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***Abstract*—Electric-vertical-takeoff-and-landing (eVTOL) aircraft, known as urban air mobility or flying cars, are being considered for widespread use as air taxis, emergency medical transportation, sightseeing vehicles, and rural transportation, owing to their reduced-size, low-cost, and low-noise characteristics. In this study, we conduct an interview at a Japanese hospital that currently uses a helicopter for medical emergencies to output the mission profile. Due to current battery-technology limitations, the new air ambulance, which will deliver a doctor to a patient, is conceived as having 2 passengers, including the pilot. Two eVTOL configurations are studied: a fixed-wing craft and a multi-rotor. The purpose of this study is to develop a cost model for a new air ambulance through a combination of 3 approaches: top-down, bottom-up, and parametric. The cost model is constructed to analyze the production cost of each configuration, broken down into the capital expense and direct operating cost. The result shows that the multi-rotor's production cost is lower than the fixed-wing craft. The direct operating cost of a fixed-wing craft at high flight hours is higher than that of the multi-rotor. Scenario analysis shows a result that the capacity difference of a battery has a significant difference in the cost in the years 2020 and 2030 due to the high cost of battery replacement.**

Keywords—eVTOL, configuration, cost analysis, systems engineering

I. INTRODUCTION

In Japan, emergency medical helicopters are known as "doctor helicopters," since doctors are onboard and are transported with the medical team to the site of the emergency. These systems ensure early treatment and result in high patient-survival rates according to HEM-net's research. Due to the high running cost of approximately 250-million yen annually, doctor helicopters have not yet been fully deployed throughout Japan [1]. Operators in the field also face problems of low ride quality due to noise and vibration, which complicate in-flight operation [2].

To find the best solution to the helicopter's problems with cost, noise, and performance, short/vertical-takeoff-and-landing (S/VTOL) aircraft, have long been developed, but only some designs are safely operable. Electrical vertical takeoff and landing (eVTOL), which has promising small-size, low-cost, and low-noise characteristics, is anticipated to relieve problems and enhance existing helicopters for use in urban areas. eVTOL is expected to reduce the total operating cost per seat mile by 26% compared to helicopters [3]. The safety of air EMS (Emergent Medical Services)will also be further increased by the development of flight controls, sense-and-avoid technologies, and fully autonomous aircraft, consequently reducing the current problem of a high crash rate [4].

In the usual case, four passengers, including a pilot, doctor, nurse, and passenger, are onboard for medical services. Due to battery-technology limitations, a 4-passenger vehicle will be available in the year 2025 only if hybrid systems are introduced. Hence, to cover needs in the year 2025, eVTOL capable of carrying 2 passengers (a doctor and a pilot) to the site of an emergency is proposed. Accordingly, the cost model for verifying the viability of 2-passenger eVTOL is studied in this research.

Conventional aircraft-cost estimation is performed using the cost-estimating relationship (CER) or a statistical equation such as the Eastlake cost model [5] to predict an aircraft's acquisition cost using only typical input variables such as empty weight, maximum velocity, and production volume. The CER method breaks down costs into subcomponents such as material and engine-production costs. Hence, eVTOL's electric-systems components, including batteries, motors, and propellers, and additional costs, including ballistic parachute systems and sense-and-avoid systems, can be integrated into conventional cost estimation for cost analysis of the eVTOL configuration design. For components regarded as automotive parts, cost estimation is related to automotive-manufacturing cost. Current eVTOL cost studies conduct estimates based on the vehicle cost per unit weight, especially for fixed-wing aircraft [6], and profitability analysis is necessary for air-taxi utility [7]. This research focuses upon collecting actual data in Japan related to an air ambulance's requirements, and discusses the components affecting cost, such as battery utilization and deterioration. With this objective and the available data, the selected methodologies are a combination of top-down, bottom-up, and parametric-cost equation.

The purpose of this research is to estimate the cost of eVTOL by developing a mathematical-cost model and inputting different commercial-configuration designs for analysis. We aim to verify that the eVTOL's cost will be lower than the current expected cost; hence, the total cost of an air ambulance will need to be lower than the Japanese government's budget. Guidelines on the expected amount of eVTOL production for the needs of air-ambulance service, and realistic cost estimation for each configuration for aircraft for operators interested in expanding eVTOLs to air-ambulance usage are proposed in this study. Commercial configurations, including fixed-wing vectored thrust with 2 different propulsors for each configuration and multi-rotors, were collected from various companies; these include A3 Vahana's tilt-wing [8], Lilium jet's fixed-wing [9], and Volocopter 2X's wingless multirotor [10] aircraft. We expect that this study will increase access to air-ambulance service in Japan.

