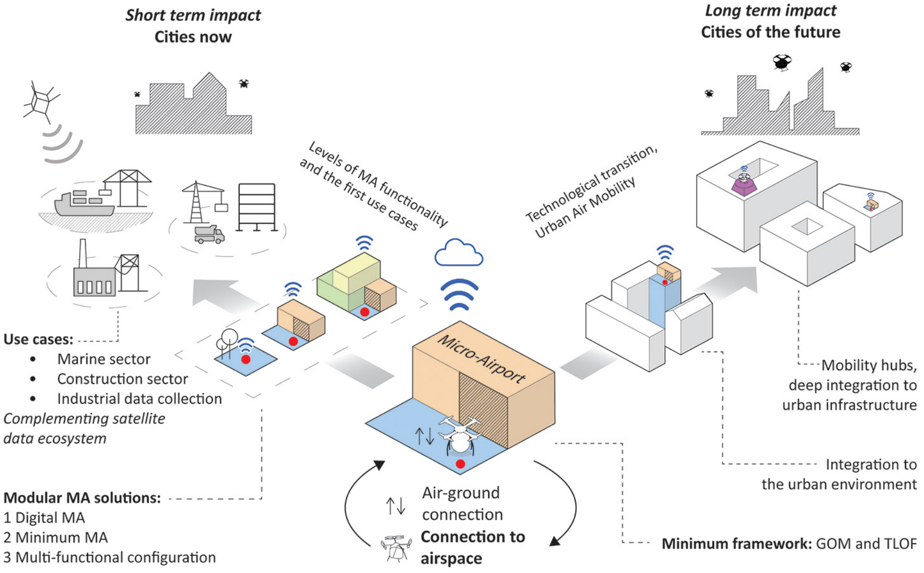


Figure 4.
Short- and long-term impacts of providing air-ground connection solutions for technological transition in urban environments

Source : Created by Edelman, H. and Stenroos, J.

legislation, regulation, insurance or social factors impacting the transition, are excluded from this study. The socio-technical system of the UAV ecosystem is elaborated in Figure 1 based on a model developed for car-based transportation (Geels, 2005).

The discovered elements of Figure 1 form the high-level requirements of the UAV ground infrastructure that are next compared to the identified service needs of manned aviation in contemporary airports. The lower-level technical solutions can be investigated and designed through requirements engineering (Kotonya and Sommerville, 1998). The drone and the ground infrastructure elements form such technical elements, for example, in defining what are the requirements for the drone platforms to be able to use the infrastructure of micro-airports. For a large-scale adoption of UAVs, the solutions need to be add-ons to the current drone platforms or easily replaceable elements of the system in a manner that allows flexible conversion of existing drones to benefit from the micro-airports.

Results

Airport systems and operation planning

The study found that most of the airport functions and the related design principles on a concept level apply to the micro-airports for establishing the air-ground connection for autonomous drones. Figure 2 summarises the results.

Airport planning is covered mainly in a few seminal books (Ashford *et al.*, 2013; Edwards, 2005; Horonjeff *et al.*, 2010; Kazda and Caves, 2015; Neufville *et al.*, 2013; Schmitt, 2016; Young and Wells, 2019) along the standards by the North American Federal American Administration (FAA, 2022) and International Civil Aviation Organization (ICAO, 2021). The following comparative analysis of the principles of airport design concentrates on the minimum elements of the functions enabling the flow of passengers and cargo in airports.

A clear observation of the functional categories of the airports can be made based on the current knowledge. The functions are separated into two distinct areas: landside and airside. This separation increases the performance of airports as it enables the services of both humans and airplanes to interact at facilities especially dedicated to them (Young and Wells, 2019).

The landside element consists of the passenger facilities that offer a wide variety of services, and the airside consists of the facilities such as runways, taxiways, aprons and roads (Neufville *et al.*, 2013). Young and Wells (2019) continue the division by categorizing airside functions between airfield and airspace and landside functions between terminal and ground access. Ashford *et al.* (2013) include runways, taxiways, aprons and gates in the airside element and passenger and cargo processing, concessions, departure and arrival concourse, piers, parking and roads in the landside element. Schmitt (2016) uses the approach adapted from Ashford *et al.* (2013), including a separate security threshold in the landside element. Kazda and Caves (2015) use categorization like previous authors and elaborate that the barrier between landside and airside occurs inside the terminal between open access interfaces such as ticketing and closed access environments such as after-security services and gates.

