# IT'S A LONG WAY UP: QUANTIFYING OPPORTUNITIES AND HURDLES FOR VTOL MANUFACTURERS

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**Abstract**

This research aims to create a transparent ranking mechanism for eVTOL manufacturers using measures and factors based on evidence from the relevant fields rather than cost proxies or algorithmic black boxes. Two factor groups that are essential when discussing firm survival are considered for the ranking mechanism: technology and certification as well as operational capabilities and resources. The main aim of the *technology and certification* group is to determine the gap between performance claims established by an eVTOL manufacturer and expected performance calculated with a fast, low-fidelity assessment method considering available vehicle input parameters and state-of-the-art technology assumptions. Further factors include the technology readiness level and the certification progress. In terms of *operational capability and resources*, we look towards knowledge captured by e.g. network diversity, entrepreneurial knowledge or initiative participation, as well as financial resources such as funding, stock exchange or the number of investors. A delphi study allows us to derive weighting factors to include the relevance of the various factor in the calculation of the overall index. Using the described ranking mechanism, Joby and Volocopter achieve the highest scores and thus have the highest probability of developing their aircraft to market readiness.

**Keywords**

urban air mobility; UAM; VTOL; technology progress; operational capabilities; market opportunities

## NOMENCLATURE

### Symbols

| | | |
|---|---|---|
| $A$ | rotor/propulsor area | m$^2$ |
| $L$ | drag force | N |
| $E$ | energy | Wh |
| $F$ | factor value | m/s |
| $G$ | acceleration due to gravity | m/s$^2$ |
| $\gamma$ | efficiency | - |
| $\gamma_P$ | propulsive efficiency | - |
| $L$ | lift force | N |
| $m$ | mass | kg |
| $P$ | power | W |
| $R$ | range | m |
| $\rho$ | air density | kg/$m^3$ |
| $T$ | thrust force | N |
| $V$ | speed | m/s |
| $W$ | weight force | N |
| $w$ | factor weight | m/s |

### Indices

| | |
|---|---|
| bat | battery |
| c | company |
| MTO | maximum takeoff |
| pt | power train |

### Abbreviations

| | | |
|---|---|---|
| DOA | design organisation approval (EASA) | |
| EASA | European Union aviation safety agency | |
| EOL | (battery) end of life | % |
| eVTOL | electric VTOL aircraft | |
| FAA | federal aviation administration | |
| IPO | initial public offering | |
| MTOW | max. take-off weight | kg |
| OC&R | operational capabilities and resources | |
| PMAD | power management and distribution system | |
| SOC | (battery) state of charge | % |

| | | |
|---|---|---|
| SOH | (battery) state of health | % |
| SPAC | special purpose acquisition company | |
| T&C | technology and certification | |
| TRL | technology readiness level | |
| UAM | urban air mobility | |
| VTOL | vertical take-off and landing | |

## 1. INTRODUCTION

Forecasts for the autonomous aircraft market project a volume of up to 1.5 trillion USD by 2040 [1]. In the urban air mobility (UAM) market, passenger services will generate an estimated yearly revenue of nearly 90 billion USD by 2050 [2]. Yet, many technologies that are to enable this shift in transportation are still in their infancy.

In this paper, we concentrate on the manufacturers of eVTOLs— battery-electric air vehicles with vertical take-off and landing capabilities—that serve the UAM market. Our central questions are:

*Q1)* How are the manufacturers situated in terms of technology, structure and finances and in which areas are their weaknesses (potential hurdles), and where are their strengths (opportunities)?

*Q2)* How strongly or weakly do these affect their opportunities in the UAM market?

*Q3)* Can we quantify the associated risks and use them to create a transparent ranking mechanism?

In this paper, we aim to establish an index-based, transparent ranking mechanism for eVTOL manufacturers, using measures and factors based on publicly available information and scientific methods from the respective fields. The index captures the diverse and manifold information on the situation and risks of a company in a structured and transparent way. Quantifying the associated risks will help to understand how far the industry is from implementing UAM as a viable transport option. The index is composed of two complementary areas, which are inspired by the resource-based view [3]: *technology and certification* incorporating product related aspects and *operational capabilities and resources* capturing company related aspects.

The paper is organized as follows. In Section 2, we describe the problem at hand and discuss what methods are suitable to analyse company success since we cannot fall back on conventional methods. In Section 3, we discuss the specific method that was chosen to answer the central research questions *Q1*–*Q3* of this paper, see above. The section is divided into four subsections. The first states some general assumptions made for defining the index. The second subsection describes the sub-index *technology and certification* including the incorporated factors and calculation methods to process the raw data to an index value. The third subsection provides an explanation on the company's operational capability and resources. The fourth subsection addresses the overall index calculation and the possibility of including a weighting for the different index factors. The data that has been collected to feed the vehicle manufacturer analysis and index creation is described in Section 3.6 and the results that are obtained when applying the chosen method/strategy is given in Section 4. The paper is concluded in Section 5, with a summary and outlook on future work.

## 2. BACKGROUND

The non-established nature of the UAM and VTOL market makes it particularly challenging to use conventional methods for analysing the success or failure of players in this field ex ante. These methods, regressions for example, rely on data that a hypothesis can be tested against, which does not exist for this future market.

Two recent attempts to analyse these markets are the ARI (advanced air mobility reality index) [4] and the Aerial Urban Mobility Ranking [5]. Both rankings have their drawbacks. Most prominently, the algorithm to create the former is not published, while the author of the latter admits to much personal bias.

We are taking inspiration from the disciplines of innovations management and strategic management in order to determine relevant factors for our analysis. "Successful innovators acquire and accumulate technical resources and managerial capabilities over time" [6, p. 76], which leads us to two main categories of analysis, the product-related and the company-related factors, which we will explain in the following.

In order to define a list of important factors, we are taking the perspective of a resource-based view [3, 7] and the notion of tangible and intangible resources. As the UAM market is not yet existent and large-scale production of VTOL vehicles has not started, some of the typically used factors are hard to retrieve or not yet existent for this emerging market. Resources and capabilities can be tangible (physical assets, financial resources or human capital [8]) and intangible (less measurable, implicit resources such as partnerships or knowledge [9]). Both resource types are necessary to ensure company success in the long run. In the following we do not clearly differentiate between operational capability, resources and practices, because they are closely related [10, p. 722].

According to [10, p. 722], the "need to develop and maintain a sustainable competitive advantage is at the foundation of operations strategy, which draws on a number of intertwined yet distinct elements, including organizational capabilities, practices, and resources." Furthermore, the "types, the amounts, and the qualities of the resources available to the firm have an important bearing on what the firm can do since they place constraints upon the range of organizational routines that can be performed and the standard to which they are performed." [11, p. 122] These organisational capabilities are "information-based, tangible or intangible processes that are firm-specific and are developed over time through complex interactions among the firm's Resources" [12, p. 35]. A major disadvantage, however, is that most factors or elements concerned with the complexity of social entities forming the basis of such processes cannot be measured directly and have to be approximated from the outside.

