INTRODUCTION OF A HIGHLY ITERATIVE DESIGN PROCESS FOR AIR TAXIS

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Abstract

The introduction of Air Taxis offers significant potential to transform the future mobility ecosystem by lifting on-demand individual mobility into the third dimension of transportation. Hence, Air Taxis are considered an innovative and promising solution for the increasing global demand of individual mobility. However, the innovative nature of Air Taxis introduces new challenges to the traditional aircraft design process. On the one hand, the multitude of Air Taxi configurations as well as the integration of innovative technologies require a novel technological alignment of the design process. On the other hand, the higher production quantities as well as the wide variety of competitors and the unclear stakeholder requirements, as markets for Air Taxis do not yet exist, pose further challenges to the design process. As a result, there is a need for an innovative aircraft design process adapted to the technical as well as market challenges of Air Taxis.
Therefore, this paper presents a process for designing a feasible, viable, and desirable Air Taxi in an innovative and highly iterative manner. An extensive literature analysis of the state of the art in aircraft design confirms the deficient depiction of these practical needs by the classical approaches from research.
Based on the assessment of established aircraft design processes, an applicable process for the design of Air Taxis is derived and described in detail. The proposed process includes advantageous features of established aircraft design processes as well as suitable elements derived from agile product development processes. Due to the high market and technology uncertainties, a continuous verification with suitable methods is necessary. Hence, the outlined design process is enriched with a multitude of verification methods matching the specific demands of each design phase.

1. INTRODUCTION

Mobility will change fundamentally in the coming years due to increasing urbanization, individualization, regulatory requirements and new technologies [1, 2]. Thus, society is increasingly striving for greener, more efficient, and more demand-driven transportation, which is supported by visions and actions of policymakers and regulators [3–7]. These visions aim to define the possible directions and areas of technological change [3], that will empower the development of innovative technologies to address existing as well as future problems through novel solutions [8–10].

A key challenge for mobility in the 21st century is that established modes of transport are reaching both capacity and infrastructure limits [1, 7, 11, 12]. This is caused by the rising global population and increasing urbanization, which will lead to an ever-increasing demand for mobility in the future [13, 14]. At the same time, people living in more rural areas are also demanding more efficient and individualized transport. This is in line with the goals of the European Commission formulated in the "Flightpath 2050". In addition to ambitious targets for reducing aircraft emissions, it states that "90% of travelers within Europe can complete their journey within 4 hours".[4]

In order to meet the urban and regional mobility needs for people and goods in the future, the expansion of transport into the third dimension, i.e., the establishment of individual air mobility, is a novel and promising solution [1, 15–17]. Enabled by technological progress, the development of so-called Air Taxis, as a mode of individual air mobility, can address the need for a more environmentally friendly, efficient, and demand-driven transportation solution [18, 19]. Thus, Air Taxis promise faster transportation, flexible and individual mobility, increased safety, improved sustainability, and a reduced impact on existing transport infrastructure [1]. Currently, more than 100 design projects for Air Taxis are under development worldwide to target the urban and regional air mobility market [20, 21].

In this context, Air Taxis are not expected to replace any part of the existing mobility landscape, but rather to become a central element of the urban and regional mobility of the future as a novel market [19, 22]. However, in order to address this new market, innovative Air Taxis need to be designed to meet completely new technical and economic requirements in terms of performance, operation, and production [23]. In addition, Air Taxis are expected to be produced in much higher volumes in the future than, for instance, commercial helicopters [20]. The large production volume makes it possible to achieve dramatically lower costs per Air Taxi [24]. However, high volumes are not typical for aviation [25], and pose changing requirements for production processes and potential economies of scale, especially from a business perspective [26]. At the same time, Air Taxis need to be accepted by society to emerge as a mode of transportation for the masses [27, 28]. Concerns about potential privacy violations, auditory and visual disruption, safety risks, and affordability are some of the biggest issues that need to be addressed early in the design process in order to design a socially acceptable Air Taxi [29].

In practice, however, experience often shows that, due to the novelty of Air Taxis, there is no comprehensive and continuous review of technical, economic and acceptance-based performance targets of the design, especially in the early design phases. Therefore, in order to ensure a

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successful product introduction of Air Taxis despite the multiple requirements, an intensive use of both technical and market side verification methods in the design process following a highly iterative approach seems advisable. However, established aircraft design processes, such as those according to GUDMUNDSSON [30] and RAYMER [31], do not support such an approach.

Based on the initial situation described above, the overall objective of this work is to develop an adapted and highly iterative process for the design of Air Taxis. The aim is to enable the user to continuously verify the design progress of Air Taxis from a technical and, in particular, from a market perspective, i.e., in terms of costs and acceptance. The development of a model for the highly iterative verification of the design progress is intended to enable the development of an Air Taxi according to the requirements.

After discussing the fundamentals and definitions in chapter 2, a literature review is conducted in chapter 3 to highlight the scientific gap addressed by this paper. The new aircraft design process is outlined and detailed in chapter 4 following a five-step approach to set up the process itself and supplement it with appropriate verification methods tailored to the different design phases. In the last chapter a conclusion as well as an outlook for future work are given.

2. FUNDAMENTALS AND DEFINITIONS

This chapter examines terms that are of central importance in the context of this paper. For this purpose, common definitions in the literature are first discussed and then a common understanding of the respective term is defined.