Horonjeff *et al.* (2010) divide the landside functions into three parts: (i) the access interface for transportation to the airport, (ii) the processing component for servicing passengers and (iii) the flight interface that includes entrance facilities to the airplane. A similar three-part approach in terminal design is used by Ashford *et al.* (2011) by dividing airport terminal functions into the processing function of passengers and baggage, channelling the flow of people to accommodate the needs of both departing and arriving passengers and the interface for change of mode from aircraft to the airport facilities. Additionally, It can be noted that from the service perspective, the passenger facilities and flow at the terminal can be separated between different customer groups (Graham, 2008).

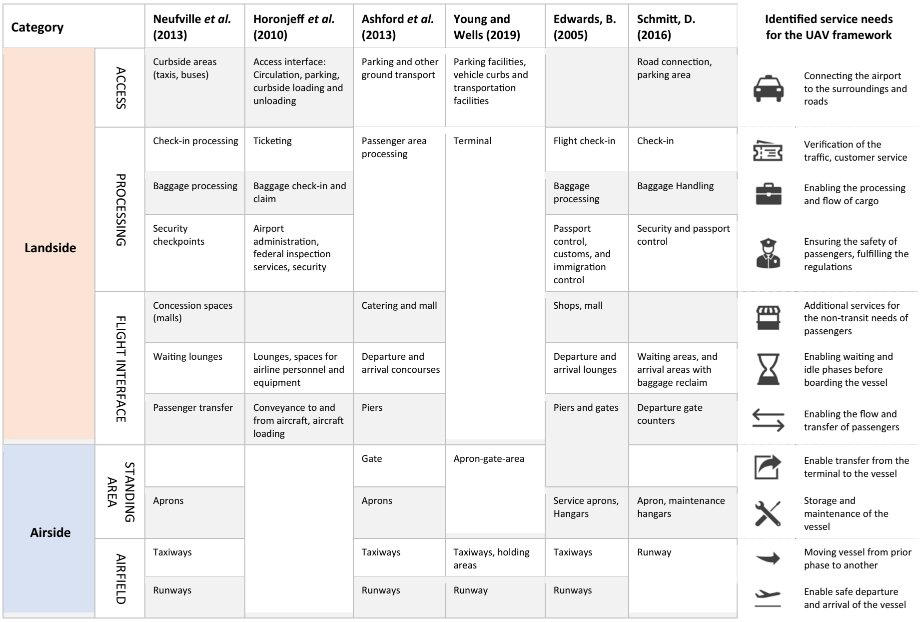
The findings on the above categories of functions are illustrated in detail in Figure 5. The common factors of the categories are then identified to define the service needs applicable to the micro-airports. Eleven service needs were identified and grouped using the airside-landside-division.

In Figure 2, the identified services of the landside are divided into three categories of functions according to categorizing by Horonjeff *et al.* (2010). The first part of the landside, *the access interface*, serves as the connection that physically connects the airport system to the surrounding built environment. The second category is the *processing* which includes verifying the traffic passing through the terminal with the check-in services and then processing through the terminal, the baggage handling and, finally, the security checks to ensure safety and compliance with regulations. The third component of the landside is the *flight interface* including non-transit services such as restaurants, dedicated areas for waiting and idle phases before boarding the vessel and piers for passenger flow and transfer. The airside functions are divided into two categories:

(1) *standing area* including operations for vessel storage and maintenance; and
(2) *airfield operations* including taxiways for moving the vessel between spatial phases and runways for safe departure and arrival shown in Figure 5.

Framework for unmanned aerial vehicles micro-airport

Next, the applicability of the identified functional categories of manned aviation is viewed against the identified elements for establishing the air-ground connection for autonomous UAVs. The identification of the components takes place through the socio-technical system (Figure 1). These components are further analysed in-depth with a comparison of generalised airport functions derived from the analysis of principles on the airport design.