Our first group of factors that we include into our analysis is related to the technology and the certification (T&C) of the individual vehicle concepts. In terms of the resource-based view, it covers the product-related aspects [3]. This factor group includes three areas: technical feasibility, demonstrated technology maturity and certification.

The second group of factors is concerned with the analysis of the company and is divided into two parts: organisational capabilities and (OC&R). Capabilities and resources within companies are expected to be a main determinant of long-term company success. This overarching factor group incorporates both tangible and intangible factors of which some are complex or even impossible to measure. Especially strategical factors such as innovation success factors [13, p. 75, 100], technology portfolio [14, p. 52] and strategy [14, p. 16] or networks [13, 15] are significant drivers of company success.

## 3. INDEX STRUCTURE AND CALCULATION

The index developed in this work is designed around two factor groups: technology and certification (i.e. product related), as well as operational capabilities and resources (i.e. company related).

### 3.1. General assumptions

In order to construct the index we make several assumptions. We assume all vehicle concepts and manufacturers to face the same market conditions independent of the respective use case. The current market actors are very heterogeneous. While most vehicle manufacturers are start-ups, some established firms from the aviation or automotive sector are active as well. We do compare the vehicle concepts from a technology and certification perspective. Yet, from an operational capabilities and resource perspective these two company types are not sensible to compare. Firstly, it is not possible to assess monetary and human resources devoted to eVTOL development in a larger company. Secondly, a general statement on whether or not an established company will be more successful than a start-up in the so far non-existent market is not feasible at this point in time. Additionally, the companies might pursue totally different strategies. As [16, p. 127] highlight, "It is these tangible resources that older firms typically have relied upon to drive their performance in foreign markets. In contrast, [startups] leverage a collection of fundamental intangible knowledge-based capabilities in the cultivation of foreign markets early in their evolution."

| Component/Parameter | Unit | Value |
|---|---|---|
| Weight per PAX | [kg] | 110 |
| *Electric Motor* | | |
| Efficiency | [%] | 95 |
| Specific Power | [kW/kg] | 5 |
| *PMAD* | | |
| Efficiency | [%] | 95 |
| Specific Power | [kW/kg] | 7 |
| *Battery* | | |
| Minimum SOC | [%] | 20 |
| End Of Life SOH | [%] | 80 |
| Discharge Efficiency | [%] | 95 |
| Specific Energy | [Wh/kg] | 300-400 |

**TAB 1. Component-specific assumptions.**

### 3.2. Technology and certification

The sub-index *technology and certification* (T&C) comprises three factors. The first, *technical feasibility*, evaluates the aircraft concept of a company and quantifies the gap between performance claims and estimated, expected performance taking into account technological progress and operational requirements. The second, *demonstrated technology maturity*, considers the technical maturity of the manufacturer's aircraft concept. Finally, the *certification progress* factor includes the state of a project regarding the certification process. In their aggregate, the factors can be considered as "remaining risk of a company to complete the development of its eVTOL aircraft for commercial passenger transportation in the companies target market". The following sub-sections describe the procedures for calculating the factors in detail.

#### 3.2.1. Technical feasibility

This factor evaluates the aircraft concept in terms of achieving the companies defined top level aircraft requirements. Therefore, a low-fidelity aircraft design loop is set up to determine a basic mass breakdown, power demand, energy consumption and finally a maximum achievable range of a battery-electric aircraft concept. In order to be able to calculate the factor for a larger number of concepts, attention was paid to keeping user effort and computation time as low as possible. The only inputs required are five easy-to-acquire concept-specific parameters as well as a set of general technology assumptions listed in Table 1.

To calculate the factor value for an aircraft concept, three input parameters are varied: battery energy density, required hover/vertical flight time and the aerodynamic efficiency during cruise, the lift-to-drag ratio of the aircraft. For each parameter value combination an aircraft design process is conducted. The factor value is defined as the ratio of the number of total aircraft designs to the number of successful aircraft designs. An aircraft design is considered successful when the maximum possible design range is equal to or greater than 75% of the target design range specified by the company. This takes into account that a company's business case can also be implemented with vehicles featuring slightly shorter ranges.

The varied input parameters are selected for different reasons. The battery and its specific energy are considered as the most critical component and characteristic limiting the range of an battery-electric aircraft. Due to the increasing electrification of various mobility segments, development effort for advanced, energy-dense batteries is high and eVTOL aircraft can directly benefit from the advances in the next years in terms of range. The specific energy on pack level is varied between 250Wh/kg and 400Wh/kg as most pessimistic and most optimistic development scenarios for 2025+ considered in this paper based on various predictions and indications from literature [17] [18] [19].

Required hover time, hover reserves and time in vertical flight depend on operating rules and regulatory requirements. Since hover and other vertical flight states are the most demanding ones regarding power demand and potentially energy consumption, the requirements in this area have a major impact on design decisions. Assessing the published concepts shows that there is a wide divergence of assumptions in the industry regarding the requirements that will apply in the future. Due to the high uncertainty regarding required hover time, it is varied between 60 seconds and 5 minutes. The minimum corresponds to very short vertical take-off and landing phases and an immediate transition to or from forward flight, while the five minutes include multiple significant vertical climb and vertical descent phases and some hover reserves.

Varying the lift-to-drag ratio is necessary from a methodological point of view, since the precise quantification of aircraft cruise drag is usually associated with larger effort and would counteract the deliberately intended simplicity and possibility of fast application of the method. Therefore, typical, vehicle type-specific lift-to-drag ratio ranges listed in Table 2 were taken from [20] and applied in the design loop.

In the following, the complete design process is described. A flow chart including selected input parameters is depicted in Figure 1. Starting off with a specified maximum take-off mass ($m_{MTO}$) of the aircraft, four mass fractions are calculated.

First, the weight of the VTOL power train, $m_{pt,VTOL}$, is determined. The total weight is made up of the component weights of the electric motors and a power management and distribution system (PMAD) representing converters, inverters and cables. For that, the VTOL design thrust,

| Aircraft Type | Lift-to-Drag Ratio Cruise [-] |
|---|---|
| Multicopter | 1-2 |
| Lift & Cruise | 8-12 |
| Tilt-Rotor | 12-16 |
| Tilt-Fan | 8-12 |
| Tilt-Wing | 10-14 |

**TAB 2. Lift-to-drag ratio ranges by aircraft type [20].**

$$T_{VTOL,Design} = T_{Hover} \cdot \frac{T}{W} = m_{MTO} \cdot G \cdot \frac{T}{W}$$

is calculated, with the thrust needed for steady hover flight, $T_{Hover}$, and a thrust-to-weight ratio, $T/W$, taking into account necessary thrust margins for vertical climb and maneuvering. Using the momentum theory, the design power is determined as

$$P_{VTOL,Design} = \sqrt{\frac{T^3_{VTOL,Design}}{2\rho A}}\eta_{P,VTOL} \quad (1)$$

where $\rho$ is the air density, $A$ is the VTOL rotor area of the aircraft and $\eta_{P,VTOL}$ is the propulsive efficiency [21]. With the known design power, weights of the electric motors and the power management and distribution system (PMAD) representing converters, inverters and cables are quantified with assumptions for specific power and system efficiencies. All component weights are summed up to an overall VTOL power train weight.