2.1.1. Air Taxi

Air Taxis are currently among the most intensely discussed emerging technologies that are intended to extend mobility into the third dimension of lower airspace [15]. The vehicles proposed for these new applications are as diverse in size and configuration as the markets and missions themselves [32]. To date, there is also wide variation in the understanding of Air Taxis. One general definition of Air Taxis describes them as small commercial aircrafts performing on-demand, short-term flights [33]. The consensus definition of Air Taxis, according to EIßFELDT, considers Air Taxis as aircrafts providing on-demand transportation for individual needs by connecting major transportation hubs, such as airports and city centers [18]. In this context, Air Taxis operate with varying degrees of autonomy [34]. In addition to these general definitions, several limited understandings exist. For instance, HUSEMANN ET AL. postulate an understanding of Air Taxis as small, electrically powered aircrafts [35]. Moreover, BEHME AND PLANING further narrow the understanding of Air Taxis to electric vertical takeoff and landing aircrafts that provide a local emission-free and infrastructure-friendly solution within cities [28]. A similar definition, limited to vertical takeoff and landing Air Taxis but including electric and hybrid electric variants, is given by ROWEDDER [21]. In contrast, broader definitions are also considered in the literature. Here, Air Taxis are described, for instance, as small, (hybrid) electric aircrafts being capable of taking off and landing in small areas due to their limited size, with Air Taxis operating both within and between different cities [16]. This understanding is supported by FAGERHOLT ET AL. who extend the operational scope of Air Taxis to small regional airfields that are often not served by regular airlines [36]. In the European Union, the maximum number of passengers allowed in an Air Taxi is set at 19 seats [37].

In the context of this paper, Air Taxis are defined as small, (hybrid) electric commercial aircrafts enabling individual, on-demand transportation of a maximum of 19 people within and between different cities.

2.1.2. Design

According to RAYMER, the term design depicts the creation of the geometric description of something to be built [31]. Following GUDMUNDSSON, it describes a process involving a preconceived goal, requiring planned actions for preparation, and serving a specific purpose. In this process, GUDMUNDSSON defines four successive phases: "Requirements-Phase", "Conceptual-Design-Phase", "Preliminary-Design-Phase", and "Detailed-Design-Phase".[30] Aircraft design often involves two activities: problem solving through mathematical calculations and the selection of a preferred variant among alternatives. In this regard, the process of aircraft design describes a multi- and interdisciplinary approach that integratively combines areas such as aerodynamics, propulsion, flight dynamics, and structure.[38] The result of the process is characterized by the overall aircraft design, which strives for the best possible compromise of all these design disciplines [39].

The ongoing advancement of the design over time during the design process will be defined as design progress for this paper. This can be characterized by the results of the design phases. The outcome of the Requirements-Phase is the specification. In the subsequent Conceptual-Design-Phase, the concept is elaborated before it is further detailed into a configuration in the Preliminary-Design-Phase.

2.1.3. Information objects

The term information can be derived from the Latin word "informatio" and translates as education or instruction. Its purpose is to inform about a certain matter.[40] A further definition describes information as the part of a message that improves the level of knowledge in relation to a decision [41]. A more general definition is given by MADDEN, who specifies information as a representation of stored knowledge [42]. In contrast, an object is to be understood as an object on which interest, thought, or action is directed [40]. In computer science, objects describe a set that belongs together in terms of content [43].

For the later development of the model, an information object is understood as a set of relevant information belonging together in terms of content and describing a specific entity.

2.1.4. Highly iterative

In linguistic terms, iterative means "repetitive" and expresses a frequent repetition of processes. In the mathematical sense, it implies approaching the exact solution step by step in repeated arithmetic operations.[40] EHRLENSPIEL AND MEERKAMM understand an iteration as multiple repetitions of a procedure on the same problem to approach the sought solution [44]. In the context of product development, SCHUH uses the term "highly iterative" to describe rapid, highly iterative testing and verification to align the product being developed with customer requirements at an early stage [45].

3. LITERATURE REVIEW

In this chapter, building on the initial situation described in practice, relevant approaches from research are considered and critically evaluated based on an assessment framework. For this, the addressed areas of the literature are presented first. Second, the criteria of the assessment framework are briefly described, and the results of the assessment are presented.

Overall, four relevant areas of literature are examined. Thus, traditional aircraft design processes are considered first [30, 31, 38, 39, 46–51], to assess the extent in which these meet the changing requirements of Air Taxis. Furthermore, aircraft design processes adapted for hybrid electric aircrafts are included [3, 52, 53]. Hereby especially the current state of research regarding power delivery challenges relevant for Air Taxis can be integrated in the assessment. The third area of literature addressed outlines aircraft design processes that have already been adapted for Air Taxis [54–56]. This is intended to evaluate the status quo with respect to the consideration of special requirements for Air Taxis and, in particular, their integration into the aircraft design process. Finally, given the highly iterative nature of the model to be developed, approaches from agile product development are considered across domains [57–59] to evaluate the agile, highly iterative approach with respect to a general suitability for the design of Air Taxis.

In order to qualitatively evaluate the existing approaches in a uniform manner, various criteria are defined that can be divided into the object and target area. The object area indicates which elements are included in the scope of the paper. Regarding the object area, the following criteria are derived from the research objective: (i) The scope of the model should be the aircraft design process with a holistic view of the aircraft design. (ii) In addition, the model should enable the user to consider individual design phases of the aircraft design in detail so that a chronological sequence of the verification methods can be applied. (iii) The objects of consideration of the model to be developed are intended to be Air Taxis. (iv) Furthermore, the model should include a description of phase-specific information objects enabling the progress of an Air Taxi design to be determined, thereby ensuring ease of application of the model. In addition to the object area, the target area, which can be derived from the challenges of practice (c.f. chapter 1), evaluates whether the approach contributes a result to any of the following objectives: (i) The model should provide a formal, technical, and market verification of the design progress. (ii) The model should ensure a highly iterative, i.e., interphase and intraphase, verification of the design. (iii) The model is intended to ensure a verification adapted to the design progress that is integrated into the design process.