This paper consists of 5 sections. Section 2 will introduce methods to achieve the goal. Section 3 will show the results of cost estimation. Section 4 will discuss our findings. The overall study will be summarized in the last section.

II. Method

A. Survey on a conventional study

During conceptual design, cost estimation is based upon statistical data. A statistical cost-estimation method is called the CER. The cost equation is obtained by plotting the cost data of many airplanes, and various datasets are analyzed by curve-fit programs. Hence, the equation has no fundamental physics. Instead, it only needs the basic input variables, including the aircraft's empty weight, maximum velocity, and production quantity to obtain cost. This method is easy to implement; however, its drawbacks are that it is difficult to develop, since the cost model itself is very specific to the past model and technological change cannot be represented [11].

In the bottom-up approach, the cost of each element is calculated and added to form a total cost. This method requires an understanding of the process [12]. It can be performed on an activity, operation, or even a feature basis. The bottom-up approach is an information-intensive method, since it generates cost estimation from the lowest level [13]. Hence, a detailed design is needed, so it is generally applied after the production stage when the design is already fixed [14].

An analogous or top-down approach based on similar products will have the same cost. The cost of the current projects or products is estimated based on historical data from past projects. Likewise, in eVTOL's case, some cost component such as pilot or operating cost will need to be analyzed in relation to Japan's current pilot salary. With past-cost data in combination, it is possible to make a reasonable approximation with less time. This technique will require knowledge and judgment to identify the analogies and differences between the two products. The difficulty in implementing this technique is that it requires an appropriate baseline and detailed data [15].

This research paper uses the combination of the parametric approach, the bottom-up approach, and the top-down approach for the cost analysis of eVTOLs of both fixed-wing and multi-rotor configurations. Conventional studies on the cost-estimation relationship of the airframe [11], direct operating cost, propeller-cost estimation [16], battery cost per kWh [17], sense and avoid systems' cost per lb [5], and motor cost from the automotive industry [18] are combined with parachute cost and ducted fan part which is constructed from survey in the market. In subsection B,C and D, cost estimation will further be separated into direct-operation cost and capital expense.

B. Cost Model

The cost model for an eVTOL is consisted of capital expense and direct operation cost (*DOC*) (Figure 1). Capital expense of the configuration will be distinguished for different types of propulsor, where $CapEx^P$ (Capital expense for the configuration with a propeller) is used for analysis of Vahana and Volocopter 2X. Both configurations share variable-pitch propellers, but differ in size and number of propellers as a reference to the commercial model. $CapEx^D$ (Capital expense for the configuration with a ducted fan) shows a ducted-fan-type configuration, which is a Lilium jet. The fixed cost, which will not change depending on a vehicle's weight, velocity, propulsion systems etc., including *SAACost*, is given by:

$$CapEx^P = VPCost + (ManCost + SAACost + BatCost + PCCost + PropCost)z \cdot QDF^{AC} \quad (1)$$