Second, the weight of a dedicated cruise power train is calculated, if available. Accordingly, the required power in cruise flight,

$$P_{Cruise,Design} = m_{MTO} \cdot V_{Cruise} \cdot \frac{D}{L} \cdot \eta_{P,Cruise} \quad (2)$$

is determined with the stationary equilibrium of forces, to again calculate the individual component weights using specific power and efficiency assumptions. Besides the cruise speed, $V_{Cruise}$, the lift-to-drag ratio as a measure of the aerodynamic quality of the aircraft and the propulsive efficiency, $\eta_{P,Cruise}$, affect the required cruise power. While cruise speed is an aircraft design parameter usually published by the manufacturer, the exact lift-to-drag ratio is typically unknown and therefore, varied as stated above.

Third, the payload is determined as the number of pax multiplied by a defined weight per passenger.

Fourth, the empty weight of the aircraft (without the powertrain) is calculated using the regression

$$\frac{m_{empty,withoutengines}}{m_{MTO}} = 0.743 \cdot m_{MTO}^{-0.06}$$

based on general aviation aircraft data [22].

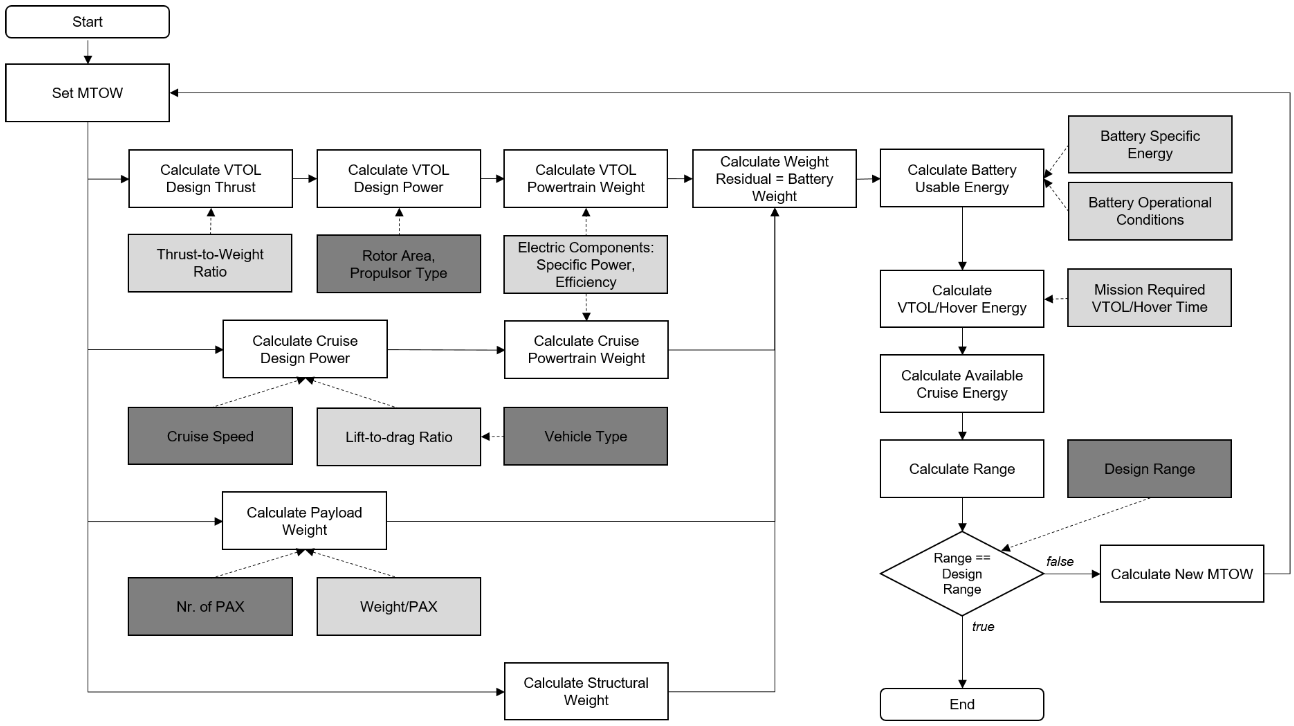


**FIG 1. Flow chart of the aircraft sizing loop with selected input parameters.**

With the known weight fractions and the fixed MTOW, the weight residual available for the battery

$$m_{bat} = m_{MTO} - m_{pt} - m_{empty,withoutengines} - m_{payload}$$

can be calculated. With a specified specific energy of the battery, a theoretical available amount of total energy, $E_{battery,total}$, is determined. This energy, however, is reduced by operational limits of the battery. In order to ensure stable operating conditions, a proper cycle life and fast recharging, a minimum state of charge, $SOC_{min}$, should not be fallen below. Further, the vehicle should be capable of the design mission at the end of life (EOL) of the battery. Battery EOL is typically defined as the point where battery capacity reaches $80\%$ of the original capacity. Using both operational constraints, an actual usable amount of energy of the battery

$$E_{bat,usable} = E_{bat,total}(1 - SOC_{min})SOH_{EOL}$$

can be determined.

Finally, a maximum achievable cruise range is calculated with a simplified three-segment mission profile. Take-off and vertical climb as well as vertical descent and landing are represented by a single segment with VTOL design power demand. Climb during forward flight, cruise and descent during forward flight are represented by a single cruise segment. With a specified required hover time, $t_{hover}$, and respective efficiencies or the power train components, an energy amount for both VTOL segments is calculated:

$$E_{bat,VTOL} = \frac{P_{VTOL,Design} \cdot t_{hover}}{\eta_{el.motor} \cdot \eta_{pmad} \cdot \eta_{bat}}$$

The achieved design range with the specified MTOW is then given by

$$R_{design} = \frac{E_{bat,usable} - E_{bat,VTOL}}{P_{Cruise,Design}} \cdot V_{Cruise} \cdot \eta_{el.motor} \cdot \eta_{pmad} \cdot \eta_{battery}$$

If the achieved design range is lower or higher than the targeted range, the loop is repeated with a decreased or increased MTOW until the design range is met. The maximum MTOW allowed is 3175kg in accordance with the current published version of the EASA SC-VTOL [23].

Due to the simplicity of the methods, the results from the design loop described can of course only be considered as an rough estimate. In addition, there are some limitations in the current implementation of the methods. Thus, although the equations 1 and 2 allow for a consideration of efficiencies in both cruise and hover, $\eta_{P,VTOL}$ and $\eta_{P,Cruise}$ are set to 1 in the context of this work. The power requirements in vertical flight and cruise flight are thus calculated as theoretical ideal power requirements and will therefore be somewhat higher in reality. Furthermore, this disregards necessary rotor design compromises, such as for tilt-rotor or tilt-wing configurations. A method for adequate selection of efficiencies for different types of rotors will be introduced in future work steps.