Category		Neufville *et al.* (2013)	Horonjeff *et al.* (2010)	Ashford *et al.* (2013)	Young and Wells (2019)	Edwards, B. (2005)	Schmitt, D. (2016)	Identified service needs for the UAV framework
Landside	ACCESS	Curbside areas (taxis, buses)	Access interface: Circulation, parking, curbside loading and unloading	Parking and other ground transport	Parking facilities, vehicle curbs and transportation facilities		Road connection, parking area	Connecting the airport to the surroundings and roads
	PROCESSING	Check-in processing	Ticketing	Passenger area processing	Terminal	Flight check-in	Check-in	Verification of the traffic, customer service
		Baggage processing	Baggage check-in and claim			Baggage processing	Baggage Handling	Enabling the processing and flow of cargo
		Security checkpoints	Airport administration, federal inspection services, security			Passport control, customs, and immigration control	Security and passport control	Ensuring the safety of passengers, fulfilling the regulations
	FLIGHT INTERFACE	Concession spaces (malls)		Catering and mall		Shops, mall		Additional services for the non-transit needs of passengers
		Waiting lounges	Lounges, spaces for airline personnel and equipment	Departure and arrival concourses		Departure and arrival lounges	Waiting areas, and arrival areas with baggage reclaim	Enabling waiting and idle phases before boarding the vessel
		Passenger transfer	Conveyance to and from aircraft, aircraft loading	Piers		Piers and gates	Departure gate counters	Enabling the flow and transfer of passengers
Airside	STANDING AREA			Gate	Apron-gate-area			Enable transfer from the terminal to the vessel
		Aprons		Aprons		Service aprons, Hangars	Apron, maintenance hangars	Storage and maintenance of the vessel
	AIRFIELD	Taxiways		Taxiways	Taxiways, holding areas	Taxiways	Runway	Moving vessel from prior phase to another
		Runways		Runways	Runway	Runways		Enable safe departure and arrival of the vessel

Figure 5.
Analysis of airport functions potentially contributing to the development of autonomous ground infrastructure for UAVs

Source: Created by Edelman, H. and Stenroos, J

The air-ground connection components are then used to construct the minimum essential elements for micro-airports. As a result, the analysis answers the question of to what extent the airports intended for autonomous UAVs can draw from the airports for manned aviation.

The micro-airport framework for autonomous unmanned aviation is presented in Figure 2, including four distinct modules: (i) the terminal, (ii) the hangar, (iii) the ground operations module (GOM) and (iv) the touch-down and lift-off module (TLOF). Furthermore, it should be noted that some of these modules may overlap, as the service needs can be met in either module depending on the use cases and the scale of operations, such as the number of UAVs serviced. The potential for overlapping functions or multi-functionality, is depicted in Figure 2 by colour-coding the functions connecting the service need to the modules of the micro-airport framework. An example of the overlapping is the maintenance and refuelling of the drone that can be serviced either in the hangar module or GOM. The components and modules are next elaborated on in more detail.

The terminal is the most user-oriented module. It includes the element of integration that connects the services that the UAVs provide to the stakeholders' ground processes. The terminal functions include the user interface for payload check-in and check-out, and they store and produce data for fleet and U-space management together with local edge and remote cloud computing services when computational offloading is needed. Terminals ensure security through scanning payloads and verifying identities of both users and autonomous UAVs, for example, having distributed ledger technologies (DLTs), i.e. blockchain, integrated into the digital service process. Digital platform infrastructure is essential to integrate autonomous UAV operations into business operations in the built environment. Modern DLTs could augment this with decentralised trust, the immutability of data and through public and private channels, simultaneously preserve private data and enable transparency of operations for the public (Chowdhury *et al.*, 2019).

Here, the terminal module is not intended to serve passenger traffic, making the flight interface inapplicable to the micro-airport framework. However, it can be argued that in the case of UAM solutions, such as urban air mobility hubs in cities, passenger functions become relevant. In Figure 2, this possible future module is called a "mobility hub".

The hangar enables drone maintenance, refuelling and storage. The maintenance of drones requires human access to the hangar, although some functions, such as inspections, could be partly automated. Furthermore, the hangar needs to include a way to insert and remove drones, payloads and other accessories from the service process. At the early stage, the refuelling consists of battery swapping, but alternative renewable energy sources are applicable, such as green hydrogen-based solutions. While hydrogen fuel cells have been the most popular approach to powering UAVs, able to substantially boost flight times due to their higher specific energy density (reaching 1 kWh/kg) as compared to batteries (0.25 kWh/kg) (Boukoberine *et al.*, 2019a; Wang and Zhao, 2022), several other fuel candidates are being investigated. Direct methanol fuel cells (DMFC) using liquid fuels offer a relatively mature technology with easy refuelling and fuel distribution options, but currently still suffer from lower efficiency and added weight due to methanol crossover and the related need to use diluted fuels (Boukoberine *et al.*, 2019b). More efficient DMFCs, as well as direct-ethanol and ammonia fuel cells with large net caloric values (20 MJ/kg, 27 MJ/kg and 19 MJ/kg, respectively), could, therefore, provide promising future solutions for the drones (Boretti and Castelletto, 2022). In smaller implementations of micro-airports, the hangar functions could be in the terminal. However, larger fleets of heavy-lift drones require a considerable amount of space to store. To that end, the hangar modules are likely to exist as independent modules of considerable size that pose requirements for the siting of micro-airports in the urban fabric.