With the help of these evaluation criteria, it can be examined to what extent the scientific approaches represent adequate solutions for the problems in terms of designing Air Taxis according to the various requirements. In the course of analyzing the existing approaches, two specific theoretical deficits emerged justifying the present paper with the described object of investigation from a research point of view: First, the absence of a holistic design process for Air Taxis with an adequate cost focus and an increased focus on social acceptance can be identified. Due to their disruptive nature, Air Taxis introduce entirely new requirements to the aircraft design process. A successful design requires an approach that addresses these requirements holistically. Second, a lack of comprehensive and continuous verification of the design progress of Air Taxis using suitable information objects must be emphasized. In addition to the formal completeness and correctness of a design, the technical and market performance of the design are particularly important requirements. For the diffusion of Air Taxis in the market, these must be verified continuously and highly iteratively with the progress of the design. As a result of these findings, the need for research regarding an aircraft design process adapted for Air Taxis, which enables a highly iterative verification of the design progress of Air Taxis, can be derived.

4. HIGHLY ITERATIVE VERIFICATION OF THE DESIGN PROGRESS OF AIR TAXIS

Based on the fundamentals described above, an initial overview of the model to be developed will be presented in this chapter. For this purpose, the five relevant steps for developing the model, as shown in Figure 1, will be briefly explained. The respective details of these steps are gradually explained over the next sections.

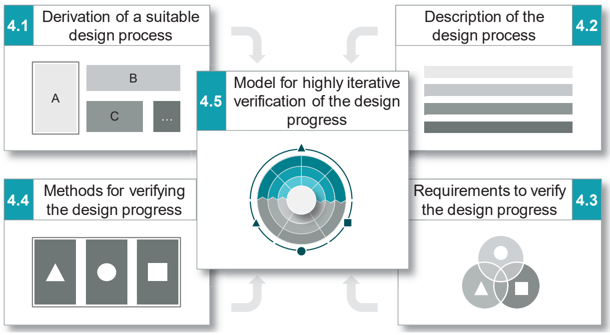

Figure 1: Structure of the highly iterative process model

First, the **derivation of a suitable design process** for developing Air Taxis is required. The derivation will be conducted based on a utility analysis. In accordance with the procedure of a utility analysis [60], the alternatives to be considered (i.e., potentially suitable aircraft design processes) must first be defined. Furthermore, selection criteria are to be described according to which the aircraft design processes are to be evaluated. The selection criteria are further to be weighted and a scale for the evaluation is to be defined. Subsequently, the aircraft design processes are evaluated, which also serves as a basis for the subsequent summation of the utility values and the selection of the aircraft design process with the highest potential for the design of Air Taxis.

Based on the derivation, the **description of the design process** best suited for the development of Air Taxis is conducted in a second step. The objective is to describe the fundamental structure and character of the most suitable aircraft design process for Air Taxis. For this purpose, the

Requirements-, Conceptual-Design- and Preliminary-Design-Phase are explained in detail using phase-specific information objects.

With reference to the overall design, the next step is to deduce **requirements for verifying the design progress**. The deduction aims to consider the dimensions to be addressed in the design of Air Taxis that require verification. Specifically, the three dimensions of Feasibility, Viability, and Desirability are examined based on specific indicators [61]. By transferring these to the design of Air Taxis, the three dimensions will be used as a basis for the deduction of requirements for the verification of the design progress.

The next step is to address **methods for verifying the design progress**. First, technical verification methods are used to address the dimension of feasibility. In addition, market-based verification methods, which are differentiated into cost-based and acceptance-based methods, are further applied to address the viability and desirability. As a result, verification methods can be described and operationalised so that a phase-specific assignment of these in the design process is facilitated. Finally, the verification methods will enable the development of an Air Taxi design that meets the requirements by addressing the previously derived three dimensions.

In a fifth step, the model for the highly iterative verification of the design progress of Air Taxis is described. For this purpose, the model will first be presented and then detailed based on its constituent elements. Here, both the derivation and the description of the suitable aircraft design process serve as the procedural and structural basis for the model. The derivation of requirements for the verification of the design aims to identify verification needs, which are considered with the help of the selection and operationalisation of the verification methods. In the synthesis, the need for research on the highly iterative review of the design of Air Taxis is addressed.

4.1. Derivation of a suitable design process

The derivation of a design process suitable for Air Taxis is based on the approach of a utility analysis. The utility analysis is a formalized method to evaluate different alternatives in a multidimensional way, using qualitative and quantitative criteria [62, 63]. By performing an utility analysis, in the first step, 10 design processes can be identified as candidates for an aircraft design process suitable for Air Taxis according to the requirements formulated earlier [3, 30, 31, 38, 39, 46–48, 54, 57]. In the second step, selection and sub-selection criteria have been defined so that the design processes can be evaluated in detail. Based on an expert interview with a business development manager of a startup developing an Air Taxi, the selection criteria are weighted using pairwise comparison. Based on this, the evaluation scale can be developed in the fourth step, i.e., a fixed evaluation value is assigned to the characteristics of all (sub-) selection criteria to perform the utility analysis as objectively as possible. In the fifth step, this allows the evaluation of the alternatives, which forms the basis for the sixth step, in which the evaluations are summed up and a selection is made. A detailed presentation of the selection criteria as well as the defined evaluation scale can be found in the appendix of this paper. Therefore, just the outcome is presented here.

As a result of the utility analysis, the two aircraft design processes according to GUDMUNDSSON [30] and according to SADRAEY [38] can be described as best suited for the design of Air Taxis. An overview of the evaluation of the two aircraft design processes plotted against the selection criteria of the utility analysis can be seen in Figure 2.

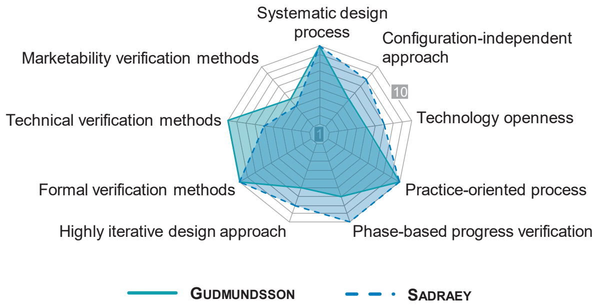

Figure 2: Assessment of design processes by GUDMUNDSSON and SADRAEY regarding the selection criteria

As shown in Figure 2, both processes achieve similar evaluations with respect to some selection criteria. Regarding the other selection criteria, the two processes also complement each other very well. To use these synergies in a best possible manner, a design process is described in the next section which is composed of the content-related principles according to GUDMUNDSSON paired with the process-related character according to SADRAEY.