It should also be noted that the index results strongly depend on the chosen limits of the varied parameters. Accordingly, a deviating estimation of best- and worst-case values for the lift-to-drag ratios, battery energy density and required hover time may lead to different results.

### 3.2.2. Demonstrated technology maturity

Whereas the previous factor evaluated the concept itself, the focus of the factor *Demonstrated technology maturity* is on development progress. The rationale for including this factor is that a high level of demonstrated technology maturity reduces the risk of failure, i.e., termination of an eVTOL project before a finished, certified product is achieved. To classify the technical maturity of aircraft projects, the concept of Technology Readiness Levels (TRLs) [24], originally defined for space industry, is used as a guideline. For the calculation of the factor values, publicly documented progress reports from and about manufacturers are collected and evaluated. The compiled information is then used to assign a TRL to each company. Finally, the TRLs are linearly scaled to a value between zero and one for further processing.

### 3.2.3. Certification

This sub-factor considers the company's remaining risk regarding the successful certification of it's eVTOL aircraft.
To determine principal certifiability and/or to evaluate the certification effort, the overall aircraft concept, power train design and many more technical details must be considered. Since such a consideration is complex and extensive, it was decided to base the assessment of remaining certification risk exclusively on company parameters and measurable, publicly communicated intermediate results in the certification process. This assumes that all aircraft concepts evaluated are certifiable as-is or at least similarly.
Certification of an aircraft is not a straightforward process and a lot of intermediate steps and accomplishments are difficult to measure - especially from an external point-of-view. Further, there are different strategies and pathways, a company can go for to reach successful certification. Therefore, a factor quantifying certification progress is difficult to define and can only be interpreted as a rough indicator. However, since certification is an essential piece to the success of an aircraft design project, the following evaluation system was established.
Eight measurable stages in the certification process, listed in Table 3, were defined and corresponding factor values assigned. The assigned values are intended to represent only the remaining risk of technical nature of a non-successful process. The financial risk is taken into account via factors in the other sub-index. The lowest stage, a company can be assigned to is to be in no public contact with EASA, the FAA or any other national certification authority. Thus, since the progress of certification is not known, this stage corresponds to a factor value of 0.0. For an assignment to the next stage, the company has to be in formal or informal exchange with EASA/FAA or another certification authority. Here, it can only be stated that the company is thinking specifically about certification and is already investing effort and resources in this regard. A company is assigned to the third stage, if it holds a type certificate of another aircraft in a class with lower requirements compared to classes for commercial passenger transportation, e.g. the Light Sports Aircraft class. This indicates that the company has a certain level of expertise with regard to certification requirements and the process. Holding a type certificate in an aircraft class with lower requirements of the actual eVTOL aircraft marks the fourth stage. It can be assumed at this point that concept-specific details were considered in terms of certification - albeit with less restrictive standards.
While the previous stages are all geared towards less restrictive certification guidelines, companies in the next stages are already working towards approval for commercial passenger transport. Accordingly, there is a significant increase in the factor values at this point. Stage five requires an EASA Design Organization Approval (DOA) or a comparable certificate from another national certification authority for the company. A DOA indicates high development standards regarding safety, reliability and quality in the company and enables an accelerated approval process. Even higher valued are companies holding a type certificate for another aircraft type, which allows commercial passenger transportation. Assignment to this sixth level implies that the company has already completed a full certification process to the highest standards, and has incorporated this knowledge into the design of their eVTOL. Accordingly, the risk of an unsuccessful certification process from an engineering point of view is lower compared to the previous stages. Finally, the last stage before a certified aircraft is available is achieved once a concrete certification program for the eVTOL concept has been established together with the certification authority. In this case, all the necessary requirements and evidences are defined and the chances are high that there are no longer any unsolvable technical hurdles preventing certification. The final stage eight is limited to companies that will have a certified eVTOL aircraft according to the EASA SC-VTOL Enhanced Category [23]. Since the SC-VTOL is not final yet, this stage is of theoretical nature and can not be achieved yet.

## 3.3. Operational capabilities and resources of companies

In terms of *operational capability and resources* (OC&R), as closer described in Section 2, we look towards factors from collaboration networks [25] (such as partner sectors or public/private engagement) and funding (putting aside established aircraft manufacturers and solely focusing on VTOL start-ups [26]).
To measure the financial base of the start-up the index includes the amount of venture capital raised in million USD (excluding money raised through initial public offering (IPO) or special purpose acquisition company (SPAC)), the number of funding rounds the company has gone through and whether or not, com-

| No. | Measurable Certification Stage | Factor Value | Comment |
|---|---|---|---|
| 0 | The company is not in public contact with EASA/FAA or any other national certification authority. | 0.0 | |
| 1 | The company is in exchange with EASA/FAA or another national certification authority. | 0.1 | |
| 2 | The company holds type certificate(s) of aircraft in classes with lower requirements. | 0.2 | e.g., Ultra-light |
| 3 | The company holds a type certificate of the eVTOL concept in a class with lower requirements. | 0.3 | |
| 4 | The company received an EASA Design Organization Approval (DOA) or a comparable certificate from another national certification authority. | 0.6 | |
| 5 | The company holds one or more type certificates of aircraft for commercial passenger transportation. | 0.7 | |
| 6 | A certification program for the eVTOL is established by a certification authority and the applicant. | 0.8 | FAA: G-1 issue paper |
| 7 | The companies eVTOL aircraft is certified according to the EASA SC-VTOL Category Enhanced or a comparable certification standard. | 1.0 | Not possible yet |

**TAB 3. Defined measurable certification stages and corresponding factor values.**

pany shares are traded on stock exchange. We consider a company to be on stock exchange both after IPO and SPAC. In order to measure quality and heterogeneity of partnerships and networks the number of investor sectors and partner sectors is also considered. Hereby each partner or investor is assigned to a specific sector, such as finance, cargo, aviation or automotive. Due to the high frequency of changes especially regarding partnerships, the index calculation is solely based on the number of sectors instead of the number of partnerships. Knowledge is captured by three more factors. Participation in an initiative (such as UAM initiative Ingolstadt), the proximity (spatially or organizationally) to a university and a measure whether or not the founder is a serial entrepreneur allow us to capture this aspect.

### 3.4. Index function

In order to answer *Q3)*, we have to think about *how* we would like to create this transparent ranking mechanism. Sections 3.2 and 3.3 describe the individual factors that can be part of such an index, here we describe how to bring these factors together.

A close inspection of the individual factors raises the question whether all of them are equally relevant for the quantification of associated risks, or whether some factors should receive more or less emphasis when being accounted for.

