UAM Team Project Report: Conceptual Design of Cargo eVTOL

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I. Motivation

We chose our eVTOL to be not for passengers, but for cargo. Why? We don't have any eVTOL operating in the real world yet. This market is immature. According to the Morgan Stanley's report, the VTOL market failed to get into the daily life. One of the key reasons is 'reliability'. The first thing eVTOL should achieve is reliability. It's an emotional stuff as well as a technical issue. In that sense, a cargo eVTOL can be a good starter. Without passengers, it is less risky. At the same time, if it works well, this new vehicle gets credibility from the public and has a chance to fly near us. Let us explain the specific vision and design in the following sections.

A. Market Needs

As the public interest on the healthy life increases, related industries are booming. One of them is food industry. People want to know 'who' produced the foods they eat, 'where' those came from, and 'how' those came to them. According to KREI's(Korean Rural Economic Institute) report, as far as food purchase is concerned, two of the most important factors to people are 'producer' and 'distributor'[1]. KREI's report also said that 63% of the people are willing to pay more for the safe foods. The rapid growth of companies providing direct distribution system and reliability explain this trend. Market Kurly and Dolfarmer are good examples. Both of them have built an image of reliable foods provider. Dolfarmer's purchase window in Fig.1 shows the identity of this company clearly. Maket Kurly started in 2015, and now it gets Series D and becomes Unicorn. Dolfarmer started in 2019, and the sales more than trippled last year.

Korean food distribution system is so inefficient that the percentage of the distribution cost relative to the retail price prices is pretty high. According to the MOF's(Ministry of Oceans and Fisheries) report, the distribution cost of most kinds of the marine products exceeds 50% of the retail prices[4]. Government has been trying to improve the supply chain. We can easily find articles with same title, like 'The government plans to diminish the distribution stages from 6 to 4.', in 2008, 2013, and 2020. It shows the Korean government's consistent interests on making a batter supply chain.

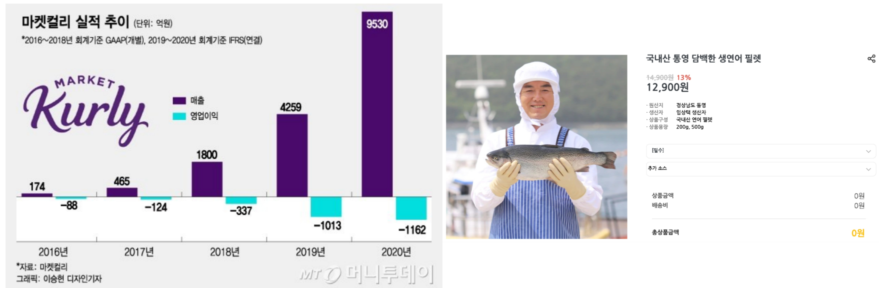

Fig. 1 Market Kurly's annual performance graph(left) and Dolfarmer's purchase window(right)[2][3]

B. Environment

Korea has a unique type of housing. 80% of the housing is the apartment, where people live in dense. A typical apartment complex can accommodate over 2000 households. This fact makes the situation easier. You can imagine the vertiport for cargo eVTOLs, near 3 to 4 apartment complexes. The horizontal range from the west side to the east side is not that far(under 300km) in Korea. Especially, Seoul, the most dense place in Korea, is from the sea foods production areas under 200km. It takes over 3 hours for ground transportation system, because of the mountainous terrain. It means that the eVTOL, which is free from the geographical factors, can carry the fresh sea foods directly and more efficiently if the infrastructure is ready.

Thanks to the AI technology and smartphone application, it becomes easier for companies to predict the demand. People purchase anything on the apps installed in their smartphones. They don't need to go to shop to buy something. It is good for the providers as for the customers. Providers can predict the future demand, and they can handle it in a flexible way. In addition, AI algorithm and accumulated data make it a way easier. All these condition increase the possibility of the production-consumption direct supply chain.

In short, our investigations shows the potential of the cargo eVTOL for Korean food distribution market. Next section is about the specific design processes.

II. Mission Profile

Our design's main purpose is to create an eVTOL delivering agricultural and marine products directly. The distance from Seoul to the west coast is about 60 to 80km. The straight-line distance from these areas to Seoul is short, but if you actually move on the road, the distance will be longer and the travel time will be increased. Furthermore, the distribution would be more complicated, which causes the unnecessary cost to the consumers. There are several detailed mission requirements which we set.

