ASSESSMENT OF TOP-LEVEL SPECIFICATIONS FOR URBAN AND REGIONAL AIR MOBILITY VEHICLES

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Abstract

Established transport modes are reaching increasingly both capacity and infrastructure limits. To satisfy transport demand for passengers and cargo in the future, an increased usage of the third dimension could be one solution. More than 100 design concepts for so called ‘air taxis’ that shall address the markets for urban and regional air mobility are currently under development. This study supports the development efforts by providing a clear picture of top-level specifications for such vehicles and measures to assess their formal, technical, and economic coherence.

Top-level specifications include a clear definition of a reference mission, top-level aircraft requirements (TLARs), and main components. All elements are adapted to the special requirements of either urban or regional air mobility, if necessary, and are fitted into the common aircraft design process suggested by literature.

As vehicle designs for urban and regional air mobility are guided by diverse technical concepts, five archetypes are introduced that mainly differ regarding the way lift and propulsion are generated. Based on a functional dissection of those archetypes, main components of air taxis were defined to serve as part of a reference frame for top-level specifications.

TLARs are frequently discussed within academia. However, there is neither a clear definition which categories shall be covered, nor a distinction between vehicles for urban and regional air mobility. This study addresses both issues by defining sets of top-level aircraft requirements and main components as a framework for top-level specifications and inserting them into a validation framework. This enables full validation of a complete specification of a given air-taxi, to check coherence to formal, technical and economic requirements.

Results are validated with the Silent Air Taxi, a piloted five-seater aircraft currently developed by German start-up e.SAT GmbH.

1. INTRODUCTION & OBJECTIVES

Until the year 2030, 60 % of the world’s population will live in cities, whose infrastructure is at its operating limit already [1]. There is a need for mobility solutions that adapt to growing demand all while relieving existing modes of transportation. Air travel based on on-demand operation, known as “On-Demand Air Mobility” (ODAM) offers many benefits concerning modern transportation needs. Not only could it divert pressure from urban mobility infrastructure, often called “Urban Air Mobility” (UAM), but it could also close the transportation gap of 100-500 km – “Regional Air Mobility” (RAM) [2]. Albeit small aircraft have been in production for many years, a considerable development effort will be necessary to adapt small CS-23 aircraft (certification category for general aviation aircraft) to new requirements of UAM and RAM. Long-term issues of small aircraft such as performance, safety and cost efficiency need to be tackled before on-demand air mobility can be established as a competitive mode of transportation [1]. These development efforts are already performed by the 100+ concepts currently being researched and developed. The market volume for ODAM is predicted to reach $32 billion until 2035, while already establishing as a mode of transportation in 2025 [3]. Companies currently competing for market entry in this market are on a strict timeline, however their focus of aircraft development fundamentally differs from past projects: Aircraft are not being developed with the next record in mind anymore, but instead to address one market need very specifically. This means a close guidance by a range of requirements. Regarding the degree of commitment to the aircraft’s configuration and technical implementation, Sadraey [4] found that most decisions are made in early development phases. At the same time, these commitments suffer from poor product specific knowledge, but already define a large share of the future product cost. Many fixed parameters lower the ease with which changes can be implemented in later phases. These findings are visualized in FIG 1.

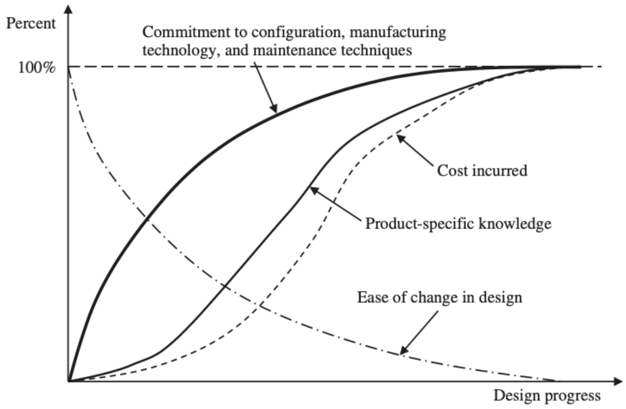

FIG 1. Product characteristics in the course of the design process [4]