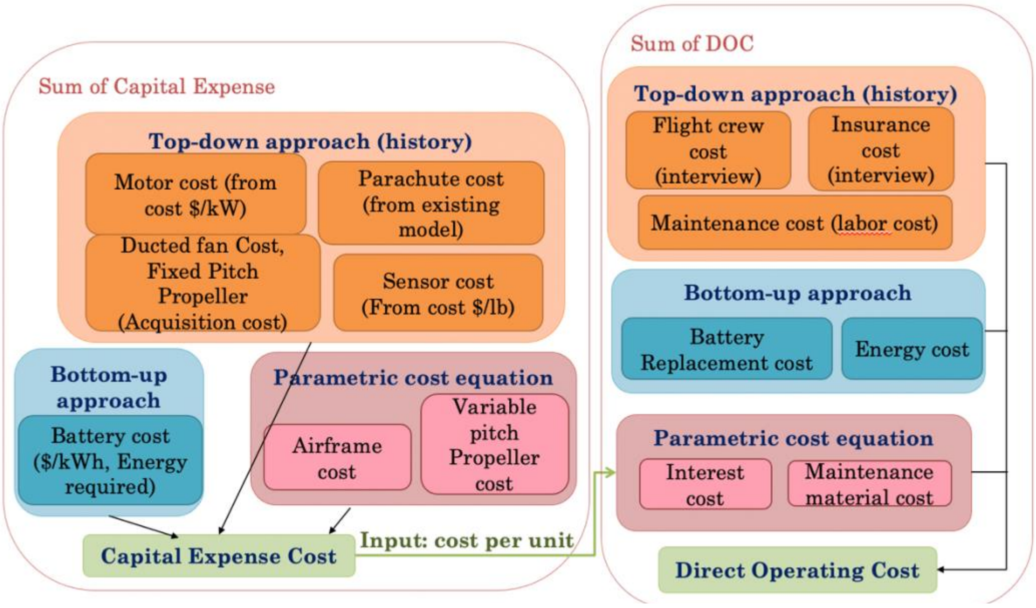

Figure 1 Summary of Methods

$$CapEx^D = VPCost + (DucCost + SAACost + PCCost + PropCost) \cdot z \cdot QDF^{AC} \qquad (2)$$

DOC is calculated per vehicle unit each year. *DOC* calculation depends upon capital expenditure, hours of flight, and total energy required. However, the capital expense cost from (3) will cover 5 years' production; thus, the parameter should be calculated by a following equation. $CapEx^A$ (Capital expense per one unit) is one parameter for calculating *DPCost* (Depreciation cost), *ITCost* (Interest Cost), and *MMTCost* (Maintenance-material cost in dollars per year).

$$CapEx^A = \begin{cases} \frac{CapEx^P}{z} \ if\ propeller \\ \frac{CapEx^D}{z} \ or\ ducted\ fan \end{cases} \qquad (3)$$

$$DOC = DPCost + ITCost + FCCost + MTCost + MMTCost + ENCost \qquad (4)$$

C. *Direct-operational Cost*

In aircraft design, estimation of the direct operating cost, seat-mile cost, and price of the aircraft is a crucial aspect for certifying the aircraft's viability. The operating costs are categorized into the DOC and the indirect-operating cost (IOC) [3][13]. However, IOC depends upon the services that the airline offers. Therefore, *DOC* is a parameter for comparative analysis in this research. Many methodologies have been developed to estimate *DOC*, by organizations such as the Air Transportation Association of America, the National Aeronautics and Space Administration. The *DOC* commonly breaks down into depreciation cost, interest cost, maintenance cost, maintenance-material cost, insurance cost, energy cost, and flight-crew cost. Regarding the detailed differences between conventional aircraft and eVTOL, modification to the DOC is presented in [11] and [19]. The estimation of the above cost follows [11][16][20][21][22].

The battery-replacement cost must be considered in the eVTOL's cost model because that battery will undergo loss in discharge capacity over time. Capacity loss has irreversible and reversible components. Reversible capacity loss can be recovered by charging the battery, while irreversible loss is related to degradation and cannot be recovered. Electric vehicles are typically designed so that the battery never become wholly charged or discharged. However, to implement this practice in an eVTOL, the weight of the battery must be increased[24].

Hence, the lifetime of a battery will be much lower, implicitly increasing the operating cost of the eVTOL, primarily if a battery-swapping model is implemented to avoid fast charging. The Sony Corporation, which was the first to commercialize Li-ion technology for all cell types (cylindrical, prismatic, soft package), found that the range of capacity loss at 500 cycles varies from 12.4 % (US18650, LiCoO2/hard carbon) to 24.1% (US18650G3, LiCoO2/graphite), given an average loss of 0.025–0.048% per cycle. Hence, we assume a battery-capacity loss of 24.1% after 500 cycles for the eVTOL. Next, assuming that for each configuration's possible flight time, the discharged capacity should always be within an allowance of 83% of the total capacity, a workflow diagram for estimating battery number appears in Fig. 2. Then, an approximation of the number of battery replacements per year can be obtained by gathering data on air-ambulance-dispatch number and dividing by the number of cycles at which it needs to be disposed.