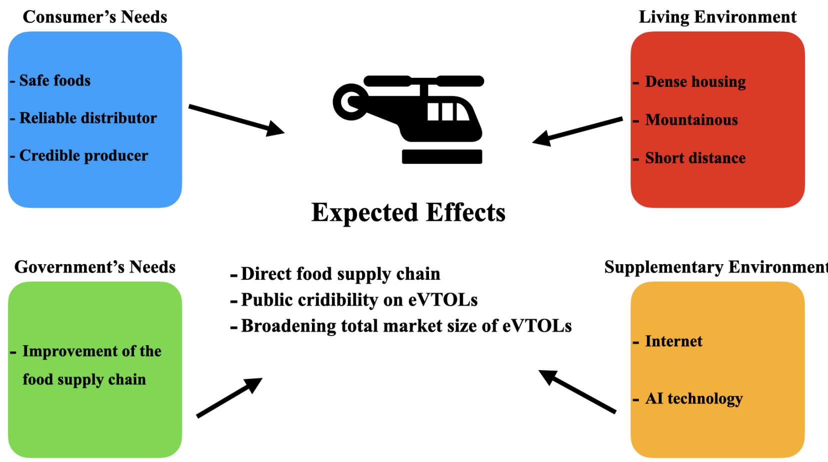

Fig. 2 Overall Motivation

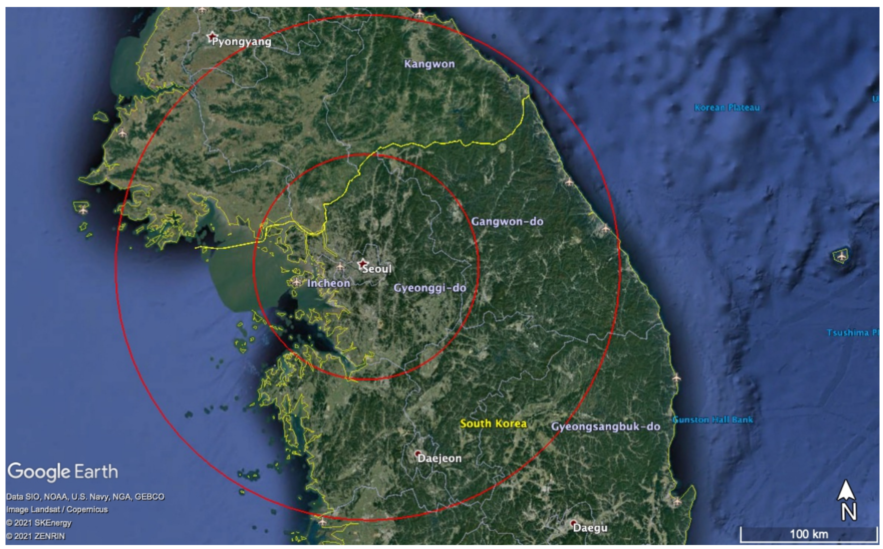

Fig. 3 Radius of 80km and 180km around Seoul

eVTOL: The vehicle uses **only electric propulsion** and must have **Vertical Takeoff and Landing capability** with short duration hover. **Total gross weight should be less than 3000kg.**

Noise: UAM eVTOL must have a low level of noise to operate near the cities. It is a nice UAM eVTOL to have external noise 15dB lower than the stage 3 noise boundary for current helicopters. Noise is directly associated with **tip speed**. The limit is **0.49M(168.1m/s)**

Battery : The given **specific energy at pack level is 200Wh/kg**. Considering other loses, **the percentage of the usable energy is 35%** of the battery. Plus, not to make the battery heavier, we select reasonable C rate. We choose C rate to under **5C**.

Payload: You can not deny the more payload is better for our purpose. We design our vehicle to be able to carry

500kg.

Range: The vehicle should be able to fly **over 80km(49.7miles)**. If we can reach over 180km(111.8miles), we can connect the Seoul and the east coast. It is important to avoid lithium battery being fully emptied, so at least 25 percent of battery should be always be in place.

Cost: It should be more competitive in price than in transporting cargo through railways and trucks. The cost of ordinary marine products,like squids(the most consumed), anchovies, mackerels, etc., is around 20 to 30 dollars per kg. According to MOF's report[4], the percentage of the wholesale and retail distribution cost relative to the retail price is over 30%. If we set the payload to 500kg, **the target cost per one-way trip is 4500 $**(=500 * 0.3 * 30). Details will be done in the cost analysis section.