While a delay of commitment would mostly prolong the aircraft design process, the correct choice of commitments and design decisions as well as an increased product specific knowledge at the beginning of the design process are needed to successfully develop aircraft.
Furthermore, each development project on its own is in need of immaculate requirements engineering. The complex cause-and-effect relationships in aircraft give rise to a strong need for individualization of development processes in order to adequately reflect the specific application. A corresponding specification process must be able to track a range of different technical parameters as well as provide means of validation. This research aims to start this process off by providing an initial framework upon which further optimization of specifications can be built.
The goal is to develop a framework that provides an assessment of top-level specifications to allow a more focused approach to aircraft development. More product specific knowledge in early stages all while using a less restrictive process compared to conventional aircraft specification and development processes are the main characteristics. This is achieved by choosing a core set of necessary requirements and specification objects.

To achieve this, a framework will be developed, that addresses the aforementioned challengers. For this, first a theoretical foundation is established, after which the individual framework elements are defined. The method of application will be described afterwards and put to the test for validation of a case study. In the end, a conclusion on the effectiveness of the framework will be drawn and possible extension options will be outlined.

2. THEORETICAL FOUNDATION

Following, a baseline for specification processes in aircraft design and requirement engineering will be established to represent the current state of the art. First a general idea of aircraft design is presented after which it will be segmented into individual phases to identify relevant parts for top-level specification assessment. After these phases were described in more detail and relevant literature was identified, a close look at current ODAM development will be taken to identify current challenges in more detail.

2.1. Aircraft Design and Specification Process

In general, a new aircraft design is started if requirements in economics, technics or design mission surpass capabilities of current designs [5], thus a market demand is present. According to Gudmundsson [6], requirements are identified and prepared in the Requirements Phase of the aircraft design process. Afterwards, a variety of concepts are explored in the conceptual design phase in order to select the one that can best fulfil the requirements. This concept is then refined to its best performance in the preliminary design phase through optimization loops. In the detailed design phase, individual components of the aircraft are designed and developed before production of the new aircraft type begins in the fabrication phase once development is complete. However, these sub-processes do not run sequentially, but partly in parallel. This description is mostly equivalent across the industry and will be the basis of all following explanations. Regarding the focus of this paper, the process from the requirements phase and conceptual design phase are most relevant.

2.2. Relevant Phases of Aircraft Design

After breaking down the general top-level process of aircraft design into its five main phases, two phases will be investigated in more detail: the requirements phase and conceptual design phase. This reflects the need introduced in FIG. 1 to improve product specific knowledge and support wide changes in configuration commitment in early development phases.

2.2.1. Requirement Phase

The requirements phase summarizes all needs which must be fulfilled by the aircraft being developed. Requirements express performance goals, guidelines and regulations [4]. These form a basis upon which a set of objectives, quantitative figures are built to guide the project on a path to meet all stakeholders' expectations. As Gudmundsson [6] puts it: “Requirements are akin to a wish list. It is a list of expectations that the new design must meet.” The set of requirements resulting from this development phase are called top-level aircraft requirements (TLAR).

While the stakeholder, from which the requirement originates, is not relevant at this point, the different categories of requirements will be discussed in greater detail. The differences of categories will be explained on the examples of certification, design mission, implicit requirements and lastly consistency and feasibility of such requirements.
Strict certification standards contribute to today's high level of aviation safety to a large extent. This also means that the requirements which result from them are very detailed [6]. In ODAM the CS-23 standard and American equivalent are the most important, as the small aircraft category is one of the main distinctions of on-demand air travel from other aviation travel products. While the actual certification of the aircraft happens at the end of a successful development process, the right predispositions must be implemented from the beginning. This ensures smooth certification approval and safe operation.
Another aspect which provides a rich source of top-level requirements is the design mission. A precise definition is of great importance, as these performance metrics will be consulted to optimize the aircraft throughout the whole development effort. As the design mission is itself part of the specification, it will later be discussed in more detail.
Furthermore, requirements may often be implied by or be derived from other requirements. It is important to understand the interrelations between the different parameters of the aircraft, to reduce the requirements coverage to the most basic set. In addition, non-quantitative requirements can be implied by e.g., the design mission, as certain equipment and furnishings become necessary.
With these connections in place, it becomes essential to ensure the consistency and feasibility of the top-level specification. Parts of a specification might behave in different ways, for example, supporting, complementary, or excluding [7]. Howe [5] suggests a feasibility study after top-level requirements have been elicited, which

determines the consistency of all requirements and feasibility with intended technologies.