$$BattNum = \frac{x^{DP}}{i} \qquad (5)$$

where $x^{DP}(Flight\ number)$ can vary according to the applications of the eVTOL (scenarios) or be estimated by dividing flight hours per year (x^T) by mission time (t) to obtain the approximate number of flights:

$$x^{DP} = \frac{x^T}{i} \qquad (6)$$

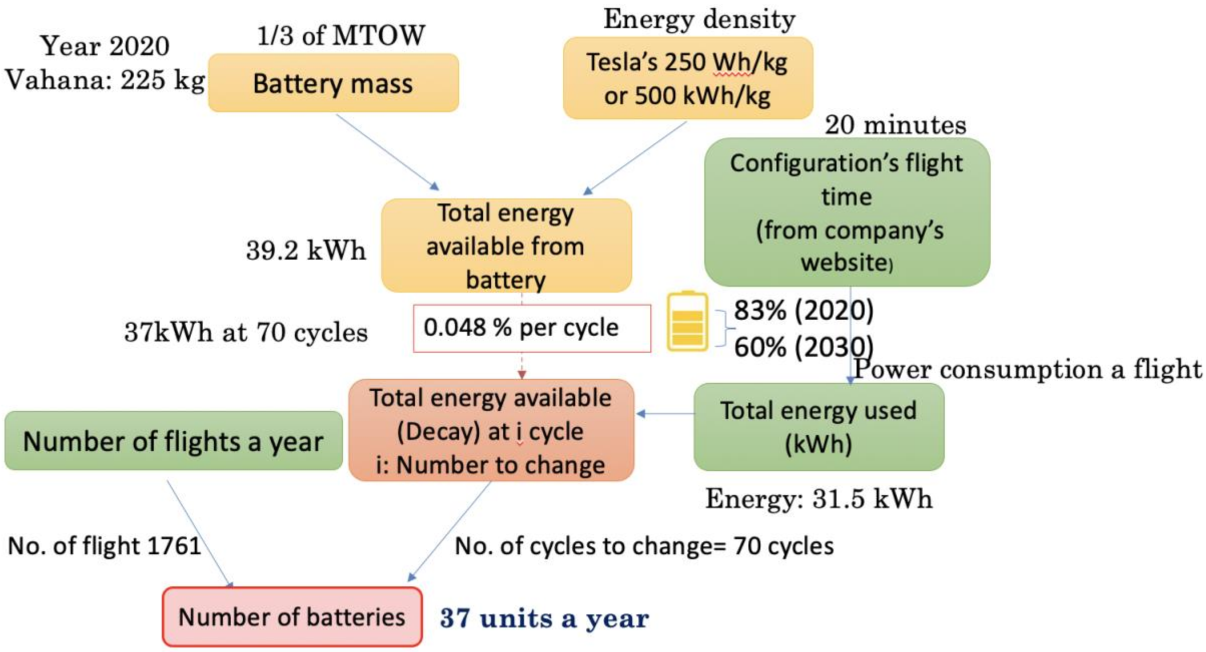

Figure 2 Workflow Diagram For Estimating the Number of Batteries.

To find i, a decayed-battery capacity ($BattD_i$) must be known

$$BattD_i = BattCap_{i-1} \cdot P_D \tag{7}$$

However, the battery-number (*BattNum*) outcome (integer) obtained by dividing x^{DP} by cycle number will need to be rounded up and further planned for a realistic schedule. Thus, more batteries may be added in some cases to make the change schedule more realistic by dividing days in a year by number of batteries, rounded down to the nearest 5:

$$DayU = \frac{365}{BattNum} \tag{8}$$

D. Capital Expense

Capital expense consists of the airframe, motor, battery, propeller, sense-and-avoid system, and parachute costs. Airframe cost is modeled as the CER, which the model itself already provided reduction in cost with respect to production number. Component costs will be calculated using either cost estimation from the equations or the initial cost survey from the market [11]. The quantity-discount factor (learning curve)[16] is applied to other components, including motor cost, battery cost, propeller cost, sense-and-avoid-system cost, and parachute cost:

$$Q\mathrm{DF}^{AC} = F_{EXP}^{1.4427\cdot\ln(z)} \tag{9}$$

Here,

$$z = \begin{cases} x^p z \ if \ apply \ to \ propeller-motor \ part \\ z \ if \ others \end{cases} \tag{10}$$

The vehicle-purchase price of fixed-wing and multi-rotor aircraft will be calculated using DAPCA IV's cost model [11], which is expected to be applicable for both UAVs and light-weight aircraft. The cost equation depends mainly upon statistical data from past models and provides maximum speed, number of productions, and empty weight as input parameters for analysis. Cost components include the total costs of engineering, development support, flight testing, tooling, manufacturing, materials, and quality control. Note that the costs of avionic and autonomous systems are not included. Research, development, testing, and evaluation (RDT&E) costs are divided into development support, quality-control, and flight-test costs from DAPCA IV. RDT&E and production cost are usually combined in CER because they are difficult to separate, since engineers spent hours in the RDT&E phase as well as supporting the production of the aircraft.