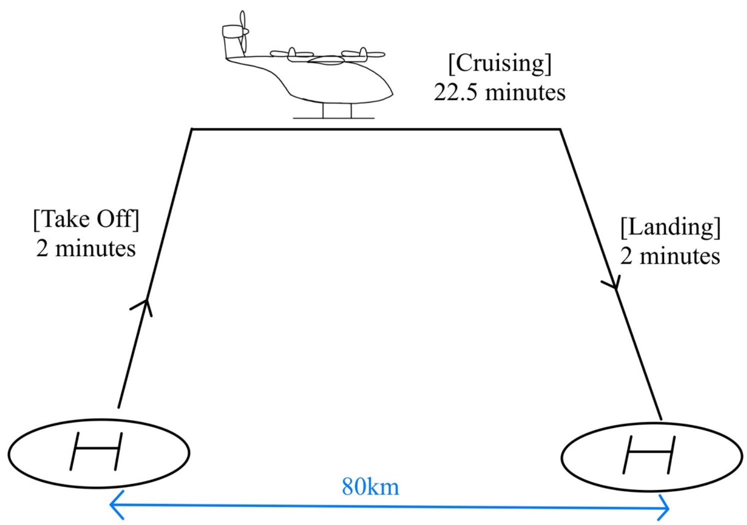

Fig. 4 Mission Profile

III. Conceptual Design Process and Result

Various conceptual configurations of eVTOL have been studied recently. They can be categorized as multi-rotor, tilt rotor, tilt wing, and lift + cruise. Firstly, the multi-rotor type aircraft has multiple rotors to generate lift during both hovering and cruising. However, multi-rotor type aircraft is very limited to short ranges and slow speed because rotor is aerodynamically inefficient to generate the lift during cruising. Secondly, tilt wing and tilt rotor are more efficient for long range mission as these type have wing component to generate lift during cruising. However, it is very difficult to design tilting device, thus resulting in expensive developing cost. Lastly, the lift + cruise type has both rotor and a wing, but the role of each rotor is clearly separated for lift or thrust. Unlike tilt rotor aircraft, the rotor of the lift + cruise aircraft has a simpler structure and can be designed much more efficiently as it is designed only for a single objective.

A. Aircraft Sizing

1. Wing

First, we will talk about the design of main wings, vertical tail wings, and horizontal tail wings. The size and performance of the rotor shall be covered further in Section 3. The wing area (S_{ref}) and aspect ratio(AR) of the main wing are sized based on mission profiles.

Generally, in the conceptual design process, lift-drag polar curve is calculated by the following simple correlation:

$$C_D = C_{D_0} + KC_L^2 \tag{1}$$

, where C_{D_0} is minimum drag coefficient, and $K = 1/(\pi ARe)$. e is Oswald span efficiency with values between 0.7 and 0.85. Oswald span efficiency is defiend by the function of aspect ratio:

$$e = 1.78(1 - 0.045AR^{0.68}) - 0.64 \tag{2}$$

C_{D_0} is correlated by the skin friction which can be calucalted by the following equations:

$$C_{D_0} = \frac{f}{S_{ref}} \tag{3}$$

$$log_{10}f = a + blog_{10}S_{ref} \tag{4}$$

, where f is equivalent parasite area, and $-2.0458 < a < -2.6990, b = 1$ are the correlation factor with respect to equivalent skin friction coefficient.

For the given reference area and aspect ratio of wing, the maximum value of lift to drag ratio can be derived from (1) which can be rearranged as follow:

$$(L/D)_{max} = \frac{1}{2}\sqrt{\frac{1}{KC_{D_0}}} \tag{5}$$

We roughly assumes that our eVTOL cruise in this maximum lift to drag ratio. When the lift to drag ratio is determined, we can calculate drag during cruise, and other component such as battery, rotor, and motor can be sized based on this value.