4.2. Description of the design process

The derived design process is described in detail based on the individual design phases. Figure 3 provides an overview of the phases and the structure of the aircraft design process suitable for Air Taxis.

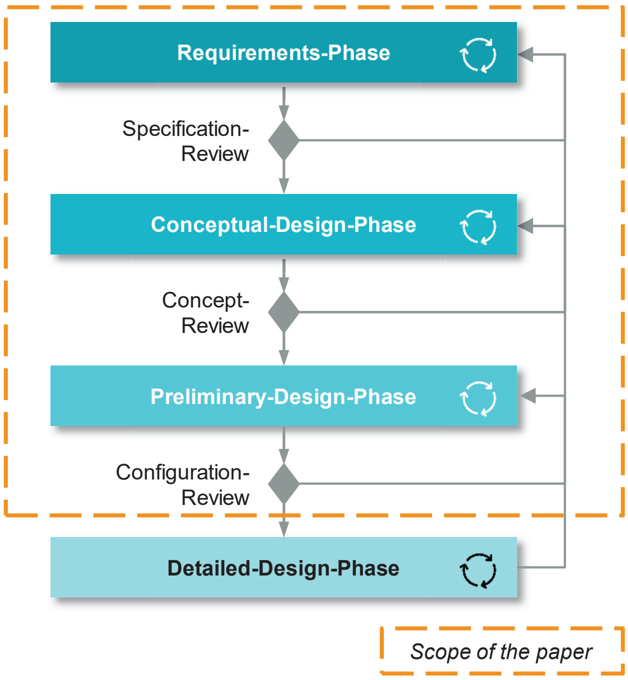

Figure 3: Structure of the highly iterative aircraft design process for Air Taxis

The highly iterative aircraft design process for Air Taxis consists of a total of four design phases. These include the Requirements-, Conceptual-Design-, Preliminary-Design- and Detailed-Design-Phase. The scope of the work is focused on the first three design phases. This is because the early design phases have the greatest impact on life cycle costs, the costs are largely not determined, and there is sufficient flexibility to make changes in the design [38, 50, 64]. Furthermore, the phases are linked by three reviews. The next phase can only be entered after a review has been successfully passed. Both the three initial design phases and the three reviews are described in more detail in the following.

The result of the **Requirements-Phase** constitutes the specification of the design (c.f. Figure 4). The aim of this phase is to identify the design requirements for the Air Taxi to be developed and to summarize the requirements space as a specification. Accordingly, the specification contains all relevant design requirements. As outlined in previous work by the authors, to develop the specification, an initial product idea of an Air Taxi is defined as an input to the process [65]. In a first step, this idea must be substantiated within the business case by analyzing relevant data about the mission to be fulfilled to map a customer benefit. Based on this, the reference mission provides initial indications of the requirements for the Air Taxi to be developed. These requirements are to be concretized into technically mature Top-Level-Aircraft-Requirements (TLARs). A specification predisposed by this requirements profile is described in terms of major components.[65] As main components, SADRAEY identifies lift and thrust, energy storage, power provision, flight control, aerodynamic contour, structure and interior, systems, and landing gear [38]. As part of the specification, these major components are to be described in broad terms. Collectively, the reference mission, TLARs, and main components form the three key elements of the top-level specification for Air Taxis. An interphase review following the Requirements-Phase can thus access these information objects of the specification allowing to make changes in a targeted manner.

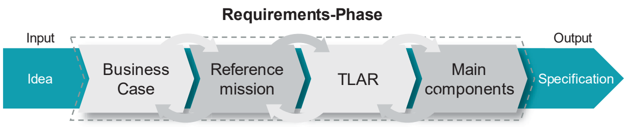

Figure 4: Structure of the Requirements-Phase of the Air Taxi design process

In the next step, the specification is analyzed interphasically in the so-called **Specification-Review** for convergence regarding the information objects initially defined in the Requirements-Phase. It must be checked whether the specification addresses the business case, the reference mission, the TLARs, and the specified main components in accordance with the requirements. In case of divergence, individual information objects must be elaborated again. In case of convergence, the requirements space is specified sufficiently precisely, and the elaboration of the solution space is initially started. This is part of the subsequent design phases.[65]

The specification as output of the Requirements-Phase serves as input of the subsequent **Conceptual-Design Phase**. At the beginning of this phase, the design requirements and constraints defined in the specification must be understood and quantified in their entirety [30, 38]. Based on this, a suitable basis for certification can be derived [30]. In a further step, the design requirements are to be prioritized [38], to enable a goal-oriented and efficient approach. This is followed by a general feasibility and market analysis to determine the performance and characteristics of current technologies [38]. Subsequently, the dominant components of the specification can be initially designed as components of the concept. These include, based on SADRAEY'S classification [38], the lift and thrust, power propulsion, flight control, and structure. As part of this initial design of the dominant components, the shape, position, and technical characteristics are to be determined. For the power provision, for instance, this means that the number, type, performance, and position of the aircraft propulsion system must be designed. As a result, the sketching of the outer shape of several potential concepts is enabled. These must be evaluated in a further step to select the concept with the highest potential (c.f. Figure 5).

