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Examining Importance of Urban Rotorcraft Operations Using Analytic Hierarchy Process

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Abstract

This study aims to determine the importance of each factor considered when operating a rotorcraft in a city. After identifying factors that could affect urban air mobility, we reviewed the influencing factors by applying an analytic hierarchy process (AHP). Level 1 classifies the essential factors of the urban operation of rotorcraft in nominal and off-nominal situations. The factors corresponding to the characteristics of each were composed of lower levels, such as Levels 2 and 3. Using this, the importance of influencing factors was analyzed and the most important factors were determined. The most influential factors of the urban operation of rotorcraft included engine failure, fire situations, and vehicle safety. Accordingly, an environment that can guarantee safe operation by considering the most influential factors in advance in an actual operation stage must be constructed.

Keywords: *AHP, Rotorcraft operation, Urban Air Mobility, eVTOL*

1. INTRODUCTION

A rotorcraft is a vehicle that can produce propulsion with one or more than two rotors. It can fly in narrow areas where fixed-wing aircraft cannot take off and land because it can take-off and land vertically and hover in the air for a considerable amount of time[1]. However, due to public opposition to their high operating costs and noise, the use of rotorcraft in urban areas has not grown significantly[2]. Accordingly, the concept of electric vertical take-off and landing (eVTOL), an electric-propulsion vehicle that can replace rotorcraft, has emerged and is expected to enable more efficient urban operations. Unlike existing rotorcraft that use fuel, eVTOL is more environmentally friendly as it uses electric power, and its noise level is expected to be relatively low[3].

As part of eVTOL flight safety and collision avoidance technology development research for urban air mobility operations, the importance of urban operations was analyzed using an analytic hierarchy process (AHP) to develop a detailed procedure associated with its importance. To realize a better operating concept that reflects the characteristics of eVTOL aircraft for operation in an urban air mobility environment that requires vertical take-off and landing, we analysed the operation of a rotorcraft, which has the most similar flight among current aircraft.

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This study conducted basic research on the appropriate operating environment for urban air mobility by calculating the importance of factors associated with the urban operation of rotorcraft. We determined and reviewed the important factors for rotorcraft similar to eVTOLs in urban areas. For this, the factors that affect the urban operation of rotary-wing aircraft were derived and an AHP survey was conducted among current rotorcraft pilots with more than 10 years of piloting experience to analyze their relative importance.

2. PROCESS OF IDENTIFYING IMPORTANT FACTORS FOR THE URBAN OPERATION OF ROTORCRAFT

To derive important factors for the urban operation of rotorcraft, the flight missions of rotorcraft for each institution were first investigated. Based on the investigation, factors influencing city flight missions were identified. In addition, by referring to domestic and foreign literature, such as Table 1, the important factors for the urban operation of the rotorcraft were finally determined. Figure 1 schematically presents the corresponding process.

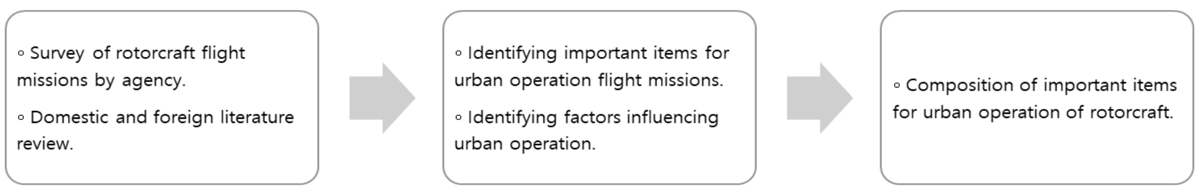

Figure 1. Identifying the influencing factors of urban operation

Table 1. Domestic and foreign literature

No	Document	Publisher	Year of publication
1	Prediction of the Future of On-demand Urban Air Transportation	UBER	2016
2	The Blueprint for the Sky	AIRBUS	2018
3	K-UAM Roadmap	MOLIT	2020
4	UAM ConOps v1.0	FAA	2020
5	UAM Vision ConOps UML4 v1.0	NASA	2020
6	Uam OpsCon Passenger-Carring Operations	NASA	2020
7	K-UAM ConOps 1.0	UAM Team Korea	2021
8	UAM Airspace Management Report	SESAR	2021
9	Demonstrating the Everyday Benefits of U-space	SESAR	2022
10	The RPAS and AAM Strategic Regulatory Roaemap	CASA	2022

3. ANALYTIC HIERARCHY PROCESS

3.1 The Basics of Analytic Hierarchy Process

AHP is used to derive ratio scales through discrete or consecutive pairwise comparisons. In general, AHP is a non-linear system that considers several factors simultaneously and performs deductive and inductive thinking without using syllogisms[4]. The usefulness of the hierarchical analysis technique is that first, qualitative or undirected standards and quantitative or tangible standards are measured on a scale ratio, and second, it can be used to solve problems with a simple two-way comparison by gradually breaking down a large problem into smaller elements[5]. AHP is performed through the procedure shown in Table 2.