2. Battery

In order to calculate the total amount of energy and the weight of batteries needed to operate eVTOL, power consumption during cruising, hovering, and of refrigerator must be calculated first. Then by considering the operating time, battery capacity(BC), and battery energy density(BED), all the figures above can be calculated as follows:

$$P_{hover} = \frac{(W_{gross}g)^{1.5}}{M}\sqrt{\frac{DL}{2\rho W_{gross}}} \tag{6}$$

$$P_{cruise} = \frac{W_{gross}gV_c}{LD \times M} \tag{7}$$

Since the C discharging rate should not exceed $5C$, we checked if the C rate based on the battery power obtained earlier was less than $5C$. If the value exceeds $5C$, we chose the amount of the energy when the value is $5C$.

$$I_{hover} = \frac{P_{hover}}{Nl \times EV_{hover}}, \quad C_{hover} = \frac{I_{hover} \times Nl \times EV}{E_{hover}} \tag{8}$$

We selected LG GR-B472Q as the standard before determining the energy consumption of the refrigerator. The model has a capacity of $790L$, a power consumption of $205W$ and a rated voltage of $120V$. Our eVTOL is designed to have a capacity of $1000L$ to load $500kg$ of cargo. Therefore, by determining the specifications in proportion to the LG refrigerator, we set the refrigerator to have a capacity of $1000L$, consumption power of $260W$, and rated voltage of $120V$.

$$E_{total} = P_{hover} \times t_{hover} + P_{cruise} \times t_{cruise} + P_{AC} \times (t_{hover} + t_{cruise}) \tag{9}$$

$$W_{battery} = \frac{E_{total}}{BC \times BED} \tag{10}$$

To meet the output condition we set above, batteries which are able to create 800 volts are connected to each rotor. Each part needs different value of Ah to meet the requirements. Therefore, we decided to connect 200S12P battery for Hovering, 200S68P battery for cruising and 30S1P battery for the air conditioner.

Additionally, Hyundai is running an electric car super-fast charging station with 350kW and charging electric cars with 800V. If our eVTOL is charged with the same charger, it is expected that charging will be completed in about 13.8 minutes.

3. Rotor

We set DL(Disk Loading) to be 12 lb/ft^2. Considering noise, power, and rotor size, we set the number of lift rotors to be 12. Combining the aerodynamics of the wing, we chose the number of the thrust rotors to be 2 and the radius of those to be 46% of of the radius of the lift rotors. The common solidity of the rotors of the lift + cruise is from 0.30 to 0.35. We set solidity to be 0.30. Considering the aspect ratio of the blades and the balance among those, 5 is a nice figure for the number of blades.

We used BET(Blade Element Theory) to design the lift/thrust units in a more specific way. Detailed formulations(from

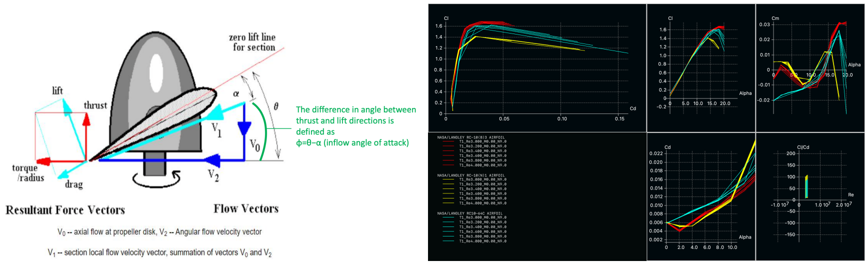

Fig. 5 BET Simplification(left) and CFD result of the NASA/Langley RC-10 series(right)

the class notes) are in the Appendix B. At first, we did CFD to choose the proper airfoil. Our approximate Re was 3e6 to 4e6 considering the chord length and the tip speed of the blades. NASA/Langley RC-10 series(which has 10% thickness) were appropriate for our condition. The result(Fig. 5) tells that stall occurs at AOA > 13°, and the slope of the AOA vs C_l is around 0.11/deg. And we set δ, which means the average profile drag coefficient of the blade, to 0.01, which is conservative value considering this result. Finally, we set θ_{tip} of the rotors to be 18.0° for thrust rotors, 10.7° for lift rotors. V_0 and α_{tip} are dependent on the speed of the vehicle. As the speed goes up, V_0 and ϕ_{tip} increase, and α_{tip} decreases. It means that alpha is larger when the vehicle starts to speed up(speed = 0) than when the vehicle gets to the maximum speed. While stall not occurring at zero speed, alpha should be maximized at the maximum speed. Our target value of α_{tip} at maximum speed was 2°, so the α_{diff} (alpha difference between zero speed and maximum speed) should be less than $11°(= 13 - 2)$. The above figures were optimized number considering all these factors.