The GOM is a connecting module for the other modules. In manned aviation, it can be compared with taxiway and apron areas. In smaller-scale solutions, services can be performed in the GOM such as swapping the payload or energy compartment of the UAV. As the volume of the operations increase, the GOM needs to be reserved mainly as a transition area between the modules. The services are then mainly provided in the hangar and/or terminal modules. The GOM is always the entry and exit space to and from the TLOF pad comparable to the runway of airports. The spatial connection of the GOM and TLOF enables a standard procedure for a human or ground robot-assisted transfer of payloads and drones. To that end, the system can be fully autonomous, or it can be operated semi-autonomously, having human interaction involved in the service process. The gradual introduction of autonomy supports the early adoption of the framework in selected use cases leading to a successful technological transition. There is mature research and development of mobile ground robots to navigate autonomously within the proposed framework (Borges *et al.*, 2022; Sánchez-Ibáñez *et al.*, 2021).

Finally, the TLOF module is needed to enable a safe arrival and departure for the UAV. TLOF is the actual air-ground connection point. Beyond the visual flight rules and markers of airports, the TLOF needs to include the sensor technology for assisting the landings and take-offs BVLOS flights. The TLOF is essential for operating in all weather conditions fulfilling similar operations needs as runways do, such as de-icing and operations under limited visibility.

In summary, the above modules, which are not necessarily separate physical modules, serve as a framework for implementing an end-to-end system for air-ground connection for autonomous UAVs. In larger-scale operations, such as high-volume micro airports, it becomes inevitable to dedicate services to separate modules. In the early stages of adopting micro-airports and in smaller volumes, even a digital platform containing sensors for the landing and take-off monitoring and controlling the UAVs could similarly perform the flight operation tasks as the GOM and TLOF modules. However, the landside service processes would then lack the full automation of the logistics or aerial data collection services. The above comparison of airport functions against the identified requirements for the air-ground connection of autonomous UAVs shows that the GOM- and TLOF modules are the minimum system for a UAV micro-airport.

Next, the physical implementations of the micro-airport framework will be discussed based on the findings on the service functions of the airports. Also, the technological transition and scalability of the proposed framework in the urban fabric will be elaborated.

Discussion

When considering the solutions for establishing an air-ground connection for autonomous UAVs in the urban fabric, the literature on airport design provides a framework for the service design. In consequence, the proposed framework can enable autonomous UAVs to contribute to near zero-carbon logistics and the collection of aerial data supporting the design and management of sustainable cities.

The investigation into the principles of the airport design found that the physical air-ground connection can be established autonomously with the GOM and TLOF modules (Figure 3).

The landside and airside functions of manned aviation are combined in this minimum framework. However, the size of the minimum framework limits the service capacity of the micro-airport significantly to only a few UAVs. When compared in size, airports are centralised and commonly large facilities (Ashford *et al.*, 2013), whereas micro-airports are small and potentially hosted in several locations in the urban fabric. This difference in scale and the number of locations may provide a partial solution to the problem of the service capacity of a single micro-airport. But when the demand for service capacity increases, it becomes inevitable to include more ground services and increase the size of the micro-airports. Therefore, the need for designated services becomes inevitable in a similar fashion as in airports. Furthermore, at least one larger micro-airport is needed in the serviceable urban area to host the UAVs, store them and maintain them. In the larger scale micro-airports, the service design and processes resemble the landside and airside processes of the airports, apart from the passenger traffic. However, in the long term, the micro-airport framework could be integrated with the air mobility hubs, enabling passenger traffic to be included in the system. The scenario of future cities presented in Figure 4 illustrates the transition of micro-airports into full-size mobility hubs connecting the different modes of ground transportation in specific urban nodes. Such solutions would require the integration of the micro-airport and their technology into the built environment at the intersections of public transportation to adopt the autonomous aerial services in passenger transportation as well as in last-mile logistics. The suitable locations of UAM hubs are already often congested and dense, calling for specific solutions such as vertical integration. For example, elevators of buildings could provide access for ground robots entering the buildings and servicing the UAVs both in exchanging the payloads and swapping the energy sources on the rooftops. To that end, physical micro-airport implementations should be incrementally applicable and offer flexible services based on the landside and airside processes.