The selected set of TLARs form the basis for a first technical implementation. As an input to the Conceptual Design Phase, it serves as a benchmark to any aircraft concept, that is created from it.

2.2.2. Conceptual Design Phase

As any process in engineering design, conceptual design contains activities of analysis, decisions and compromise [5]. Sadraey [4] defined three phases of any design process, which are: analysis, evaluation and synthesis. The goal of these recurring phases within conceptual aircraft design is to explore all feasible combinations of component specifications to find a concept promising enough to fulfil all requirements recorded in the previous phase [8]. This combination of component specifications will from here on be called a configuration. The configuration contains a description of the characteristics of every main component of a system, such as an aircraft. Therefore, main components are first identified and configured to their specific task derived from top-level requirements. Afterwards, they are integrated into the overall system and optimized to function in unity. A configuration enables the description of a complex system by the individual specifications of its components. Logically, an iterative process is required to come to a configuration solution, that fulfils the stated purpose.

In an exemplary conceptual design process [9] design requirements and available technologies are evaluated to result in a first concept draft. This draft passes through multiple iterations of the aforementioned cycle of analysis, evaluation and synthesis to further detail decisions taken or adjust for a feasible solution. These iterations start coarsely and become finer in resolution each time. At last, one conceptual design is chosen to pass on to preliminary design. Only if there is no feasible solution, an adjustment of top-level requirements is intended. A shortcoming of this process, however, is the lack of logical structure, especially concerning the main components of the aircraft being developed. In a more systems engineering focussed approach [4], a selection of configurations is entered into a review process. This assumes a multitude of concept solutions being developed on a system specification level. By choosing a configuration-based approach, more than one solution concept can be developed and entered into the trade-off to eventually pass on to preliminary system design.
In the end, to find the technically and economically superior solution, a focus on abstraction to main components and the top-level aircraft requirements is necessary. This ensures a solution based on a problem-solving approach, that is guided by market demand. While structuring an approach by the configurations main components benefits the development effort, there is yet to be a comprehensive definition of the set of components to use.

2.3. Challenges of ODAM Development

Before introducing a framework to tackle the general challenges of aircraft design, the special challenges developing aircraft for an on-demand mobility market should be considered. Holmes et al. [1] describe ODAM as the “future for transportation of people and goods, anytime, anywhere, for productivity, or pleasure, with levels of safety and affordability we take for granted in our automobiles today.” This promise entails a number of challenges, which are furthermore amplified by external factors. Following, the most relevant segments of challenges containing technical, environmental, market and integration as well as certification related obstacles will be presented.

Currently there are over 100 new concepts being developed to fulfil the overall goal of ODAM to become a major transportation mode as early as 2025 [3], [10]. Until now, there are only few if any projects actually realized and entering commercial operation. German start-up Lilium was recently put under pressure by aviation publication “aerokurier” [11]. Credible sources from academia had reason to doubt the technical feasibility of Lilium’s approach to complete the intended design mission. Especially vertical take-off and landing (VTOL) concepts suffer from requiring a very powerful propulsion system, in order to maintain flight (thrust to weight > 1.2) and therefore carry much more weight compared to a classical aircraft. If the propulsion system is also specified to be electric, even more challenges arise. Current battery technology struggles to achieve energy densities high enough to allow for prolonged fully electric flights. [2]

In general, the landscape of concepts tackling different parts of the on-demand air mobility spectrum is widespread. It includes two main sectors: UAM focuses on short inner-city connections (<100 km), while RAM challenges high-speed travel up to 1,000km [2]. While UAM dates back to the 1950s when passengers and mail were transported by helicopter in New York and Los Angeles, intra-city air travel has since undergone numerous restrictions. However, demand is still high and waiting to be met by a new class of clean and quiet air transportation vehicles [12]. Even if the range for different mission profiles is small, there are many different technical solutions looking to serve various design missions [13]. These mostly realize technologies to start and land vertically, flight is realized either as hybrid vertical and horizontal flight or purely as a hover.
The long-range focused RAM connects small airfields otherwise not used for commercial air transportation offerings. These airfields open up a dense network of nodes, which increases accessibility to high-speed transport and reduced door-to-door travel time significantly in suburban and rural areas. Such an operational range has its own set of challenges, mostly a tradeoff between speed, efficiency and overall range.