For each company $c$, we devise the following formula to determine the rank:

$$Index_c = w_{tc} \cdot \sum_i w_i F_{i_c} + w_{ocr} \cdot \sum_j w_j F_{j_c} \quad (3)$$

where $F_{i_c}$ and $F_{j_c}$ respectively denote the technology and certification factors as well as the operational capabilities and resources factors of company $c$. Factors $F_{i_c}$ and $F_{j_c}$ have been normalised to values between $0$ and $1$ across companies, either according to the available or achievable data range. The associated weights $w$ are scaled to $w_{tc} + w_{ocr} = \sum_i w_i = \sum_i w_i = 1$.

When a problem does not allow for precise analytical techniques, as is the case with weighting factors for assessing a non-existing market and technology in its infancy, the Delphi technique is a suitable group communication process for gathering expertise from a range of backgrounds, see [27]. For this work, we are using a *conventional Delphi*, in which a small team designs a questionnaire, sends it out to a respondent group, summarises the results and sends a new version to the respondent group for reevaluation (at least once). A comprehensible introduction into this technique as well as its benefits and drawbacks can be found in [27]. The Delphi technique is used in a broad range of research fields, including door-to-door air travel [28].

### 3.5. Factor weights by conventional Delphi

In order to establish an initial set of weights for the factors that form our index, we conducted a conventional Delphi, see Section 3.4. The process we chose consisted of two rounds, where ten aviation and economic experts were asked to weigh the factors within two groups as well as give weights for those two groups, compare Equation 3. The initial questionnaire contained a detailed factor description and gave the possibility of coarsely weighing the index factors (1, 3, 5, 7, 9) . The second questionnaire contained the aggregated results of the first round and gave the possibility of revising the weights on a finer scale (1,2,3,. . . 9). Table 4 summarises the aggregated factor weights after the second round, where a weight of 1 means ‘no impact’ up to a weight of 9, meaning a ‘very high im-

pact' on the entry to market for a VTOL concept or manufacturer.
Overall, the aggregated results of the second round deviated at most by 0.5 points from the aggregated results of the first round. Notably, the standard deviation decreased on average by 0.3 points for the second round, which indicates a stronger consensus on the weights. Several participants offered comments on the different factors, a few of which we would like to relate here:

- Technology and certification
  - maturity can be reached without public communication of successes
  - certification necessary for any type of business operation
  - certification very much depends on local authorities
- Operational capabilities and resources
  - enough funding must be available to get to certification
  - many highly complex problems in UAM are suitable to be addressed by university research
- General comments
  - the challenge of getting UAM off the ground is more severe than competing with other players on the UAM market
  - the evaluation would be quite different if other factors were brought in

| Factor (*Group*) | Weight |
|---|---|
| *Technology and Certification* | |
| Technical feasibility | 7.2 |
| Demonstrated technology maturity | 6.3 |
| Certification | 8.0 |
| *Operational Capabilities and Resources* | |
| No. of partner sectors | 5.3 |
| Initiative participation | 5.3 |
| University proximity | 4.2 |
| Serial entrepreneur | 4.1 |
| Venture capital in mio USD | 7.0 |
| No. of funding rounds | 3.8 |
| No. of investors | 4.8 |
| No. of investor sectors | 4.8 |
| On stock exchange | 4.8 |
| *Group Weights* | |
| Technology and Certification | 7.7 |
| Operational Capability and Resources | 6.7 |

weight scale: 1 = no impact, . . . , 9 = very high impact

**TAB 4. Delphi Study Results**

### 3.6. Data collection

In order to quantify the above described factors, company and aircraft-related data is gathered. The following section closer describes the process of data collection, data sources and limitation to the data collection. The data for the different factors was gathered from a multitude of publicly available sources such as company websites, initiative websites, databases such as Crunchbase, and relevant newspapers and technical papers. Further, publicly available photos and technical sketches were used to estimate the aircraft and rotor dimensions. The data set is representative as of June 2021 and is listed in Tables 5, 6 and 7 in the appendix. While some factors are based on absolute values others are binary and indicate whether or not a statement is true (similar to a dummy variable for regression analyses). The data for each of the factors (both continuous and discrete) is then min-max feature scaled, yielding a value between 0 and 1 for each factor for a given set of companies. The weights of the different factors are discussed in more detail in Section 3.5.
There are several limitations to the data collection. Foremost, the communication strategies of VTOL manufacturers strongly differ. While some companies very openly communicate current developments and strategies, others keep this information confidential. Due to the partly restrictive information policies of the companies, data can be outdated or not correspond to the actual, current company state or project state. Joby, to name a prominent example, has paused public communication for several months in 2020, however gave profound feedback on our request to review our data collected on them. Being based on publicly available data, this research strongly relies on the availability and accessibility of information. The second limitation to the collected data is its limited comparability due to different data sources.

## 4. RESULTS

As can be derived from Equation 3, the partial indices are calculated as

$$\sum_i w_i F_i \quad \text{where} \quad \sum_i w_i = 1.$$

which gives the results for the tech index and the OC&R index. Multiplying them with their respective group weights yields the overall index.
At this point, it is important to highlight, that the T&C index is calculated for 15 vehicle configurations, while the OC&R index has only been calculated for 10 companies. Five companies are established firms in a relevant field or closely affiliated to such a company and have therefore not been included. As a statement on the OC&R performance of these companies is not possible, an overall index is also not given for them.

### 4.1. Technology and certification

Figure 2 shows the results of the T&C sub-index. Considering the factor *technical feasibility*, about 50% of the concepts reach the a value of or close to 1. Accordingly, achieving the stated range targets is likely and relatively independent of prescribed hover times and the specific energy of future batteries. Two concepts, the Beta Alia-205c and the Lilium Jet, never reach 75% of their stated target range within the considered parameter ranges. This may indicate overly ambitious goals, but also a suboptimal aircraft concept for the specific use case. The *demonstrated technology maturity* scores are very heterogeneous and vary from 0.11 to 0.79. It should be noted once again at this point that the results reflect the publicly known status at the time of the data collection. Due to different information strategies of the companies, the actual technical maturity may deviate from this. The top *certification* score is marked by Joby, which have reached agreement with the FAA on a certification basis for their aircraft and can now work through this in a targeted manner. The overall T&C sub-index values range from the highest value of 0.76 for the Boeing PAV to a lowest score of 0.17 for the Lilium Jet. Besides Boeing PAV, the top group includes the Joby S4, the EmbraerX Eve and the VoloCity.

### 4.2. Operational capabilities and resources

The detailed results of the OC&R index are displayed in Figure 3, ranging from 0.19 and 0.77. Joby and Volocopter perform best and are closely followed by Ehang and Lilium. Beta Technologies, Overair, Vertical Aerospace and Archer reach medium values of 0.33 to 0.44. Jaunt and Pipistrel score last due to the little amount of money available. Note that the OC&R index performance is not only driven by venture capital and whether or not a company is on stock exchange but also depends on a diverse investor and partnership portfolio.

### 4.3. Overall results

The index combining the T&C and OC&R part is shown in Figure 4. Overall, Joby performs best and reaches an index value of 0.75. Volocopter scores second with 0.72, Ehang scores third (0.55) with already a larger distance. All other companies achieve index values between 0.35 and 0.45. Joby and Volocopter also lead the T&C and OC&R indices. Embraer and Boeing that also perform well in the T&C index do not appear in the overall index as they are established aircraft manufacturers.