$$VPCost = DevCost + QCCost$$
$$+FTCost + EngCost + TCost + ManCos + MatCost \tag{11}$$

The propulsion systems of the eVTOL configuration include the motor, propeller-type (fixed pitch or variable pitch) or ducted fan-type propulsor, and battery. Motor cost and Propeller cost (*ManCost*, *DucCost*) are estimated by referring [18][16].

Referring to [23], the costs of Li-ion-battery packs continue to decline and those among market leaders are much lower than previously reported. From the graph trend, battery cost reduction can be estimated as an exponential-decay function. Tesla model 3 SR's Li-ion battery has a pack cost of 19,541 yen/kWh as of 2018 with 250 Wh/kg has been found promising for aircraft applications, providing very safe and high-energy battery packs [24] [25][26]. However, there is an alternative battery cost provided by NEDO of 22,206 yen/kWh and 11,103 yen/kWh in the years 2020 and 2030, respectively. Hence, for direct-operating-cost estimation, scenarios will be provided for both cases.

Battery cost will be calculated by accumulating the battery capacity of each configuration and cost in yen/kWh. First, the battery mass is calculated by assuming one-third of the maximum takeoff weight to balance the weights of the vehicles [15] and to account for the fact that most transport aircraft have a maximum fuel weight of 1/3 of the maximum takeoff weight. Battery mass (x^M) is multiplied by the battery-energy density ($BattD$) to learn the battery capacity of each configuration. With the available battery capacity (kWh) of each configuration and cost in yen/kWh ($CellCost$), the battery cost can be predicted, as shown in equation (12). This can be recalled as the bottom-up approach, since it breaks down parts into features and composes them to form the total battery cost.

$$BatCost = BatCap(CellCost) \tag{12}$$

where

$$BatCap = x^M BatD \tag{13}$$

SAACost (Sense-and-avoide systems cost) is calculated by referring [11][26][27][5]. Also *PCCost* (Parachute cost) is calculated by referring [28].

III. Result

A. Mission Profile

From our interview data, the mission profile of each configuration will depend on the configuration's rate of climb/descent and cruising speed. With the required maximum operating distance of 31 km and a 15-minute constraint from calling, the following results can be concluded.

Table 1 Vahana Mission Profile

Vahana		
Rate of climb/descent	5.6 m/s	Ref: [8]
Takeoff and landing time	1.8 min	Computed
Cruising time	10.2 min	Computed
Cruising speed	230 km/h	Ref: [8]
Cruising distance	39.1 km	Computed

Table 2 Lilium-jet Mission Profile

Lilium jet		
Rate of climb/descent	5.6 m/s	Assumed
Takeoff and landing time	1.8 min	Computed
Cruising time	10.2 min	Computed
Cruising speed	280 km/h	Ref: [9]
Cruising distance	47.6 km	Computed

Table 3 Volocopter 2X Mission Profile

Volocopter 2X		
Rate of climb	3.6 m/s	Ref:[10]
Rate of descent	2.5 m/s	Ref:[10]
Takeoff and landing time	3.7 min	Computed

Cruising time	8.3 min	Ref:[10]
Cruising speed	100 km/h	Ref:[10]
Cruising distance	13.8 km	Computed

Table 1 shows the mission profile of the Vahana where the rates of climb and decent are computed based on data given from Vahana's official website, accumulated from the capable flight time to the ceiling height of the air-taxi service. As it will reach within 90 sec given a rate of climb/decent of 5.6 m/s. Hence, for an air ambulance, assuming a service attitude of 300 m, it is possible to assume for takeoff and landing times of 1.8 minutes. As 15 minutes are required to increase the survival rates of patient (including 3 minutes for calling and 12 minutes for transportation), 10.2 minutes will be used for cruising; hence, with a cruising speed of 230 km/h, a distance of 39.1 km can be achieved.

Table 2 shows the mission profile of the Lilium jet. The climb rate and descent rate are set to be 5.6 m/s (= 500 ft/min) as same as the Vahana. Therefore, when a vehicle flies at the attitude of 300m, the vehicle consumes 1.8 minutes to take off and land. Assuming the same hypothesis for the total necessary time to rescue a patient, the cruise time is calculated to be 10.2 minutes. The cruise speed is based on its official website [9] With a cruising speed of 280 km/h, a distance of 47.6 km can be achieved.