The capabilities aspired for regional air mobility make it part of the solution to reach the ambitious goals of Flightpath 2050. While reducing CO^2 emissions by 75% and NO_x emissions by 90% respectively, travel times are to decrease to 4 hours for 90% of all connections throughout Europe by the year 2050. Furthermore, perceived noise levels must decrease by 65%. [14] As a key benefit of ODAM is its accessibility in many places, susceptibility to regulation and public opinion, especially concerning noise, increases [15]. Public acceptance is also closely tied to perceived noise levels.

To achieve high market acceptance and therefore be able to operate at high load factors, one must not only approach challenges of transportation in the aviation sector but keep improving at a similar pace as other modes of transportation. There, especially digital products are rolled out regularly to improve the long-lasting supply of transit products [3]. ODAM itself is mostly dependent on two main success factor: Fleet size and price-per-kilometre. However, there are many more to consider [16]. Additionally, ODAM success factors may not solely be in control of the aircraft industry, but at the mercy of political decision makers, according to Bauhaus Luftfahrt [17]. Especially fleet size and availability of airports and vertiports (vertical airports) are strongly dependant on political goodwill. A convincing value proposition is needed to ensure a favourable route to market. An effective integration into existing transportation modes such as long-haul air travel, high speed trains and public transportation can aid in this case. These integrations can be realized as feeder, supplement or new direct connections, especially in an urban setting. [18] The resulting challenges from scheduling and special connection need addressing.

Lastly, certification challenges should be addressed early on, as they are particularly pressing with entirely new aircraft concepts in ODAM. Many aircraft base their performance and operations on designs that have yet to receive a fully developed certification standard. EASA [19] offered the first certification basis for vertically operating aircraft with its SC-VTOL certification standard. Mostly, regulatory bodies are still reacting to developers' ideas instead of guiding the process from the beginning. This makes ODAM design even more uncertain. [1]

In summary, the following lessons learned can be formulated: Market requirements are very sensitive, but critical to make ODAM a feasible mobility alternative. To meet the existing transportation gaps without environmental violations, the technical performance envelope must be pushed. In conclusion, a correct and reviewable specification as well as plausible and traceable configurations must be established. This will allow for easier compliance with the multitude of requirements introduced before. An according development framework must respect the different states of development and result in domain-spanning solutions. In the end, these efforts ensure the development of ODAM into a feasible mobility alternative.

3. DEVELOPING A TOP-LEVEL AIRCRAFT SPECIFICATION FRAMEWORK

A framework to assess top-level aircraft specifications and review individual parts in context of the aforementioned multitude of challenges will be developed. Therefore, it is necessary to cover multiple dimensions of validation, such as economical, technical and formal. Firstly, a basis will be established as to exactly what a top-level specification is. Individual elements are defined in a way to accommodate technical and operational differences of all forms of on-demand air mobility. Next, corresponding forms of validation from a variety of fields of practice are introduced exemplarily to detail the validation of top-level specifications. In the end the framework can be applied in the full spectrum of ODAM to aid development adhere to specific key figures, from technical parameters to operational performance indicators.

3.1. Framework Introduction

The framework to accomplish this task is mainly comprised of the top-level specification, which gets validated after the first stage technical development cycle. This specification contains the key information objects relevant to early development stages. It comprises of the design mission, TLARs and main components and it foots on the business case for the foundational market need. These steps are depicted in FIG 2 and detailed in the following.