### 4.4. Discussion

As described above, this research aims to construct an index including both technological and economical aspects to provide a transparent ranking of VTOL manufacturers. The presented results hint us towards a group of findings the index allows to derive while at the same time also outlining the borders of what the index allows to infer.
The index indeed gives a first impression of which companies, according to public information, are currently at the forefront of developments and what companies might be slightly over ambitions in what they communicate regarding technology and application case relationship. The UAM market is developing fast and the presented results hence only give a snapshot. Yet, the case of Joby show well that despite the volatility, the change of one factor does not have a significant impact on the results of the index. Thus, even an information asymmetry might be less problematic then it might appear to be in the beginning.
The difference in treatment of start-ups and established companies somewhat blurs the index results. As has been highlighted the overall index only includes start-ups as the OC&R factors can not be calculated for established companies. In general the authors do not want to make any statement on the advantages and disadvantages of established companies in comparison to start-ups. It might well be that their experience in aviation or automotive outweighs the innovative character of start-ups and hence predominantly vehicle concepts of long-existent companies make it to the market. The overall index in the current version might suggest that Embraer and Boeing, that are at the forefront regarding technological developments do not have a promising overall concept.
Besides that, omitted factors also have the potential to penalize or push different concepts. Ehang might be an example for overly penalizing certain concepts by not including all possible factors. Omitting the broader regulatory environment and the attitude towards innovation in a country or region might hinder us from giving a full picture. Ehang is already operating first flights for emergency application in China, allowing the company to gather important experience and information. An example for the opposite side could be Archer. The company is ranked fifth in the index, yet is currently facing sever legal disputes with Wisk with regard to patents. Disregarding this aspect clearly puts Archer in a better position.
Summarizing, this index allows us to derive general findings and gives a first impression on the current status of the VTOL manufacturer start-up market. Yet, due to the large group of omitted variables it clearly does not allow to infer investment advice or any statement on the future business models or use-cases for UAM.

#### 4.4.1. General remarks on the index and partial indices

The numbers show that weights have considerable impact on results and can even change the rank order. The weights used in this paper build on the described delphi study. Yet, Tables 8 and 9 in the appendix give the full set of normalized results so that the reader is able to recalculate the index with customized weights. As the UAM sector develops fast, it is important to highlight that the data presented here is as of June 2021. The mentioned companies and manufacturers have been invited to verify the used data and some have done so. Yet, especially the data on venture capital and whether or not a company is on stock exchange, can change rapidly. One such example is Joby. While the company was not on stock