Table 3 shows the mission profile of Volocopter 2X. The climb rate, the descent rate, the cruising time, and the cruising velocity are referred [10]. From the calculated climb rate and descent rate, the take-off and landing time of this vehicle type is set to be 3.7 minutes. With the referred cruise time and speed, the cruising distance is assumed to be 13.8 km.

B. *Cost-analysis result*

Cost per unit in 2030 will be based on Tesla's battery roadmap, because slight differences in cost per unit do not show significant changes in cost. Calculation for each year's production cost, however, will still be necessary as the cost or capital expense per unit will be an input parameter for the DOC. The production profile of the 5-year results for the three commercial models is shown in Figure 3 The cost is expected to be lower than that of 16 R22 helicopters (31 million yen).

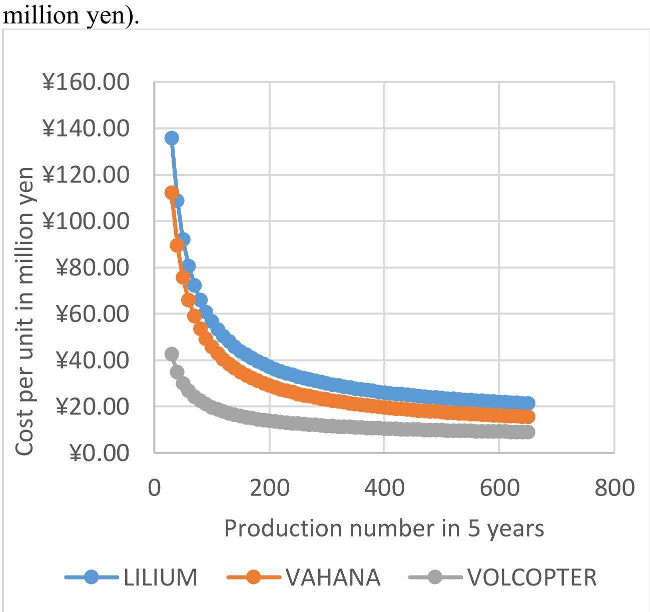

Figure 3 Cost Per Unit

The graph shows a rapid decrease in cost in the first region and then the curve becomes horizontal, indicating no significant change in price even when raising the production volume. Volocopter's cost per unit approaches 11.47 million yen at 300 units and continues to reduce slowly. Vahana's cost per unit approaches 17.3 million yen at 500 units and also declines slowly. Lilium jet's trend line as well becomes almost horizontal at 500 units where it approaches the value of 23.3 million yen and continues to slowly decline. Although 30 doctor-helicopter units are required, since they are 2-capacity vehicles, around 60 units or more are proposed to mitigate the problem of dual requests. For 60 vehicles the costs are 80.4, 65.7, and 26.5-million yen. respectively for Lilium jet, Vahana, and Volocopter.