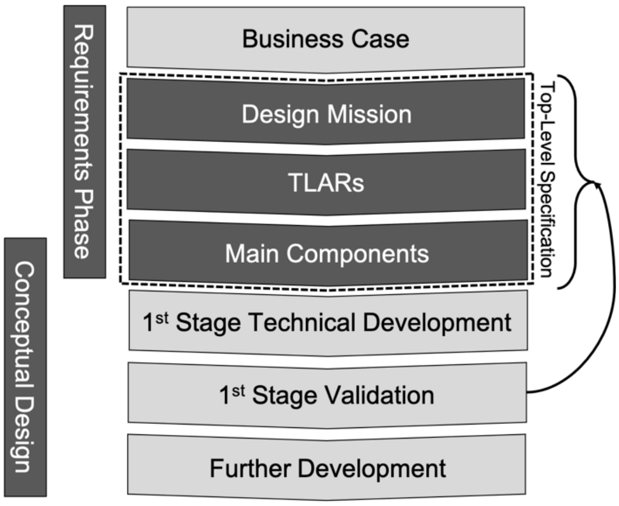

FIG 2. Overview of framework for top-level specification assessment

Initial description of the task to be solved originates in the business case. In aviation this mostly consist of the fulfilment of the reference mission along with optional qualitative features, such as comfort. An exemplary flight must be abstracted to quantitative figures such as payload, mission distance and duration. These first performance figures continue to be a relevant validation aid throughout the process ahead.
In an initial technical evaluation, information from the reference mission is processed into more detailed technical figures, the TLARs. These are the facts, technical development and first conceptualization upon which the aircraft is based. In correspondence to the goals of this research, the amount of specification should be kept to a minimum, as to not close off any possible solution paths too early. To accomplish this, a minimal set of top-level requirements will be defined, so that the solutions space stays as unrestricted as possible. The system which fulfils all these requirements is comprised of different main components. These will be determined to establish a top-level structure for the specification. For this purpose, the range of ODAM implementations was analysed and separated into relevant archetypes. They represent the distinctly different technical approaches, that arise by combination of several specifications of main components. Plenty of examples for each of these configurations can be found, which offer more insight into the general design mission of the respective archetypes.

This gives configuration decisions more context and makes them easier to reproduce.

Once the individual elements of the top-level specification are defined, these information objects are passed on to the first cycle of technical development. This process was introduced earlier and will not be discussed further. Results from technical development need to be validated based on the top-level specification, to ensure full compliance from the beginning. To assist with validation, different categories of validation methods available, will be discussed. A well-rounded arsenal of specification examination ensures requirement adherence from all angles. Therefore, formal, technical and economical validation methods will be presented.

3.2. Reference Mission Breakdown

A reference mission is a normative description of the fundamental problem to be solved by the aircraft. It describes the underlying problem, whose solution induces a benefit for the user. Fundamentally, a reference mission is based on a connection of a start and an end point by flight, in a given time and transporting a given payload. The mission profile contains simplified and abstracted figures to describe the main task of the aircraft, once it is in regular operation [20], [21]. It is therefore a link between the business case and technical requirements. For this framework, a description of the reference mission by the figures range, duration and payload will be used. These figures allow for a normative description, enabling simpler comparison and benchmarking. With little effort, the energy required to complete the mission can be estimated and compared with the amount of energy available. Overall, the flight performance of the current technical concept is continuously compared with the reference mission as a benchmarking basis.

3.3. TLAR Assessment

Supplementing the definition of technical parameters describing the reference mission, an extended set of parameters usually form the starting set of requirements in aircraft development. These requirements are called TLARs. Sets of these requirements can differ in content depending on the application field of the specific aircraft. To determine these differences and establish a common base upon which sets of TLARs can be built, a sample of literature from aircraft development was analysed by [22]. The analysis gave insight into the irregularity, with which sets of TLARs are defined. The study found that cruise speed and payload are almost always defined, while emissions and economics were not present in over half of the literature sample. All samples showed implications for a certain aircraft configuration, while this decision is only due during the first technical development cycle. In general, the level of detail is mostly consistent across publications, however the scope of parameters widely differs. This confirms the motivation to define a common information frame for such elements of top-level specifications, while ensuring independence of any particular aircraft configuration.

As a result, a set of top-level requirements is defined, which is tailored to the needs of ODAM. The individual requirements all address challenges outlined earlier to ensure a market demand is met without ecological violations and the business case is profitable at the same time. A distinction between urban and regional applications is made for several requirements, because the nature of corresponding reference missions differs significantly in these places. Urban mobility most often requires the ability to start and land in a vertical hover and short mission distances are not as sensitive to flight speed improvements as longer routes. For this reason, the definition of a minimum hover duration instead of a flight speed requirement is a sound decision to adjust top-level aircraft requirements to the special application needs. Similar reasoning was applied for differentiation in infrastructure needs, specifically the area needed for take-off and landing. The complete set of TLARs applied for the overall specification framework can be found in TAB 1.