Table 2. Procedure for the analytic hierarchy process

Stage	Content
Step 1	Establishing a decision-making hierarchy
Step 2	Pairwise comparison between factors
Step 3	Relative weight estimation and consistency calculation

Step 1 sets up a decision-making hierarchy where the goal to be achieved constitutes Level 1 and the main factors that must be considered to achieve it constitute Level 2. Sub-factors constituting Level 2 constitute Level 3. Step 2 performs the pairwise comparison of factors affecting decision-making, and the pairwise comparison matrix A is an inverse matrix in which the sum of factors on the main diagonal is 1, as shown below.

$$A = \begin{pmatrix} 1 & a_{12} & a_{13} & \cdots & a_{1n} \\ a_{21} & a_{22} & a_{23} & \cdots & a_{2n} \\ a_{31} & a_{32} & a_{33} & \cdots & a_{3n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & a_{n3} & \cdots & 1 \end{pmatrix} \qquad \text{where } a_{ij} = \frac{1}{a_{ij}} \tag{1}$$

Step 3 estimates the relative weights of the factors and calculates their consistency. To determine the relative weight, the matrix obtained through pairwise comparison must be expressed as a vector. As the sum of each column of the pairwise comparison matrix is 1, the average of each row is obtained to create a relative weight vector.

Element a_{ij} of the comparison matrix A is the weight ratio of elements i and j as follows:

$$a_{ij} = \frac{w_i}{w_j} \quad (i,j = 1,\cdots,n) \tag{2}$$

The pairwise comparison matrix A composed of a_{ij} in Equation (2) is as follows.

$$A = \begin{pmatrix} \omega_1/\omega_1 & \omega_1/\omega_2 & \omega_1/\omega_3 & \cdots & \omega_1/\omega_n \\ \omega_2/\omega_1 & \omega_2/\omega_2 & \omega_2/\omega_3 & \cdots & \omega_2/\omega_n \\ \omega_3/\omega_1 & \omega_3/\omega_2 & \omega_3/\omega_3 & \cdots & \omega_3/\omega_n \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \omega_n/\omega_1 & \omega_n/\omega_2 & \omega_n/\omega_3 & \cdots & \omega_n/\omega_n \end{pmatrix} \tag{3}$$

The following equation is derived by multiplying matrix A of Equation (3) by the weight vector $\omega = [\omega_1, \omega_2, \omega_{3,} \ldots, \omega_n]$ to derive the relative importance of each factor.

$$A \cdot \omega = n \cdot \omega \tag{4}$$

In Equation (4), n represents the largest eigenvalue of matrix A.

In general, since it is difficult to maintain consistency and evaluate objects like matrix A, λ_{max}, which is the maximum eigenvalue of pairwise comparison matrices A and A, is substituted for n.

$$A \cdot \omega = \lambda_{max} \cdot \omega \tag{5}$$

λ_{max} is always greater than or equal to n, and the closer the value of λ_{max} is to n, the better the consistency. Therefore, the consistency index is defined as Equation (6) below.

$$C.I. = \frac{\lambda_{max} - n}{n - 1} \quad (6)$$

In AHP, when testing consistency, the consistency index is tested using the inconsistency ratio divided by the average random index $R.I.$. The inconsistency ratio is shown in Equation (7).

$$C.R. = \frac{C.I.}{R.I.} \quad (7)$$

The closer the inconsistency ratio is to 0, the more consistent the respondent. If the inconsistency ratio is less than 0.1, its consistency is considered reasonable.

3.2 Hierarchy for analysis

For hierarchical composition, the major flight missions of each institution operating domestic rotorcraft were investigated. The target institutions include operating civilians, the police, maritime police, firefighting, forestry, and military helicopters, and the flight missions for urban operations by the institutions are shown in Table 3.

Table 3. Major flight missions by domestic agency

Classification	Item		
Police	Personnel transport	traffic enforcement	Counterterrorism mission
Maritime police	Personnel transport	Search and rescue (Patient transfer)	
Firefighting	Personnel transport	Patient transfer	
Forest	Fire extinguishing	Aerial pesticide application	
Private helicopter	Personnel transport	Tourism	
	Emergency medical support	Aerial photography	
Military helicopter	Personnel transport	Patient transfer	

Based on Table 3, flight missions excluding special missions for each agency were selected to form hierarchical elements, and the contents are shown in Figure 2.