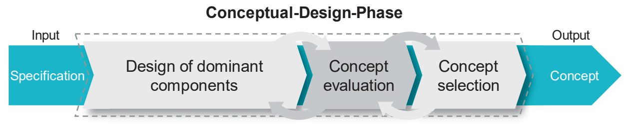

Figure 5: Structure of the Conceptual-Design-Phase of the Air Taxi design process

With the development of a concept, the elaboration of the solution space is initiated. The extent to which there is convergence between the solution space and the requirements space must be determined in the subsequent **Concept-Review**. In this process, the concept is to be reviewed from a technical and market perspective regarding the design requirements of the specification. In a further step, the solution space of the design is to be further concretized. This is carried out in the Preliminary-Design-Phase.[38]

The concept of an Air Taxi design is to be further developed into a configuration in the **Preliminary-Design-Phase**. Thus, the essential purpose of this phase is, on the one hand, to further concretize the previously initially designed dominant components into potential configurations. On the other hand, the subordinate components, i.e., the type of main components that are dependent on the dominant components, must be initially designed. The subordinate components include energy storage, aerodynamic contour, interior, systems, and landing gear. With the detailing of the dominant components and the initial design of the subordinate components, the design of different configurations is empowered. In a further step, these configurations, which correspond to different elaborations of the selected concept, must be evaluated and finally the most potential configuration of the Air Taxi design must be selected [30]. The process of advancing the concept to the configuration is shown in Figure 6.

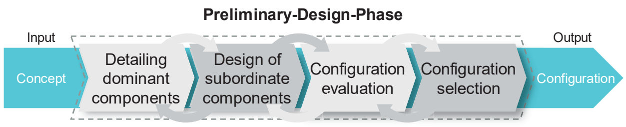

Figure 6: Structure of the Preliminary-Design-Phase of the Air Taxi design process

The result of the Preliminary-Design-Phase represents the configuration of the Air Taxi. The configuration is characterized by configured main components, i.e., dominant components are further detailed, and subordinate components are initially designed. In the transition from the Preliminary- to the Detailed-Design-Phase, the configuration must be verified in terms of convergence with the specification. This is the subject of the **Configuration-Review**.[38]

With the detailed description of the design process suitable for Air Taxis, the basis for the development of the postulated model is thus established. In the following, requirements for verifying the design progress of Air Taxis can be derived to be able to identify relevant verification methods subsequently in the fourth step.

4.3. Deduction of requirements to verify the design progress of Air Taxis

The objective of this section is to derive requirements for the verification of the design progress. To elaborate the requirements for the design verification, three dimensions are considered. These three dimensions are based on the proposal by Schuh and Dölle and are shown in Figure 7. According to Schuh and Dölle, sustainable innovations must be technically feasible (Feasibility), economically viable (Viability) and desired by the market (Desirability). For a successful implementation of an innovation, these three dimensions must be consistently verified in the product development process.[61] The three dimensions will be concretized below for Air Taxis, as innovative products in aviation, by elaboration of examples.

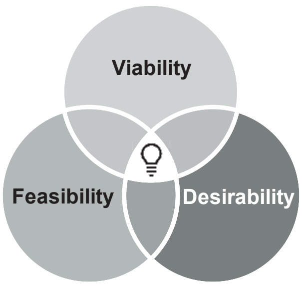

Figure 7: Overview of the three requirement dimensions according to Schuh and Dölle [61]

In terms of the feasibility, the question to be answered is: "Is the innovation technically feasible?" [61]. This involves the necessity of the physical feasibility of a product. Accordingly, both the realization of individual main components must be possible and the integrative function in the overall system must be guaranteed. To evaluate and verify feasibility during the development process, various indicators can be used. These include, for instance, temperature and weather conditions or unusual mechanical loads. In addition, the manufacturability of the product must be feasible with available materials and manufacturing processes.[61] With regard to technical feasibility in aviation, and in particular with regard to Air Taxis, the legal conformity of the aircraft design or compliance with the strict certification requirements for the initial approval of the design is essential [66]. Furthermore, requirements for maintenance and manufacturability of the aircraft must also be verified as part of the design process [30]. With regard to the function of individual main components or the overall design, performance and weight requirements are further key aspects of the design process [38]. These and other technical indicators must be considered in the design of Air Taxis to evaluate the feasibility of the aircraft design.

In addition to the feasibility, it is also essential to ensure the economic viability of the product. When considering viability, the following questions must be answered: "Can the innovation be implemented in an economic manner for the company?" and "Is the customer willing to pay for the innovation?" [61]. The product must therefore be economically advantageous in two respects: for the company as provider and for the customer as user. In particular, the customer's willingness to pay can and should be adequately verified during the development process. The focus when considering viability is accordingly clearly on economic criteria.[61] In the context of the design of Air Taxis, this means on the one hand that the Air Taxi to be developed places demands on economic viability from the company's point of view, which must be verified in the design process [54]. On the other hand, from the customer's point of view, willingness to pay represents an indicator of viability that must be determined at an early stage and verified progressively based on the design progress [67, 68]. In aviation, the complexity of the cost structure of an aircraft gives rise to further requirements for the verification of life cycle costs, which must be addressed holistically [24, 39].

The consideration of the desirability focuses on the requirement to create particularly high added value for the customer. The questions "Is the innovation even desired by the market?" and "Does the innovation meet the needs of its potential users?" must be addressed [61]. When considering desirability, the focus is therefore clearly on the customer. Especially in the case of innovative products or technologies, desirability must be verified regularly during the development process.[61] Particularly with regard to the novelty of Air Taxis, as radical innovations, desirability thus represents another essential requirement to be verified for the design of Air Taxis. Specifically, indicators such as ease of use, general safety, and requirements for sustainability as well as perceived comfort of the Air Taxi can be described for the evaluation or verification of desirability in the design of Air Taxis [7, 38]. Furthermore, specifically for Air Taxis, requirements for low noise emissions are significant to achieve public acceptance of individual air mobility [55].

The individual requirements describe an introduction to the three requirement dimensions which must be considered in order to verify the design progress of Air Taxis. It is important that the three requirement dimensions are considered holistically and continuously in the design process of Air Taxis. The individual requirements and indicators of the respective dimension must be substantiated individually and phase-specifically for the respective design project in accordance with the given framework conditions.