4. Weight Estimation

The weight of the aircraft can be broken down with several components; wing, rotor, motor, motor controller, empennage, fuselage, flight controller, avionics, furnishing, landing gear, and anti icing equipment. Weight of each components are estimated by several empirical correlations, which can be found in the previous researches [5–8]. Overly, the weight of components, such as wing, fuselage, flight controller, avionics, and anti icing equipment, are proportional to gross weight. The weight of rotor-related components, such as rotor, motor, and motor controller, is mainly a function of power, thrust, and torque. The detailed formulation are described in Appendix. A.

While the weight of landing gear and furnishing is generally proportional to gross weight, we assumed it zero because our designed eVTOL is not intended for runway landing or human transportation. In addition, we multiplied the weight of fuselage by light factor of 0.8. It is because our eVTOL is autonomous flight, and we expect to save weight by eliminating heavy components such as windshield. Also, we multiplied the weight of motor and motor controller by tech. factor of 0.8, as we expect technological improvements in near future.

5. Sizing Results

Combining the contents presented so far, we selected a design point suitable for the mission profile. Aspect ratio and reference area were selected as major design variable. Other design variables, such as disk loading, number of rotor, ratio between rotors, equivalent skin friction, and fuselage length, were adjusted slightly by trial and error. With the fixed mission range of $80km$, optimal cruising speed ($V_c > 190km/h$), rotor tip speed ($V_{tip} < 0.49M$) , α_{diff} of cruising rotor ($\alpha_{diff} < 11°$), and gross weight ($W_{gross} < 3000kg$) were used as constraint. The results were plotted in Fig. 6

Several trends can be observed from the result in Fig. 6. First, higher aspect ratio leads to higher maximum lift to drag ratio, resulting in the increase of cruising efficiency. However, as it also increase the weight of wing, the increase in weight offsets the benefit of increasing the lift to drag ratio. This can be observed by the 'valley' of gross weight in Fig. 6. Second, large wing reference area leads to low cruising speed, and higher gross weight. This is because wing area is proportional to lift, which should be fixed during cruising. Thus, cruising speed constraint forces design point to lower reference area. Third, wing reference area is strongly correlated with α_{diff} constraint. This is because the smaller the wing area, the higher the cruising speed, which makes the design of cursing rotor very difficult.

We extracted design point from the region that satisfies all of these constraints. Aspect ratio of 6.4 and reference area of 33.5 m_2 was selected. The weight breakdown results are showed in Fig 7 and table 1, and the sizing results are presented in table 2 and Fig. 8. The sizing results was the maximum lift to drag ratio of 19.1, wing span of 14.6m, wing loading of 18.3 lb/ft^2, and the diameter of rotor for lift and cruise of 2.3m and 1.2m each. We think that all this numbers are within a reasonable range. Meanwhile, the tip speed of cruising rotor is over noise constraint of 0.49M. This is because, in the case of eVTOL, hovering mainly takes place in the urban area, whereas cruising mainly takes place in the suburb or rural area. Therefore, an advantage in aerodynamic efficiency was obtained by alleviating the noise constraint. In Fig. 8, the battery were placed on the container horizontally. This is because this type is robust for the change of the center of gravity depending on whether the cargo is loaded or not.

B. Cost Analysis

A cost analysis is required to ensure that the designed eVTOL can also be successful from a business point of view. In this project, cost analysis was conducted using the data in [8] as a reference. In this method, operating cost is categorized by book depreciation, variable cost, and fixed cost. Book depreciation cost means the amount of depreciation expense calculated for fixed assets. When the life cycle of the eVTOL is 10 year, 10 year payoff cost is included in this category. Variable costs are costs that change as the quantity of the good or service that business produces changes. In case of eVTOL, the costs for battery charging, battery replacement, and maintenance are included in this category. Fixed costs are costs that does not change with an increase or decrease in the amount of goods or services produced. The costs of pilots and crew, insurance, hanger and all overhead are included in this category.