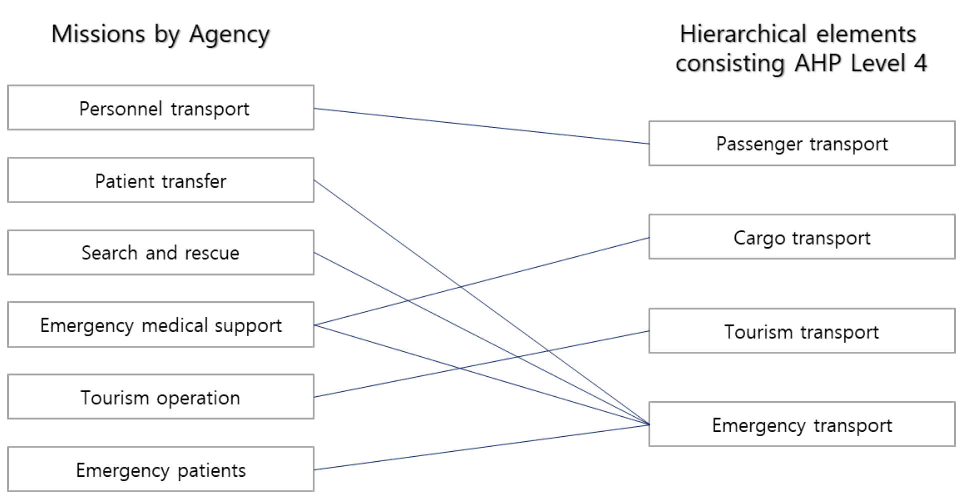

Figure 2. Relations between agency-specific missions and hierarchical elements

Domestic documents, including the Korean urban air mobility roadmap published in May 2020, and overseas data published by the FAA and NASA were collected, and based on their content, hierarchical elements were additionally constructed, and their list is shown in Table 4.

Table 4. Hierarchical elements based on domestic and international documents

Classification	Item	
Operational safety	Flight corridor operation	Aircraft safety
	Airspace separation safety	Airfield adequacy
	Pilot proficiency	Boarding procedure (security)
Environmental aspects	Noise	Privacy
	Ecological impact	-
Social acceptability	Safety verification	Convenience (reduction of time)
	Operation cost (transportation expenses)	Resolving traffic congestion
	Job creation	-

K-UAM Concept of Operation v1.0 (hereafter referred to as K-UAM ConOps) is an operational concept document published by the Ministry of Land, Infrastructure, and Transport for urban operations in South Korea, which includes details on UAM operation phases, roles, and responsibilities among stakeholders and scenarios. In this document, the UAM operation situation is classified as shown in Table 5.

Table 5. Defining operational status of K-UAM ConOps

Operational status		Situation description
Nominal situation	Nominal operation	A state in which all systems related to UAM operation remain nominal
Off-nominal situation	Abnormal operation	A rotorcraft can fly the initially planned destination, but some systems and environments are off-nominal.
	Contingency	A rotorcraft cannot fly to the planned destination due to factors with a dangerous level. Necessary actions can be taken to contingency plans, etc.
	Emergency	A rotorcraft cannot be controlled due to critical factors. It requires measures based on accident response procedures, etc.

In abnormal operation, the initially planned flight plan can be followed and flight to the destination can be reached by continuing the operation. Examples of abnormal operation include air conditioner malfunction, navigation error, communication network connection error, the sudden appearance of an aircraft, and severe weather. A contingency, which is one level more dangerous than abnormal operation, is a situation in which the flight plan cannot be followed and the flight to the planned destination is impossible. In the event of a contingency, an emergency landing must be made through rapid response. Examples include component failure due to bird collision, the occurrence of an emergency patient, and an inability to designate an alternative flight route in severe weather. Lastly, an emergency situation is one where it is impossible to control the aircraft due to a fatal level of factors occurring during operation. Since K-UAM ConOps did not specify an example of an emergency situation, detailed factors were configured by referring to the aircraft manual.

In this study, lower levels were constructed based on the off-nominal situations presented by K-UAM ConOps, as shown in Figure 3.