4.4. Methods for verifying the design progress

The aim of this section is to ensure that the design is verified in a phase- and dimension-specific manner in accordance with the requirements placed on the individual Air Taxi design. To answer the question of when and to what extent these individual requirements are to be verified, this section first identifies phase-specific verification needs. Based on

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this, phase-specific verification methods can be identified to finally address the question in the model of how the design progress can be verified.

To determine the verification needs, the procedure according to SCHUH from agile product development is used [45]. An overview of the approach is given in Figure 8 and will be interpreted for Air Taxis below.

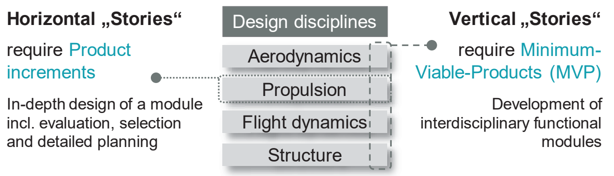

Figure 8: Possibilities for reviewing the design disciplines in accordance to SCHUH [45]

The general design of aircrafts can be subdivided into individual design disciplines, here exemplified by aerodynamics, propulsion, flight dynamics and structure [38]. Based on this, and following SCHUH, so-called product increments are required to verify the progress of the project horizontally, i.e., within a design discipline, with the help of a prototype. In this context, product increments are to be understood as prototypes which, through detailed mapping of relevant modules, enable developers to improve development by making the innovation spatially tangible [61]. Minimum-Viable-Products (MVP), in contrast, serve to develop and verify the design progress vertically, i.e., concerning all design disciplines simultaneously, by means of interdisciplinary prototypes. Thus, MVPs describe prototypes for various stakeholders who are not visionary developers and who can provide meaningful feedback on product ideas that can only be experienced [61].

4.4.1. Product increments

Within these two categories of possible prototypes, various verification methods can subsequently be mapped. An overview of verification methods for the product increments is given in Figure 9.

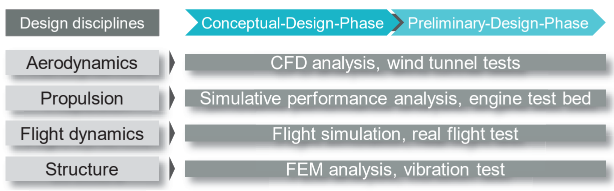

Figure 9: Product increments for verifying the individual design disciplines

Computational fluid dynamics (CFD) analysis represents an example of a design verification method with respect to aerodynamics [47, 69]. CFD analysis can be used, for instance, to examine the wing as part of the aerodynamics for sufficient lift provision. The results of the CFD analysis can then be used to optimize the flight model and, for instance, be tested in reality as part of wind tunnel tests under representative conditions [30, 69].

4.4.2. Minimum-Viable-Products

In addition to methods for verifying individual product increments, verification methods can also be determined at the overall design level. An excerpt of verification methods regarding MVPs is shown in Figure 10 and will be described in the following exemplary.

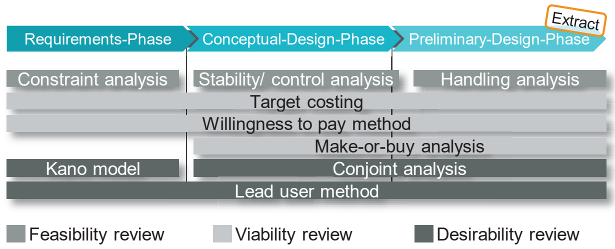

Figure 10: MVPs for verifying the overall design

One possibility in the form of an MVP to verify the design progress on the overall design level regarding technical feasibility is the stability and control analysis. In the context of aircraft stability and control analysis, the main interest is to determine the moment of inertia about the x-, y-, and z-axes [30]. This analysis can thus be used to fully evaluate the dynamic stability and control of the aircraft [31]. With the willingness-to-pay approach, there is also the possibility to determine whether an improvement in product features or components leads to an increased willingness-to-pay on the side of the customer [70]. Accordingly, this approach is a method of verifying the viability of the design at various points in the design process. To answer the question of whether components should be produced independently or whether they should be sourced externally (make-or-buy analysis) [71], the main components must already be described in more detail, which is why this analysis is only considered useful from the beginning of the Conceptual-Design-Phase. Furthermore, the Kano model represents a procedure, in order to determine the influence of customer requirements on the customer satisfaction [72]. It is used to prioritize the features of a product or service defined by the customer as critical or relevant to quality, which are most important for successful function or purpose fulfillment [73]. The Kano model thus enables an early review of customer requirements and is therefore assigned to the Requirements-Phase.

4.5. Model for highly iterative verification of the design progress of Air Taxis

In this section, the model for highly iterative verification of the design progress of Air Taxis is presented and detailed based on its constituent characteristics. An overview of the model is given in Figure 11. The basis for the description of the model is built by the derivation (c.f. section 4.1) and the description of the design process for Air Taxis (c.f. section 4.2). The two addtional foundations are the requirements for verifying the design progress (c.f. section 4.3) and the verification methods (c.f. section 4.4).

The highly iterative model can generally be divided into two halves. In the upper half, the individual design disciplines of aerodynamics, propulsion, flight dynamics and structure are addressed (c.f. Figure 11). In the lower half, the overall design is considered based on the three requirement dimensions feasibility, viability, and desirability. To further detail the model, the four constituent characteristics are described below.