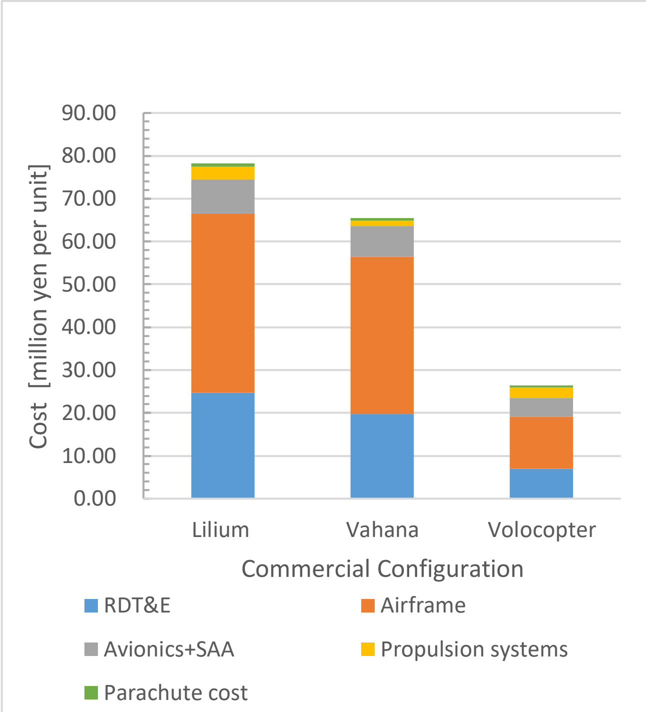

Figure 4 Component-cost Breakdown

Figure 4 shows that the eVTOL purchase cost is broken down into costs for RDT&E and production (airframe, SAA, Propulsion systems), and additional costs (Parachute cost). RDT&E costs include research-and-development, quality-control, and flight-test costs. Propulsion systems consist of batteries, propulsors (either ducted fan or propellers) and motors. At 60 units, eVTOL's highest cost is for airframe fabrication. Lilium jet's RDT&E cost is highest among the configurations at 25 million yen, while Volocopter is the lowest at 7 million yen. The chart implies that electric systems (which comprise only a small part of the overall cost) can lower the cost per unit compared with traditional helicopters.

DOC is broken down in Figure 5 into crew, maintenance, maintenance-material, battery replacement, interest, energy, and insurance costs. The result is separated into the cases of 200 flight hours with 60 vehicles (a case of a hospital in Chiba prefecture) and 500 flight hours with 100 vehicles (a case of a hospital in Hyogo prefecture) for years 2020 and 2030 by extrapolating the battery cost from the Tesla model (19,541 yen/kWh in 2020 and 6,883 yen/kWh in 2030). The only fixed cost for the 2 scenarios is the crew cost of 80 thousand