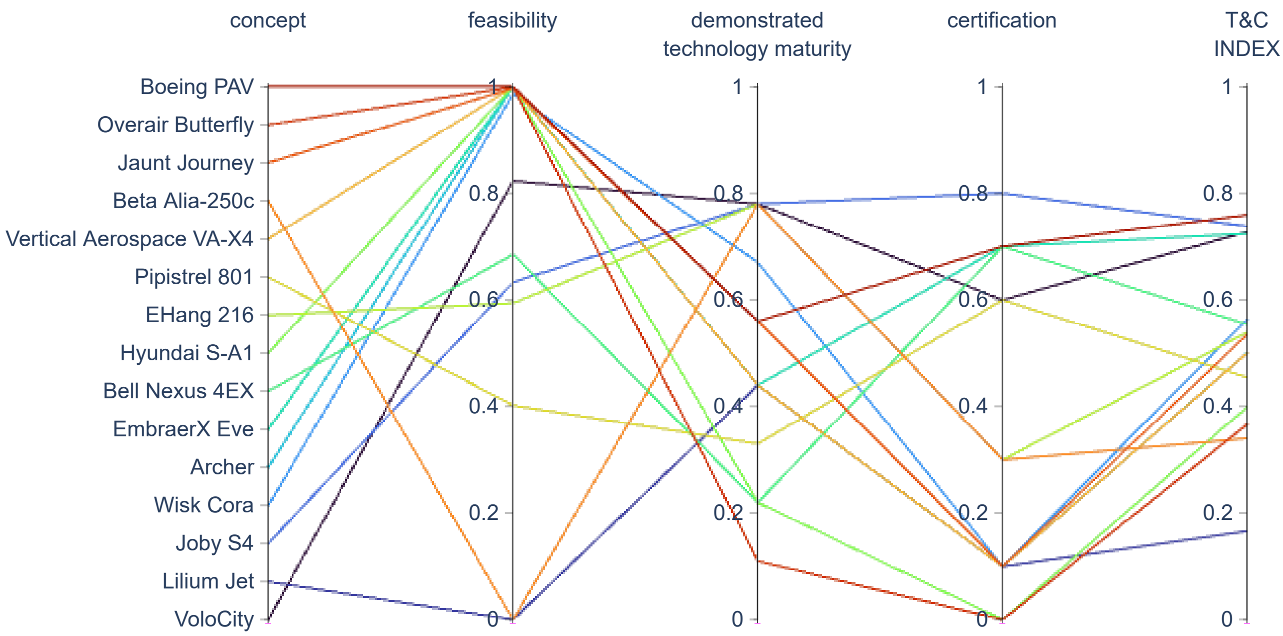


**FIG 2. Technology and certification (T&C) index**

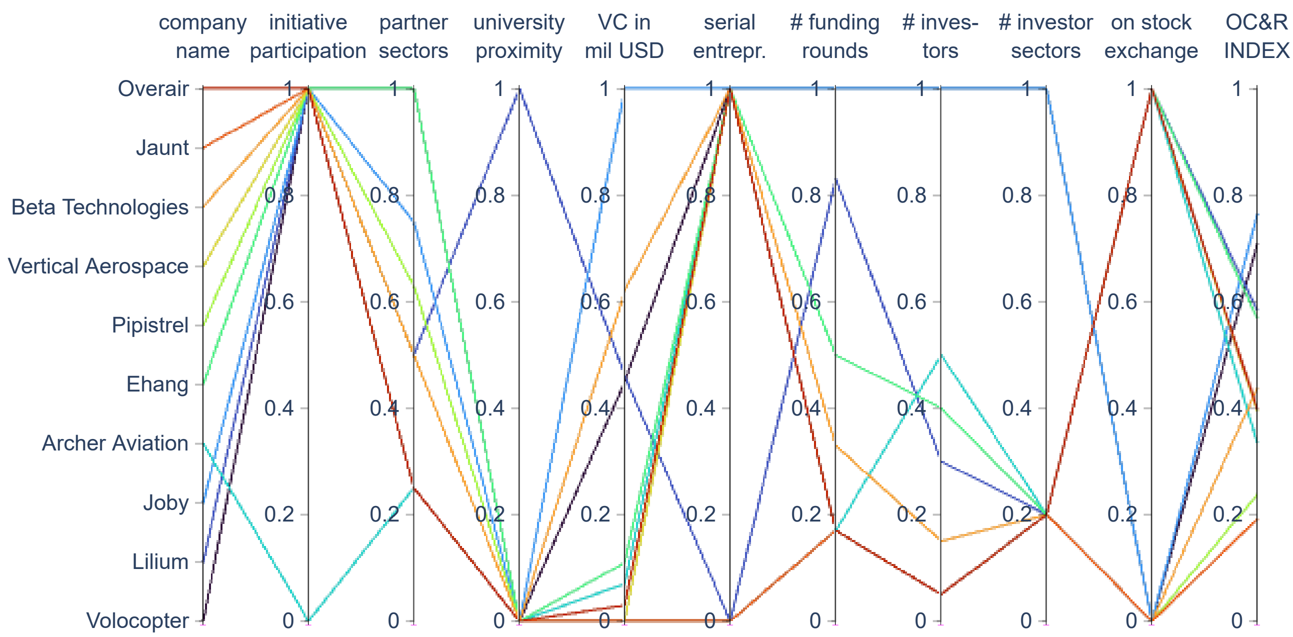


**FIG 3. Operational capabilities and resources (OC&R) index**

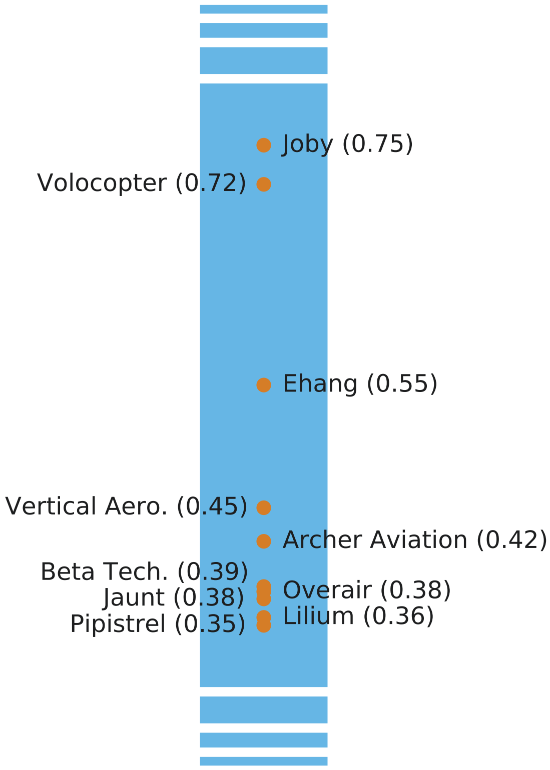


**FIG 4. Overall Index**

exchange in June 2021, it closed the SPAC in August 2021, which would result in a even higher overall index for Joby S4.

### 4.4.2. Questions answered

This research aimed to answer 3 overarching questions.

*Q1)* How are the manufacturers situated in terms of technology, structure and finances and in which areas are their weaknesses (potential hurdles), and where are their strengths (opportunities)?

*Q2)* How strongly or weakly do these affect their opportunities in the UAM market?

*Q3)* Can we quantify the associated risks and use them to create a transparent ranking mechanism?

By identifying factors defining the potential for firm survival both from a technological and resources perspective, this research was able to answer *Q1*. As discussed in section 3.2, companies not able to reach 75% of their state range are likely to face problems as they might not be able to serve the targeted markets. The situation is similar for the OC&R index, where hurdles might arise due to e.g. no available money or little knowledge. In contrast, when achieving high levels for the OC&R factors companies have good opportunities to be successful on the market.

*Q2* has been answered by a range of aviation and economic experts. Concluding from the results of the conventional Delphi (see Table 4), we can see that more emphasis is put on technology and certification factors than on operational capability and resources factors. Within these groups, the highest potential of being an opportunity or hurdle to the success on the UAM market is accredited to the certification progress and to the venture capital. The least overall impact is accredited to the number of funding rounds, followed by the fact whether or not a startup has been established by a serial entrepreneur.

The presented index shows well that a quantification of associated risks (*Q3*) indeed is possible. The paper shows a transparent and reproducible ranking mechanism, giving access also to a full set of primary data that allows to recalculate the presented index with different weights or additional factors.

### 4.4.3. Limitations

Yet, the approach also has some limitation. Firstly, the index only shows a snapshot representing public information as of 23rd June 2021. Secondly, when consulting experts on so far non-existent markets, answers are inherently opinionated. The Delphi study and the resulting weights therefore have to be treated adequately. As mentioned before, the full data set is given in the appendix for the interested reader to revisit the weighting and the resulting ranking. Thirdly, the factor design was limited by data availability. Many relevant factors such as detailed certification progress, aircraft design details, production schedule or supplier agreements are not typically made public and were therefore not included. In the case of the *technical feasibility* factor, missing information was compensated by a range of engineering assumptions, which have significant impact on the results. Accordingly, more aggressive or conservative technology assumptions lead to different results. Again, the interested reader is invited to use the methods presented and the data from the appendix to calculate index values with their own assumptions.

## 5. SUMMARY & CONCLUSION

This paper presents an index that quantifies opportunities and hurdles for UAM. The method incorporates 1) the development levels of different vehicle concepts and 2) shows resources owned by companies in order to be successful in the market. We believe that our work offers unique insights into the progress of eVTOL manufacturing and can serve as a tool for investors, certification bodies and policy makers to evaluate the hurdles and opportunities that manufacturers face. We took great care to include all necessary information into the paper. The input parameters (see appendix) and the specific methods (see Section 3) that were used for the development of the index factors as well as the resulting factors (see appendix). Additionally, the input parameters were given to the eVTOL manufacturers for review. The weights used to collate the factors into an index were determined by conducting a conventional Delphi study with experts from the field, see Table 4. Using these details, the reader is invited to re-rank the factors according to their own judgement. The version we compiled from the data is pictured in Figure 4. By assessing the pathway to success or firm survival of the different UAM start-ups, we provide insights on risk levels. Yet, we do want to highlight, that this is not to be seen as direct investment advice, but can rather serve as a thought-provoking impulse.