<table>
<tr><th>Urban</th><th>Regional</th></tr>
<tr><td colspan="2">Payload</td></tr>
<tr><td>Minimum Hover Time</td><td>Flight Speed</td></tr>
<tr><td colspan="2">Efficient infrastructure usage and dependency</td></tr>
<tr><td>Needed Parking Area</td><td>Take-Off / Landing Distance</td></tr>
<tr><td colspan="2">Design Range</td></tr>
<tr><td colspan="2">Maximum Take-Off Weight</td></tr>
<tr><td colspan="2">Financial Needs in Development</td></tr>
<tr><td colspan="2">Total Cost of Ownership</td></tr>
<tr><td colspan="2">Environmental Footprint</td></tr>
<tr><td colspan="2">Business Case Features</td></tr>
<tr><td colspan="2">Configuration</td></tr>
</table>

TAB 1. Minimum Set of Top-Level Aircraft Requirements

The result is a set of TLARs, that reduces traditional requirements to a minimum and introduces application focus, economic factors and individual features from the business case. This way, the focus on actual market needs can be maintained while keeping financial investment during development within a realistic scope. As a result, the specification is not only easily comparable, but also complete according to the specific project stage.

3.4. Derivation of Main Components

ODAM is mostly categorized by urban and regional application; however, every design mission requires a degree of aircraft specialization to achieve best results and therefore market success. To gain a better understanding of the spectrum of solution used in the ODAM space, firstly five main archetypes are defined. Furthermore, these archetypes are analysed to determine specific differences, which can be abstracted to a common concept or function. These main functions will be used to find a set of main components, whose configuration can be altered to represent each of the defined archetypes.

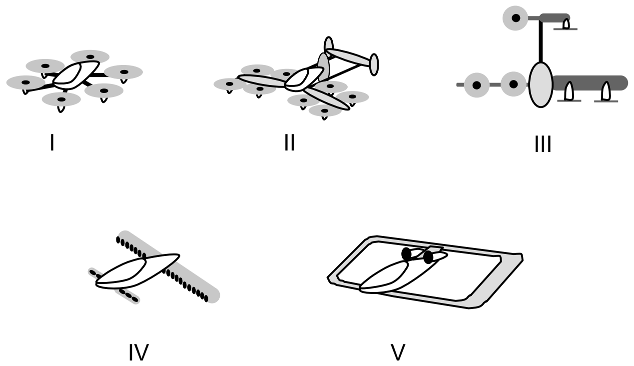

FIG 3. Archetypes of On-Demand Air Mobility

FIG 3 depicts the five main technical concepts that can be found in the ODAM market: Multicopter. (I), Lift & Cruise (II), Tilt Wing (III), Fixed Wing Vectored Thrust (IV) and Classic/Vertical Take-off & Landing (V). These concepts mainly differ in the way lift, thrust and flight control are implemented. Either aerodynamic or thrust based concepts are applied and the different combinations of those result in the aforementioned archetypes. Despite the obvious differences, which also contribute to the characteristic look of each concept, there are further differences within the aircraft. By defining a set of main components, these differences can be categorized at a top-level and enable a standardized representation in the aircraft's specification. According to IEEE/IEC/ISO 15288 [23], a system is the combination of interacting components, that are arranged to fulfil a certain task or purpose. A component is therefore a discrete part of the set, that describes the system as a whole. Components can be systems as of their own, however in this case, only the top-level disassembly is considered. In case of the ODAM aircraft, ten different main components were defined, to completely describe a full aircraft by individual definition of its parts. They can be found in TAB 2.

Lift	Thrust
Energy Storage	Power Provision
Flight Control	Aerodynamic Contour
Structure	Interior
Systems	Landing Gear

TAB 2. Main Components for Top-Level Spec.

The main components chosen for the specification framework partly align with standard disciplines and departments engaging in aircraft development. However, some distinctions are made, e.g., the energy system was divided into storage and provision, as practice shows several combinations of the possible implementations of each system to provide unique power systems characteristics. Also, as mentioned before, lift and thrust are defined in separate components, to accommodate the main differences in the archetypes. From the authors perspective, the overall resulting set of main components allows for a complete top-level specification of any aircraft, if each component itself is defined on a top-level basis.