The model consists of a **four-phase understanding** of the Air Taxi design process, which is represented by the circular segments in the selected illustration (c.f. Figure 11). The increasing workload associated with the progress of an Air Taxi design is symbolized by the increasing circumferences. The model is initiated with an idea of the implementation of an Air Taxi. This initial idea is further advanced in the Requirements-Phase into a specification. This involves determining the requirements space for the Air Taxi, i.e., the requirements that the Air Taxi must fulfill both within individual design disciplines and at the overall design level. Based on the specification, the concept of the Air Taxi design is developed in the Conceptual-Design-Phase, i.e., the requirements space is to be concretized by developing a solution space. For this purpose, the dominant components of the specification are to be initially designed. The shape, position and properties of the dominant components constitute different concepts of the Air Taxi design in the Conceptual-Design-Phase. An evaluation and selection of the most potential concept form is the result of this phase. Subsequently, the concept is further detailed into a configuration within the Preliminary-Design-Phase. In addition to detailing the dominant components, the initial design of the subordinate components is also completed within this phase. With the initial design of these subordinate components, the design can be further elaborated in form of different configurations. An evaluation of the configurations enables the selection of the most promising configuration, which describes the result of the Preliminary-Design-Phase. In the subsequent Detailed-Design-Phase, the dominant and subordinate components of the configuration are to be fully extracted. Due to the low flexibility and the high percentage of fixed costs in this design phase, the Detailed-Design-Phase is not considered in greater depth in the model.

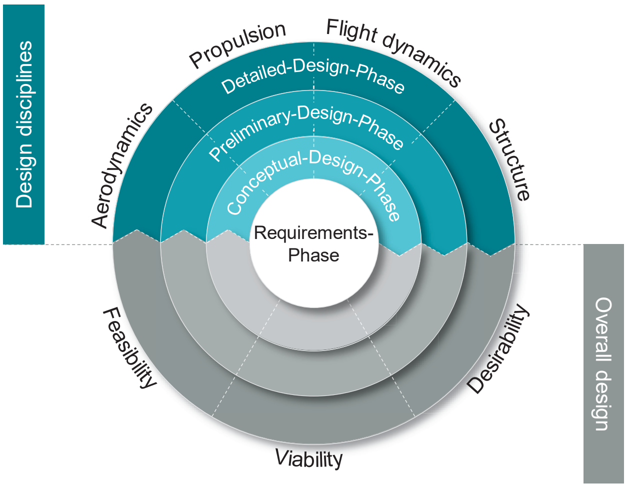

Figure 11: Depiction of the model for the highly iterative verification of the design progress of Air Taxis

The model also enables an inherent, highly iterative verification of the design progress of Air Taxis through an **interphased and intraphased structure**. The intraphase verification is performed within the design phases. In the context of the individual design disciplines aerodynamics, propulsion, flight dynamics and structure, the technical feasibility can be verified intraphase-specific to the discipline based on the product increments. At the overall design level, the design progress is to be verified intraphasically using the MVPs holistically regarding desirability, viability, and feasibility. This is followed by the interphase review of the design progress in the phase transition to the next design phase. Here, the specification is checked for convergence in the Specification-Review, the concept in the Concept-Review and the configuration in the Configuration-Review (c.f. section 4.2). The interphase reviews are thus to be understood as a verification step to check the requirements fulfillment of the design progress. In case of convergence, the design proceeds to the next design phase. In case of divergence, the design progress must be iteratively adapted or improved in the existing design phase, so that the essential requirements for the transition to the next phase are fulfilled.

Within the design disciplines, **product increments** are provided for the technical verification of the design progress. Within the key design disciplines of aerodynamics, propulsion, flight dynamics and structure, individual product increments are required for separate technical verification of the disciplines. The sum of the design disciplines constitutes the overall design of an aircraft, which is to be verified by means of the **MVPs**. As derived in section 4.3, three requirement dimensions are to be considered at the overall design level when verifying the Air Taxi design progress. With respect to the requirement dimension of feasibility, the technical feasibility of the design is to be verified. In the context of viability, the design must be verified in terms of economic criteria from the company's and the customer's point of view. Regarding the dimension of desirability, an Air Taxi desired by the market must be ensured.

For the application of the highly iterative model, it is first necessary to determine the design progress of the Air Taxi design under consideration. For this purpose, the phase-specific information objects from section 4.2 must be consulted. The degree of the addressability of the information objects can be used to determine the progress of the Air Taxi design. The determination should be performed by an expert from the Air Taxi company's development team who is involved in individual design disciplines as well as having insight at the overall design level. With knowledge of the design progress, the model can be used for highly iterative verification of the design progress of Air Taxis. Applying the model subsequently enables a generic derivation of **phase-specific verification methods**. Accordingly, methods can be derived for the technical verification of individual design disciplines or for the technical, economical and acceptance verification of the overall design (c.f. section 4.4). According to the dimensions, the overall design can thus be verified highly iteratively in terms of feasibility, viability, and desirability.

5. CONCLUSION AND OUTLOOK

In conclusion, the process model contributes significantly to the design of Air Taxis according to the various and complex requirements. With the application of the model, a feasible, viable and desirable design of an Air Taxi is enabled by means of a highly iterative approach. Thus, the model serves as a strategic tool for business development managers and executives of companies designing Air Taxis to enable a transparent depiction of phase-specific verification needs and methods.

However, further research is evidently needed. On the one hand, a strategic alignment of the design process requires the systematic collection of all requirements from relevant stakeholders. Based on these requirements, specific development objectives for the design can be aggregated and substantiated. In a further step these development objectives can then be used to specify the described generically derived verification needs and methods. Thus, a prioritization of the generically derived verification methods for individual Air Taxi design projects would be enabled. On the other hand, application experience has shown that the model can be particularly useful in the early phases of the design process. This suggests further detailing of the highly iterative approach, especially in the Requirements- and Conceptual-Design-Phase, to enhance the value of using the model for the design of Air Taxis.

All in all, the outlined model provides a clear structure and can be beneficial for the requirement compliant design of an Air Taxi. In future work, the model needs to be validated in a real-world use case to further improve its practicability and to assure its added value for the design of Air Taxis.