First, in order to calculate book depreciation cost, it was assumed that the cost of aircraft would be scaled with

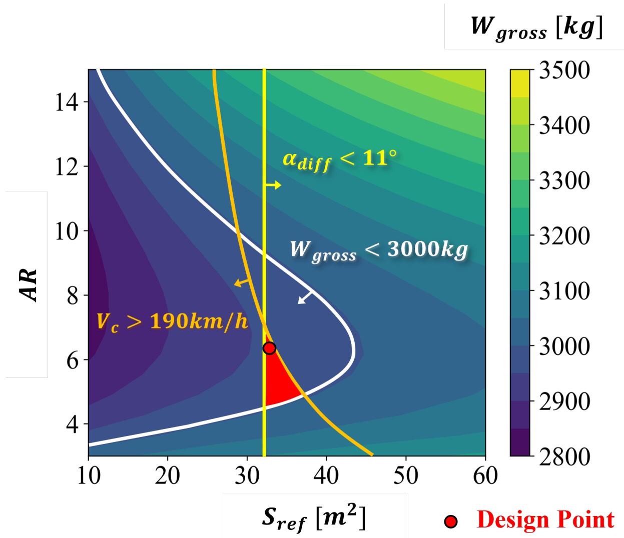

Fig. 6 Design Results of cargo eVTOL

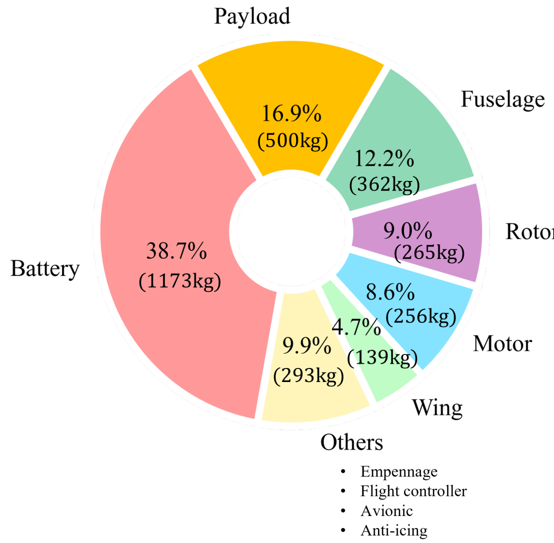

Fig. 7 Estimated mass fraction of each aircraft components

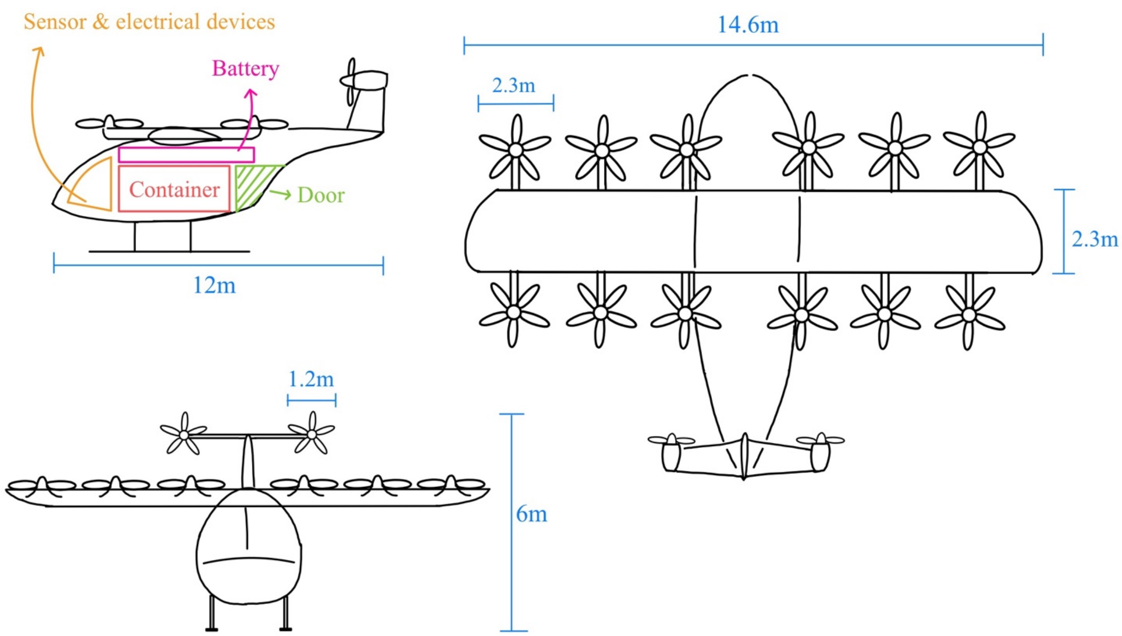

Fig. 8 Three-view drawing of designed eVTOL

respect to the gross weight. We employed Robinson R44 aircraft as a baseline, whose price are listed at $ 473,000 with a gross weight of 1,134 kg. Given the scaling assumption, our estimated cost is $1,251,000 per 10 years. If we assume 4 times of one-way operation per day, this costs $86 per one-way trip.