The flexible services offer ways to catalyse the transition. The first implementation of services connects the technology development to the market applications and early use cases (Adner and Levinthal, 2002). In the best case, there is no need for a physical infrastructure to launch the initial services. In the short term, the micro-airport could provide services in the cities through fully digital solutions such as digital micro-airports (DMAs). A DMA can be established using mobile gadgets to monitor the safety of autonomous landings and take-offs in point-to-point drone deliveries. Mobile gadget communicates with the cloud system and the U-space enabling the user to designate a landing zone without the need for a complex infrastructure or expertise in operating the UAV. In an urban setting, such an approach could be used to designate public spaces such as parks as TLOF areas. This opens multiple possibilities for increasing the utilisation rate of urban spaces as well as delivering zero-carbon logistics services.

The DMA can support the first steps of technological transition in adopting aerial services based initially on manual operations. However, the DMAs have an important service role in fully autonomous aerial services, such as point-to-point deliveries, but such autonomy is not likely to be in place in the short term. To that end, it is important to identify the ways to launch services now based on partially manual operations first. The different role of autonomy in airports and micro-airports is profound. In the field of manned aviation, the level of autonomy is relatively high only in the airside at the level of “computer executes automatically, then necessarily informs the human” (Cook *et al.*, 2019). In turn, the UAV services for all users call for end-to-end autonomy and on-ground operations for achieving both cost efficiency and the needed easy-to-use services. The DMAs can play a role, for example, in aerial deliveries to the construction sites or seaports that are restricted areas and operated by professionals who could participate in the manual operations at the early stages of launching aerial services. The first use cases are likely to take place in restricted or remote areas mitigating the air risks of the operations until the U-space services are more widely available.

In the long term, when the technological transition proceeds and use cases take more regular and established forms, digital and transportable solutions may be replaced with permanent ground infrastructure with various modules and variations of them. The shape and functions are not necessarily rectangular object-like but can take any architectural form and scale. The introduction of various functional modules enables different levels of multi-functionality, as modules can be used to construct a variety of systems based on the needs of the user. For example, depending on the volume of UAV traffic, hangar modules for storage and maintenance can be scaled accordingly. Another example could be the efficient use of space by using the smallest system in a situation with a small surface area and then locating or stacking the actual servicing and storage site in a location with more space.

Conclusion

The research looked at the design principles of airports and in what ways the current knowledge could contribute to the design and development of the evolving autonomous unmanned aerial services. Ways to establish an air-ground connection for autonomous UAVs were studied to enable easy-to-use and scalable drone services.

The findings of this study provided a framework for establishing the air-ground connection for autonomous aerial services. The lack of such framework and ground infrastructure has hindered the large-scale adoption and easy-to-use solutions for sustainable logistics and aerial data collection for decision-making in the built environment. The study implies that the adoption could take place seeking short-term impacts of the aerial services using first digital, lightweight and transportable infrastructure while bearing in mind the applicability of the technology in the long-term solutions.

A framework for autonomous aerial services was proposed based on the findings on applicable service processes described in the literature on contemporary airport design. A minimum physical infrastructure of a micro-airport consists of a GOM and TLOF. Additional modules in varying architectural forms, such as terminal and hangar modules, enable scaling the services and creating a similar service process as in the airports for manned aviation.

For the early adoption of autonomous UAV services, a digital solution may provide the least infrastructure-intensive alternative in early use cases at restricted areas such as construction sites or seaports. Such digital solutions or a DMA could be established as an app and mobile gadget enabling the monitoring of the UAV during the landing and take-off. The digital solution could involve a lower level of autonomy at the early stage and proceed towards full autonomy as the need for services increases. Full autonomy is required for consumer-level services that could facilitate beyond business-to-consumer commerce, even consumer-to-consumer transactions in the second-hand market, supporting the evolution of a circular economy.

As the study is limited to the findings on the principles of airport design, the evolution of solutions may provide features supporting deviating solutions. The role of autonomy and cloud-based service processes are quintessentially different from the conventional airport design and are likely to impact real-life solutions as the area of future research.

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