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APPENDIX

A1: (Sub-) selection criteria of the utility analysis

I Systematic design process
1) Holistic perspective
2) Systematic structure of the process
3) Appropriate level of detail

II Configuration-independent approach
1) General applicability
2) Powertrain independence

III Technology openness
1) Considering new technologies
2) Interface for new technologies
3) Considering technology maturity

IV Practice-oriented process
1) Degree of maturity
2) Degree of usability

V Phase-based progress verification
1) Phase-specific information objects
2) Phase-based verification

VI Highly iterative design approach
1) Iterative basic structure
2) Interphased iterations
3) Intraphased iterations

VII Formal verification methods
1) Differentiation of requirements
2) Methods for documenting the requirements

VIII Technical verification methods
1) Methods for verifying individual design disciplines
2) Methods for verifying the overall design

IX Marketability verification methods
1) Methods for cost estimation
2) Methods for profitability analysis
3) Methods for social acceptance verification

A2: Evaluation Table I – Systematic design process

Systematic design process		
Subcriteria	Evaluation possibilities	Score
Holistic perspective	Consideration of **one** specific **design phase**	1
	Consideration of at least **two design phases**	2
	Consideration of **all design phases but focusing** on a specific	3
	Holistic consideration of **all design phases**	4
Systematic structure of the process	**Rough guideline** with predefined design activities **without order of activities**	1
	Predefined design activities with **rough sequence of activities**	2
	Predefined design activities with **detailed sequence of activities**	3
	Structured guideline with predefined design activities and **detailed sequence**	4
Appropriate level of detail	Level of detail with **undefined information density**	0
	Medium level of detail with **increasing information density**	1
	High level of detail with **increasing information density**	2

A3: Evaluation Table II – Configuration-independent approach

Configuration-independent approach		
Subcriteria	Evaluation possibilities	Score
General applicability	**No differentiated consideration** of different takeoff and landing characteristics	1
	Selective applicability for CTOL, STOL or VTOL	2
	Partial applicability for CTOL and STOL, CTOL and VTOL, or STOL and VTOL	3
	Universal applicability for CTOL, STOL and VTOL	5
Powertrain indepen-dence	Consideration of **classic powertrain concepts**	1
	Consideration of **classic** and **partly alternative drive concepts**	2
	Consideration of **classic** and **alternative drive concepts**	3
	Integrative consideration of classic and **alternative drive concepts**	5

A4: Evaluation Table III – Technology openness

Technology openness		
Subcriteria	Evaluation possibilities	Score
Considering new technologies	Alignment with **classic technologies**	0
	Isolated consideration of new technologies	2
	Consideration of new technologies	3
	Integrative consideration of new technologies	4
Interface for new technologies	Interface for integration of new technologies **not provided**	0
	Interface for integration of new technologies **provided**	2
	Interface for the integration of new technologies **explicated in detail**	4
Considering technology maturity	**No consideration** of the technology maturity level	0
	Consideration of the technology maturity level	2

A5: Evaluation Table IV – Practice-oriented process

Practice-oriented process		
Subcriteria	Evaluation possibilities	Score
Degree of maturity	**New** process, **previously untested**	1
	Process **validated on practical examples**	3
	Industry proven and accredited process	5
Degree of usability	**Low usability** with high complexity	1
	Medium usability with high complexity	3
	Simple usability with reasonable complexity	5

A6: Evaluation Table V – Phase-based progress verification

Phase-based progress verification		
Subcriteria	Evaluation possibilities	Score
Phase-specific information objects	**No phase-specific consideration** of information objects	0
	Formulation of phase-specific information objects at the **macro level**	2
	Formulation of phase-specific information objects on **macro and meso level**	3
	Formulation of phase-specific information objects on **macro, meso and micro level**	5
Phase-based verification	**No** phase-based **verification** of the design progress	0
	Phase-based **verification within or between design phases**	2
	Phased **verification within and between design phases**	5

A7: Evaluation Table VI – Highly iterative design approach

Highly iterative design approach		
Subcriteria	Evaluation possibilities	Score
Iterative basic structure	**No iterations** included in the process	0
	Isolated iterations included in the process	2
	Multiple iterations included in the process	4
	Highly iterative process	6
Interphased iterations	Iterations between the design phases are **not included**	0
	Iterations between the design phases are **included**	2
Intraphased iterations	Iterations within the design phases are **not included**	0
	Iterations within the design phases are **included**	2

A8: Evaluation Table VII – Formal verification methods

Formal verification methods		
Subcriteria	Evaluation possibilities	Score
Differentiation of requirements	**No differentiation** of requirements	0
	Consideration of different requirements	3
	Differentiated consideration of various requirements	5
Methods for documenting the requirements	Methods **not** explicated	0
	Methods **partially** explicated	2
	Methods **largely** explicated	3
	Methods **comprehensively** explicated	5

A9: Evaluation Table VIII – Technical verification methods

Technical verification methods		
Subcriteria	Evaluation possibilities	Score
Methods for verifying individual design disciplines	Methods **not** explicated	0
	Methods **partially** explicated	2
	Methods **largely** explicated	3
	Methods **comprehensively** explicated	5
Methods for verifying the overall design	Methods **not** explicated	0
	Methods **partially** explicated	2
	Methods **largely** explicated	3
	Methods **comprehensively** explicated	5

A10: Evaluation Table IX – Marketability verification methods

Marketability verification methods		
Subcriteria	Evaluation possibilities	Score
Methods for cost estimation	Methods **not** explicated	0
	Methods **partially** explicated	1
	Methods **largely** explicated	2
	Methods **comprehensively** explicated	3
Methods for profitability analysis	Methods **not** explicated	0
	Methods **partially** explicated	1
	Methods **largely** explicated	2
	Methods **comprehensively** explicated	3
Methods for social acceptance verification	Methods **not** explicated	0
	Methods **partially** explicated	2
	Methods **largely** explicated	3
	Methods **comprehensively** explicated	4

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