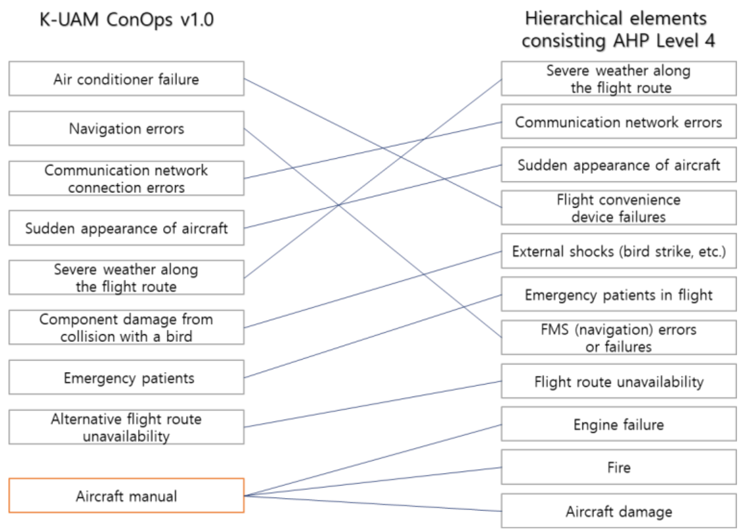

Figure 3. Relationship between K-UAM ConOps and hierarchical elements

Table 6. Hierarchy diagram for analyzing the importance of urban rotorcraft operations

Level 1	Level 2	Level 3	Level 4
Calculation of the importance of urban rotorcraft operations	Nominal situation	Urban operation	Passenger transport (regular route)
			Cargo transport
			Tourism transport
			Emergency transport
		Operational safety	Flight corridor operation
			Air vehicle safety
			Airspace separation safety
			Airfield adequacy
			Pilot proficiency
			Boarding procedure (security)
		Environmental aspects	Noise
			Privacy
			Ecological impact
		Social acceptability	Safety verification
			Convenience (reduction of time)
			Operation cost (Transportation expenses)
			Resolving traffic congestion
			Job creation
	Off-nominal situation	abnormal operation	Flight convenience device failures
			Communication network errors
			Severe weather along the flight route
			Sudden appearance of aircraft
		Contingency	External shocks
			FMS errors or failures
			Emergency patients in flight
			Flight route unavailability
		Emergency	Engine failure
			Fire
			Aircraft damage

Table 6 organizes the analysis hierarchy. Level 1 is the purpose of AHP, which affects the calculation of the importance of urban rotorcraft operations. Level 2 is divided into nominal and off-nominal situations. Level 3 is divided into factors associated with nominal situations, such as urban operation, operational safety, environmental aspects, and social acceptability, and with off-nominal situations, such as abnormal operation, contingency, and emergency situations. Level 4 consists of the sub-factors of Level 3, including passenger transport (regular route), cargo, tourism, and emergency transport under urban operations, as well as flight corridor operation, aircraft safety, airspace separation safety, airfield adequacy, pilot proficiency, and boarding procedure (security) under operational safety. Environmental factors include noise, privacy, and ecological impact, and social acceptability includes safety verification, convenience (reduction of time), operation cost (transportation expenses), resolving traffic congestion, and job creation. abnormal operations include flight convenience device failures (air conditioners, etc.), communication network errors, severe weather along the flight route (flight route change), and the sudden appearance of aircraft (in the flight corridor); contingencies include external shocks (birds, etc.), FMS (navigation) errors or failures, emergency patients in flight, and flight route unavailability; and emergencies include engine failure, fire, and aircraft damage.

4. ANALYSIS OF THE IMPORTANCE OF URBAN ROTORCRAFT OPERATIONS

4.1 Overview of the analysis and upper-level (Level 2) analysis

To calculate the importance of urban rotorcraft operations, presurvey items were prepared by referring to the Delphi survey and related literature. For AHP, deriving weights through comparison between survey items may have low consistency without a clear understanding.

The subjects of the survey were limited to rotorcraft pilots, most of whom had more than 10 years of piloting experience. From August 10 to 22, 2022, 60 questionnaires were collected for analysis. For analysis, the AHP analysis program Expert Choice 11.5 was used. The consistency index was 0.04, and there was almost no logical contradiction among the judgments of the evaluators who participated in the hierarchical analysis.

From the analysis, the evaluation of the nominal and off-nominal situations, which are the upper-level factors for evaluating the importance of urban rotorcraft operations, revealed a weight of 0.661 for the off-nominal situation and 0.339 for the nominal situation, indicating that the off-nominal situation has more influence. The greater influence may mean that the prompt action of the pilot in an off-nominal situation is an important factor in urban operations.