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## A. APPENDIX: RAW DATA/COMPUTED FACTORS

Please find the raw data for computing the technology and certification factors in Tables 5 and 6 respectively; the raw data for calculating the operational capabilities and resources factors can be found in Table 7.
The computed factors for the technology and certification index are listed in Table 8 and the factors for the operational capabilities and resources index can be found in Table 9.

| aircraft concept | type | PAX | energy source | design range [km] | cruise speed [km/h] | # VP | propulsor type(s) | estimated propulsor radius [m] |
|---|---|---|---|---|---|---|---|---|
| VoloCity | MC | 2 | b-e | 35 | 100 | 18 | Rot | 0.9 |
| Lilium Jet | TP | 7 | b-e | 300 | 300 | 36 | TF | 0.12 |
| Joby S4 | VT | 5 | b-e | 241 | 322 | 6 | TR | 1.31 |
| Wisk Cora | LC | 2 | b-e | 100 | 160 | 12 | Rot | 0.66 |
| Archer | TP | 5 | b-e | 96 | 240 | 12 | 6 TR/6 VR | 1 |
| EmbraerX Eve | LC | 5 | b-e | 96 | 240 | 8 | Rot | 1.8 |
| Bell Nexus 4EX | TP | 5 | b-e | 96 | 240 | 4 | dTR | 1 |
| Hyundai S-A1 | TP | 5 | b-e | 96 | 290 | 8 | 4 TR/4 sVR | 1.76 |
| EHang 216 | MC | 2 | b-e | 35 | 100 | 8 | sRot | 0.92 |
| Pipistrel 801 | LC | 5 | b-e | 96 | 282 | 8 | dRot | 0.77 |
| Vertical Aerospace VA-X4 | TP | 5 | b-e | 161 | 240 | 8 | 4 TR/4 sVR | 1.66 |
| Beta Alia-250c | LC | 2 | b-e | 400 | 160 | 4 | Rot | 1.93 |
| Jaunt Journey | LC | 5 | b-e | 129 | 282 | 1 | Rot | 7.625 |
| Overair Butterfly | TP | 5 | b-e | 161 | 240 | 4 | TR | 2x3.25/2x1.5 |
| Boeing PAV | LC | 2 | b-e | 80 | 180 | 8 | Rot | 0.9 |

VP=VTOL propulsor; MC=multicopter; TP=Tilt-Prop; VT=Vectored-Thrust; LC=Lift&Cruise; b-e=battery-electric; TR=Tilt-Rotors; TF=Tilt-Fans; Rot=Rotors; VR=VTOL Rotors; s=stacked, d=ducted;

**TAB 5. Technology Data**

| aircraft concept | Publicly known testing status | certification stage |
|---|---|---|
| VoloCity | Manned Flight Testing | 4 |
| Lilium Jet | Sub-Scale Flight Testing | 1 |
| Joby S4 | Full-Scale Flight Testing | 6 |
| Wisk Cora | Full-Scale Flight Testing | 1 |
| Archer | Sub-Scale Flight Testing | 1 |
| EmbraerX Eve | Full-Scale Ground Testing | 5 |
| Bell Nexus 4EX | Conceptual Design | 5 |
| Hyundai S-A1 | Conceptual Design | 0 |
| EHang 216 | Manned Flight Testing | 3 |
| Pipistrel 801 | Sub-Scale Flight Testing | 4 |
| Vertical Aerospace VA-X4 | System Flight Testing | 1 |
| Beta Alia-250c | Manned Flight Testing | 3 |
| Jaunt Journey | Sub-Scale Flight Testing (Carter Aviation Technologies) | 1 |
| Overair Butterfly | Conceptual Design | 0 |
| Boeing PAV | Full-Scale Flight Testing | 5 |

Defined certification stages according to Table 3.

**TAB 6. Technical maturity and certification stages.**

| company name | # partner sectors | initiative participation | university proximity | serial entrepreneur | venture capital in mil USD | # funding rounds | # investors | # investor sectors | on stock exchange |
|---|---|---|---|---|---|---|---|---|---|
| Volocopter | 8 | 1 | 0 | 1 | 369 | 6 | 20 | 5 | 0 |
| Lilium | 4 | 1 | 1 | 0 | 376 | 5 | 6 | 1 | 1 |
| Joby | 6 | 1 | 0 | 1 | 820 | 6 | 20 | 5 | 0 |
| Archer Aviation | 2 | 0 | 0 | 1 | 56 | 1 | 10 | 1 | 1 |
| Ehang | 8 | 1 | 0 | 1 | 92 | 3 | 8 | 1 | 1 |
| Pipistrel | 5 | 1 | 0 | 0 | 2 | 1 | 1 | 1 | 0 |
| Vertical Aerospace | 2 | 1 | 0 | 1 | 3 | 1 | 1 | 1 | 1 |
| Beta Technologies | 4 | 1 | 0 | 1 | 511 | 2 | 3 | 1 | 0 |
| Jaunt | 2 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 |
| Overair | 2 | 1 | 0 | 1 | 25 | 1 | 1 | 1 | 1 |

**TAB 7. OC&R Data**

| aircraft concept | feasibility | demonstrated technology maturity | certification progress |
|---|---|---|---|
| VoloCity | 0.823 | 0.78 | 0.60 |
| Lilium Jet | 0.000 | 0.44 | 0.10 |
| Joby S4 | 0.633 | 0.78 | 0.80 |
| Wisk Cora | 0.986 | 0.67 | 0.10 |
| Archer | 1.000 | 0.44 | 0.10 |
| EmbraerX Eve | 1.000 | 0.44 | 0.70 |
| Bell Nexus 4EX | 0.685 | 0.22 | 0.70 |
| Hyundai S-A1 | 1.000 | 0.22 | 0.00 |
| EHang 216 | 0.594 | 0.78 | 0.30 |
| Pipistrel 801 | 0.402 | 0.33 | 0.60 |
| Vertical Aerospace VA-X4 | 0.999 | 0.44 | 0.10 |
| Beta Alia-250c | 0.000 | 0.78 | 0.30 |
| Jaunt Journey | 0.997 | 0.56 | 0.10 |
| Overair Butterfly | 0.999 | 0.11 | 0.00 |
| Boeing PAV | 1.000 | 0.56 | 0.70 |

**TAB 8. Computed technology and certification (C&T) factors**

| company name | # partner sectors | initiative participation | university proximity | serial entrepreneur | venture capital in mil USD | # funding rounds | # investors | # investor sectors | on stock exchange |
|---|---|---|---|---|---|---|---|---|---|
| Volocopter | 1.00 | 1 | 0 | 1 | 0.45 | 1.00 | 1.0 | 1.0 | 0 |
| Lilium | 0.50 | 1 | 1 | 0 | 0.46 | 0.83 | 0.3 | 0.2 | 1 |
| Joby | 0.75 | 1 | 0 | 1 | 1.00 | 1.00 | 1.0 | 1.0 | 0 |
| Archer Aviation | 0.25 | 0 | 0 | 1 | 0.07 | 0.17 | 0.5 | 0.2 | 1 |
| Ehang | 1.00 | 1 | 0 | 1 | 0.11 | 0.50 | 0.4 | 0.2 | 1 |
| Pipistrel | 0.63 | 1 | 0 | 0 | 0.00 | 0.17 | 0.1 | 0.2 | 0 |
| Vertical Aerospace | 0.25 | 1 | 0 | 1 | 0.00 | 0.17 | 0.1 | 0.2 | 1 |
| Beta Technologies | 0.50 | 1 | 0 | 1 | 0.62 | 0.33 | 0.1 | 0.2 | 0 |
| Jaunt | 0.25 | 1 | 0 | 0 | 0.00 | 0.17 | 0.1 | 0.2 | 0 |
| Overair | 0.25 | 1 | 0 | 1 | 0.03 | 0.17 | 0.1 | 0.2 | 1 |

**TAB 9. OC&R factors**