Second, variable cost consists of fuel, daily maintenance, overhaul, etc. Rather than calculating these lists one by one, the total variable cost was calculated inversely from the cost of electric fuel, which accounts for about 25 percent of the total cost. We assumed $0.12/kWh$ for charging, $400/kWh$ for battery pack, and 2,000 cycle of battery life.

Components	Weight [kg]	Components	Weight [kg]
Wing	**138.9**	**Fuselage**	**361.6**
Main spar	60.2	*Main tube fraom*	188.9
In-plane truss	9.7	*Attachments and fittings*	11.2
Attachments and fittings	6.8	*Wires*	7.5
Ribs	17.6	*Fuselage fairing*	74.6
Leading-edge-sheeting	26.2	*Drive system*	79.5
Trailing edge	5.9	*Landing gear*	0
Covering	4.7	*Furnishing*	0
Bat tip	8.1		
Motor	**253**	**Rotor**	**265**
Stator core	110.7	*Main spar*	120.5
Rotor core	69.0	*Leading-edge-sheeting*	72.3
Permanent magnet	22.1	*Trailng edge*	67.5
Shaft	12.1	*Others*	4.8
Windlings	39.0		
Empennage	**11.3**	**Refrigeration system**	**100**
Horizontal tail	0	*Compressor*	54
Vertical tail	11.3	*Structural frame*	32
		Insulating materials	14
Battery	**1173**	**Motor Controller**	**65.1**
BMS (cruise)	119.3	**Flight controller**	**11.1**
Battery Cell (cruise)	477.1	**Anti-icing**	**24**
Battery Pack (cruise)	596.4	**Avionics**	**80.4**
BMS (lift)	126.3	**Payload**	**500**
Battery Cell (lift)	505.2	**Gross weight**	**2984**
Battery Pack (lift)	631.5		

Table 1 Weight breakdown list

General		Wing		Rotor	(lift)	(cruise)
Range $[km]$	80	Span $[m]$	14.6	# of rotor	12	2
Cruising Speed $[km/h]$	190	Aspect ratio	6.4	Diameter [m]	2.3	1.2
Payload $[kg]$	500	Area $[m^2]$	33.5	RPM	1380	3100
Lift to drag	19.1	Loading $[lb/ft^2]$	18.3	$V_{tip}[Mach]$	0.49	0.60
Disk loading $[lb/ft^2]$	12			$\theta_{tip}[°]$	10.7	18.0
Fuselage length $[m]$	12					

Table 2 Sizing Results of Cargo eVTOL

When we calculated electric fuel cost per one-way trip, the cost for the battery charge and replacement was $12 and $48, respectively. Thus, variable cost can be estimated by $ 240 per one-way trip.

Lastly, fixed cost consists of crew, facility, flight services, and insurances. We estimate the fixed cost to be about half of the variable cost, which is \$ 120 per one-way trip. Thus, the total operational cost is about \$450. This amount excludes infrastructure costs. In general, infrastructure cost accounts for $15 - 50\%$ of the total cost. So, if you conservatively set it to 50%, the total cost would be \$900. The detail breakdown of cost analysis is presented in table 3. Since the revenue was originally estimated by \$4500 for one-way operation, we expect that the profitability is sufficient even considering the additional expenses required for the company management.

Category	Cost per one-way trip [$]
Book Depreciation	**86**
Variable Cost	**240**
Fuel (gas, electricity)	12
Daily Maintenance	84
Overhaul engine	0
Other major maintenance	96
Battery replacement	48
Fixed Cost	**120**
Crew, Facility, Flight Services	78
Insurance	34.8
Aircraft avionic modernization pool	13.2
Infrastructure Cost	**450**
Total	**900**

Table 3 Cost breakdown

IV. Conclusion

In this project, we presented a novel idea to meet the demands for the safe foods in Korea with eVTOL technology. In order to confirm the business feasibility of this idea, we conducted a conceptual design of cargo eVTOL. We employed various theories, such as lift to drag theory, battery power theory, and blade element theory, to reasonably design the whole structure of the eVTOL for the given mission profiles. The sizing results and cost analysis show that food distribution using cargo eVTOL is feasible object from both technical and economical point of view. Currently, the operating range is limited to about 80 km, but this technical barrier is expected to be resolved in the near future by the development of battery technology. For our calculation, if the battery density reaches $300kW/kg$, the designed cargo eVTOL can cover the operating range up to $180km$ which can connect Seoul to the east coast.