3.5. Validation methods

The specification pieces introduced into the framework until now project a target image, which must be validated accordingly to have the pursued impact. To ensure the completeness of this evaluation, a range of validation methods is necessary. Formal validation controls defined norms in the documentation and representation within the specification. The validation of single departments and of the overall configuration is done by technical validation methods. Lastly economic validation ensures, the aircraft meets market needs in an economically reasonable way. Otherwise, the willingness of all parties to pursue the project is not present.

Formal validation not only specifies the external appearance of the specification but helps understand and regulate the interaction between requirements. This is to ensure the specification can be used most efficiently to pursue development goals. First of all, different types of requirements can be defined, to give context to changes in numbers and variables. Mattmann [24] defines fixed requirements, range requirements and optimum requirements. These allow for a multitude of variable behaviour to be modelled and put into easy-to-understand terms. Additionally, collections of measures of formal quality [25] norms [26] and guidelines [27] are applicable.

Technical validation provides insight into whether the quantitative measures of the aircraft actually hold up to the stated TLARs and all conclusions that can be drawn from them. Coordination and overall validation are done by the development lead, individual departments contribute validation from their area of expertise. However, validation methods also combine some disciplines, like a V-n-diagram which requires input from structural and aerodynamic engineering as well as flight control [6]. In addition to specific methods, general validation steps, such as checking the assembly space on all components must be included.

The foundation of economic feasibility are the assumptions made in the business case and their support by real world performance. While technical validation ensures that flight parameters are met, economic validation looks after the profitability of the business, given the current specification. Meeting the target revenue range is crucial to ensure the development of the aircraft is worthwhile. Operating cost are a good indicator, that can already be estimated in early project phases, based on performance numbers of the aircraft for the design mission. For example, they could be compared on an iteration-basis to track progress as the aircraft development process moves through its phases. As stated before, operating cost and therefore pricing for the customer are a major success factor of ODAM.

4. VALIDATION

After the individual elements of the framework to assess top-level specifications have been defined, they need to be composed into a method, that can be easily applied.

The following is a brief description of the method used to apply the framework in a real-world use case. The defined information objects are combined following the process earlier depicted in FIG 2. The specification can then be evaluated by a checklist logic, to determine the degree to which it conforms with all requirements stated in the requirements phase. Inconsistencies or flaws in the specification must be uncovered in order to ensure a successful further development of the project after appropriate touch ups.

First of all, the existence of a specific reference mission must be checked. The description should at least consist the reference distance, a corresponding duration and the payload to be transported. Derived from this, the TLARs must have been defined for the aircraft. In doing so, care must be taken to ensure that the information is unambiguous with regard to the way these requirements are to be met. Compliance with the requirements must also be checked after the aircraft has been configured. The configuration of the major components should be briefly described and must be complete. A corresponding mass split of the individual masses of the respective main components must be set up and validated with the corresponding requirement. The appropriate procedures and methods must be applied by the respective disciplines both in their field of expertise and for the overall concept of the aircraft.
After a technical specification check, the economic aspects of corporate planning are also evaluated accordingly. For this purpose, several cost and revenue statements have to be specified in a comprehensible way. The development cost should provide a statement of the financing requirements over the course of the project, while the target revenue ensures the profitability of the aircraft after successful development. This also includes a sales forecast, which can, for example, be derived from a market model. A parts list allows a more precise analysis of unit costs and cost drivers. The combination of this information enables a holistic evaluation of the economic planning of the project.
Finally, a corresponding check of the formal specification quality is carried out. It is to be evaluated whether the specification in its present form meets the requirements [25]–[27]. In particular, the completeness and consistency of the specification are of importance, but also the traceability, modifiability and unambiguity. This facilitates and improves the continuous work with the specification. The types of requirements presented above should also be selected according to the respective requirements in order to put the specifications in their form in the right context.
All in all, a holistic evaluation of the top-level specification takes place in order to be able to assess whether further development steps are prepared and can be initiated in an appropriate way, or whether a revision of some or all technical assumptions made is necessary. The finished procedure is to be evaluated using a practical example.