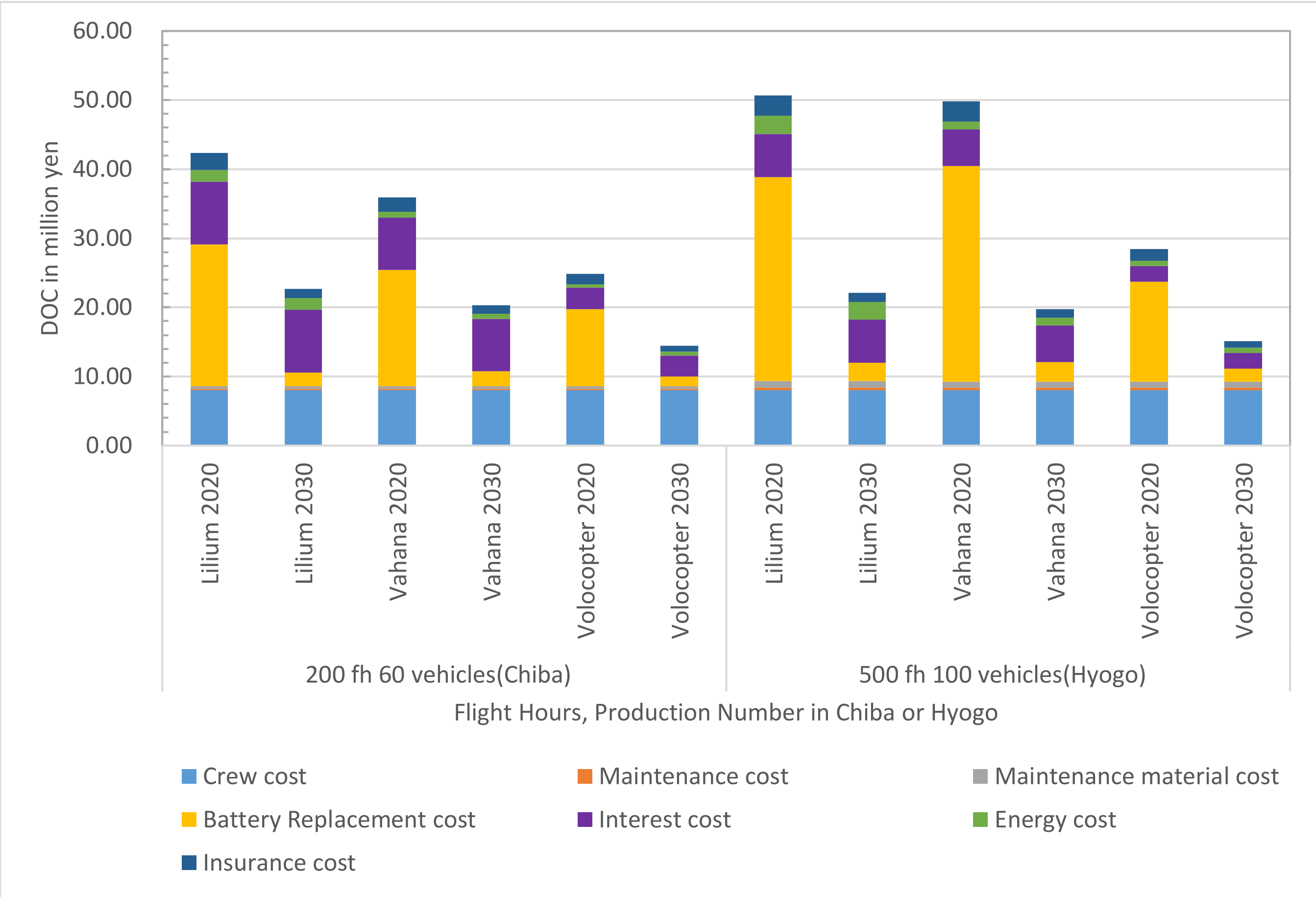

Figure 5 Cost Breakdown of Direct Operating Cost

yen. Obviously, cost contributes to the battery-replacement cost in the year 2020, which for all configurations and both cases, accounts for approximately 50% of the DOC. Interest cost is primarily based upon vehicle cost; hence, it makes a higher cost at 60 units and becomes lower at 100 units. The energy cost becomes higher as the number of flight hours increases in Hyogo. The insurance cost is 6% of the operating cost and therefore changes with DOC.

IV. Discussion

Volocopter, a multi-rotor configuration, is the only configuration that cannot meet operational requirements. Table 4 shows the list of criteria of each configuration and whether the results meet the requirements or not. Costs per unit at 60 units are 80.4, 65.7, and 26.7 million yen for Lilium jet, Vahana, and Volocopter, respectively. Hence, only Volocopter can achieve a lower cost than the R22 Robinson helicopter's cost of 31 million yen. Vahana and Lilium jet will need to raise production volume to 230 and 380 units to attain the same cost as Volocopter. The baseline for verifying the reduction and viability of the cost here is 25 million yen, which is 10 times lower than the current operating cost of 250 million yen. Volocopter is the only configuration that is applicable to achieve a DOC below 25 million yen with 90 production units, but only with the integration of a Tesla battery (19550 yen/kWh, 1$ = 110.03 yen) and 200 flight hours per year (Chiba). The other configurations will only reach 25 million yen in the year 2030. At 60 units of production, all configurations can achieve a cost below 25 million for the best-case situation in 2030, when the Tesla battery has a cost of 6883 yen/kWh and the advancement of the battery is increased to 500 kWh/kg, a doubling from 2020.

Table 4 List of Criteria

Criteria	Lilium jet	Vahana	Volocopter 2X
Meet requirements of operating distance (≥31.28 km)	Yes (47 km)	Yes (39 km)	No (13 km)
Cost per unit (60 vehicles)	80.4 million yen	65.7 million yen	26.7 million yen
DOC worst case in Hyogo (60 vehicles)	58.8 million yen	57.2 million yen	32.3 million yen
DOC best case in Chiba (60 vehicles)	23.6 million yen	21.2 million yen	15.3 million yen
Reduce to ≤ 25 million yen budget (DOC)	At 100 units (NEDO, Hyogo) Or 70 units (Tesla, Hyogo) Only year 2030	At 60 units (NEDO, Hyogo) Or 50 units (Tesla, Hyogo) only year 2030	At 90 units (Tesla, Chiba) 2020

V. Conclusion

Cost-estimation results show a tradeoff between the performance and life-cycle cost of fixed-wing and wingless aircraft. The Lilium jet has the highest DOC but will be comparable to Vahana when both configurations need more batteries in the year 2020. Volocopter achieves the lowest cost, but suffers for not achieving the air ambulance's operating-distance requirement of 31 km. In conclusion, there is no configuration that meets the requirements in 2020. In the year 2030, all configurations meet the cost requirement.

This study shows the results for DOC and Japan's circumstances for only 3 commercial models: Lilium, Vahana, and Volocopter. In future studies, with cost study, an optimized configuration design for verifying the trade-study between a vehicle cost and vehicle's performance can be determined based on which configuration is more promising for integration with more precise cost estimation. For additional future study, the cost analysis for not only medical emergency but also air taxi service should be conducted because of its high potential in urban cities.

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