V. Appendix

A. Weight estimation

All the weight equations are in lb unit.

$$W_{gross} = 6W_{payload} \tag{11}$$

$$W_{wing} = 0.0467W_{gross}^{0.347}S^{0.36}N_{ult}^{0.397}AR^{1.712} \tag{12}$$

$$W_{rotor} = 1.763T_{rotor}^{2.00} \times 10^{-5} \tag{13}$$

$$W_{motor} = 0.3225\tau_c^{0.7476}N_c + 0.3225\tau_l^{0.7476}N_l \tag{14}$$

$$W_{motorcontrol} = 2.20462(49.9/398 * (P_c - 2) + 0.1)N_c + 2.20462(49.9/398 * (P_l - 2) + 0.1)N_l \tag{15}$$

$$W_{empennage} = 0.72S_h^{1.2}AR_h^{0.32} + 1.05 * S_v^{0.94}AR_v^{0.53} \tag{16}$$

$$W_{fuselage} = 6.9(W_{gross}/1000)^{0.49}L_f^{0.61}S_{wet}^{0.25}\eta_{light} \tag{17}$$

$$W_{flightcontrol} = 11.5(W_{gross}/1000)^{0.4} \tag{18}$$

$$W_{avionics} = 0.0268W_{gross} \tag{19}$$

$$W_{antiicing} = 8(W_{gross}/1000) \tag{20}$$

$$\begin{aligned} W_{tot} &= W_{wing} + W_{rotor} + W_{motor} + W_{motorcontrol} \\ &+W_{empennage} + W_{fuselage} + W_{flightcontrol} + W_{avionics} \\ &+W_{antiicing} + W_{battery} + W_{payload} \end{aligned} \tag{21}$$

B. Rotor

All the rotor equations are in SI units.

$$R_{lift} = \sqrt{\frac{W_{gross}}{DL\pi N}} \tag{22}$$

$$C_T = \frac{\delta}{4}a(\theta_t - \phi_t), \quad C_Q = C_P = \frac{\delta\sigma}{8} + \frac{C_T^{3/2}}{\sqrt{2}} \tag{23}$$

$$T = C_T\pi R^2\rho(\Omega R)^2, \quad P = C_P\pi R^2\rho(\Omega R)^3 \tag{24}$$

$$M = \frac{1}{\sqrt{2}}\frac{C_T^{3/2}}{C_Q} \tag{25}$$

$$V_{0,speed=0} = \sqrt{\frac{T}{2\rho\pi R^2}} \tag{26}$$

$$V_{0,speed=V} = \frac{V}{2}(1 + \sqrt{1 + \frac{2T}{\rho\pi R^2V^2}}) \tag{27}$$

References

[1] "The Consumer Behavior Survey for Food 2019," *Korea Rural Economic Institute*, 2019. URL https://www.krei.re.kr/krei/researchReportView.do?key=67&pageType=010101&biblioId=527881&pageUnit=10&searchCnd=all&searchKrwd=&pageIndex=1&engView=.

[2] . URL https://news.mt.co.kr/mtview.php?no=2021040115072374414.

[3] . URL https://www.dolfarmer.com/Goods/Detail/SSM21309396.

[4] "A Survey on the Production and Distribution of Fisheries Products in 2020," *Ministry of Oceans and Fisheries*, 2021. URL https://www.mof.go.kr/article/view.do?menuKey=851&boardKey=22&articleKey=42505.

[5] Kadhiresan, A. R., and Duffy, M. J., "Conceptual design and mission analysis for eVTOL urban air mobility flight vehicle configurations," *AIAA Aviation 2019 Forum*, 2019, p. 2873.

[6] Roskam, J., "Aircraft Design Part V: Component Weight Estimation," , 1999.

[7] Prouty, R. W., *Helicopter performance, stability, and control*, 1995.

[8] Duffy, M., Sevier, A., Hupp, R., Perdomo, E., and Wakayama, S., "Propulsion scaling methods in the era of electric flight," *2018 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS)*, IEEE, 2018, pp. 1–23.