As an exemplary case study, a small aircraft for regional on-demand air mobility was evaluated in its early development stages. The validation of the specification framework will be conducted using the Silent Air Taxi (SAT) by e.SAT GmbH as a case study. Developers of this 5-seater aircraft are looking to create a new mode of regional transportation, that rivals high-speed trains and short-haul CS-25 flights for business travellers. A hybrid powertrain enables the SAT to fly up to 1,000 km with a speed of up to 300 km/h. With a maximum take-off mass (MTOM) of 1,600 kg, the take-off distance is still only 400 m [28]. To achieve these goals and succeed in certification under CS-23 in 2024, the specification must be aligned with development goals from the beginning and requires due validation. For reasons of confidentiality, the results will be presented in a qualitative manner.

The reference mission was fully defined to represent the utility-inducing task from the business case. Respective figures were defined early on and in a way to exceed existing modes of transportation.
The given set for TLARs was met and additional information was defined in appropriate places, for improved clarity. Two slight anomalies were found during this process of validation. The MTOM-goal was slightly overshot, which must be validated with the reference mission. Also, the emission requirements were only specified for noise emissions, but have yet to be specified for exhaust gases. Requirement compliance could not be checked at this point. In this case, certification requirements are applicable.
Configuration validation was also mostly successful, uncovering only the following small oversights. While a FIKI-system (Flight Into Known Icing) was added as a business case feature requirement and configured as a main component under systems, the specific mode of operation was not specified. This leaves inaccuracy in the balances of structure, mass and energy, as different operating principles entail differing dimensions and energy requirements. Lastly the configuration of the landing gear is not yet defined, which also adds a certain inaccuracy to weight and balance measures. Otherwise, all main components are fully defined in implementation and function and assembly space is ensured. All components are taken into account for a mass split, which gives plausible validation for the overall weight. All adequate procedures and methods of validation of individual disciplines were applied and the overall concepts was validated as well. Extensive simulations were conducted for structural and aerodynamic analysis. Despite the minor oversights and a yet to be defined landing gear, the specification appears complete and coherent. Technical validation is therefore successful.
Next is the economic validation of the project: The underlying business case defines target revenues, which are reached by the presented concept configuration. A bill of materials aids in identifying major cost factors and working out cost saving potentials. A roadmap of expected development expenses was used as a planning method, to ensure successful project progress until certification and beyond. First predictions on sales and production planning were made. Generally, corporate planning was derived in a comprehensible and non-arbitrary manner.
The given specification is formally satisfactory by upholding required specification standards. Measures to reduce ambiguity to a minimum were taken. Consistency of all numerical values is maintained by the appropriate validation methods of individual departments and the technical development lead.

In conclusion, the validation of the SAT's top-level specification gives positive results. Only minor information deficiencies and one missing specification of a main component still make for a mostly complete specification in terms of project progress. The further progression of the specification into more detailed development processes is approved under the condition of defect elimination. The framework used for assessment delivered a simple method to carry out a full review of the top-level specification in a timely and effective manner. It was able to identify little shortcomings still present in the configuration and was otherwise also able to prove the coherence to formal, technical and economic requirements.

5. CONCLUIONS & OUTLOOK

A framework to assess top-level specifications of on-demand urban and regional air mobility vehicles was created and successfully tested in a real-world development effort. The framework is able to ensure an appropriate level of definition of the aircraft specification at any of the early stages of requirement or concept engineering. Coherence to formal, technical and economic requirements can be proven with this method and domain-spanning solutions are presented. Furthermore, a degree of documentation is achieved, which guarantees the ability to check and modify parts at any time. The approach takes into account the challenges and peculiarities of ODAM stated in 2.3 and was created with corresponding references to practical implementations. The developed procedure thus directly faces the individual challenges of ODAM on a specification level. As far as possible, the results are available in quantitative form and can be repeated and verified using the checklist logic.

To expand this framework for top-level specification validation to more detailed stages of the aircraft development process, further research is needed. The effort required for the application depends on the general scope of the items to be checked. This increases considerably with an application in later development stages, since specifications experience a significant influx of information up to that point. By the increased level of detail, far more information objects, whose examination could be necessary, arise. The corresponding abstraction and concentration on a relevant and controllable set of test points is necessary. To, however, still carry the certainty of the requirement and specification processes further into the development timeline, a morphological box can be created from the defined set of main components. This makes the plausibility of the configuration decision verifiable and can evaluate the suitability of the concept for the task at hand. The effects of the components on each other and on the overall concept and corresponding blocking logic must be deduced. The collected connections can then not only contribute to the examination of the specification, but also represent from the start a supporting tool in configuration finding.

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