Table 7. Importance of the factors affecting urban rotorcraft operations

Classification	Off-Nominal	Nominal
Weight	0.661	0.339

4.2 Mid-level (Level 3) analysis

The importance evaluation for the sub-factors of the nominal situation provided a weight of 0.566 for operational safety, 0.154 for social acceptability, 0.150 for environmental aspects, and 0.130 for urban operation, with operational safety analyzed to have more influence than the other factors. This greater influence means that operational safety has a higher priority than other factors due to the nature of the aviation field, which has a significantly higher fatality rate for accidents compared to other transportation methods.

Table 8. Importance of the nominal situation factors

Classification	Operational safety	Social acceptability	Environmental aspects	Urban operation
Weight	0.566	0.154	0.150	0.130

The importance evaluation of the sub-factors of the off-nominal situation revealed the weights of 0.672 for emergency, 0.231 for contingency, and 0.097 for abnormal operation, with emergency analyzed to have a greater influence than other factors.

Table 9. Importance of the off-nominal situation factors

Classification	Emergency	Contingency	abnormal operation
Weight	0.672	0.231	0.097

4.3 Lower level (Level 4) analysis for the nominal situation

The importance evaluation for the sub-factors of the urban operation under the nominal situation showed weights of 0.536 for emergency transport, 0.260 for passenger transport (regular route), 0.114 for tourism transport, and 0.091 for cargo transport, with emergency transport closely associated with human life analyzed to have more influence than other factors.

Table 10. Importance of sub-factors of urban operation

Classification	Emergency transport	Passenger transport (regular route)	Tourism transport	Cargo transport
Weight	0.536	0.260	0.114	0.091

As a result of the importance evaluation for the sub-factors of operational safety under the nominal situation, the weight was 0.344 for aircraft safety, 0.169 for airspace separation safety, 0.132 for airfield adequacy, 0.112 for flight corridor operation, and 0.091 for boarding procedure (security). Aircraft safety, which is directly related to operational safety, had the greatest impact on urban operations, and pilot proficiency, airspace separation safety, airfield adequacy, and flight corridor operation had a similar impact.

Table 11. Importance of sub-factors of operational safety

Classification	Aircraft safety	Pilot proficiency	Airspace separation safety	Airfield adequacy	Flight corridor operation	Boarding procedure (security)
weight	0.344	0.193	0.169	0.132	0.112	0.049

The importance evaluation for the sub-factors of environmental aspects under the nominal situation revealed the weights of 0.544 for noise, 0.281 for privacy, and 0.175 for ecological impact. Noise was analyzed to be more important than other factors, which suggested that the influence of noise was large due to the characteristics of the city with a high population density.

Table 12. Importance of sub-factors of environmental aspects

Classification	Noise	Privacy	Ecological impact
Weight	0.544	0.281	0.175

The importance evaluation for the sub-factors of social acceptability under the nominal situation showed weights of 0.520 for safety verification, 0.149 for operation cost, 0.135 for resolving traffic congestion, 0.131 for convenience (reduction of time), and 0.064 for job creation. The importance of safety verification was analyzed to be high, which means that social acceptance is limited without safety verification due to the nature of aircraft flying in three-dimensional space. Operation cost, resolving traffic congestion, and convenience have similar levels of impact, and the impact of job creation on urban operation was analyzed to be low.

Table 13. Importance of sub-factors of social acceptability

Classification	Safety verification	Operation cost (Transportation expenses)	Resolving traffic congestion	Convenience (Reduction of time)	Job creation
weight	0.520	0.149	0.135	0.131	0.064

4.4 Lower level (Level 4) analysis for the off-nominal situation

The importance evaluation for the sub-factors of abnormal operation under the off-nominal situation showed weights of 0.371 for severe weather along the flight route (flight route change), 0.306 for communication network errors, 0.271 for sudden appearance of aircraft (in the flight corridor), and 0.052 for flight convenience device failures (air conditioners, etc.). Severe weather along the flight route, communication network errors, and the sudden appearance of aircraft were analyzed to have similar importance, while the flight convenience provision device was analyzed as being of relatively low importance.

Table 14. Importance of sub-factors of minor off-nominal situation

Classification	Severe weather along the flight route	Communication network errors	Sudden appearance of aircraft (in the flight corridor)	Flight convenience device failures (air conditioners, etc.)
Weight	0.371	0.306	0.271	0.052

The importance evaluation for the sub-factors of contingency under the off-nominal situation showed weights of 0.371 external shocks (bird, etc.), 0.360 for emergency patients in flight, 0.153 for FMS (navigation) errors or failures, and 0.116 for flight route unavailability. External shocks and emergency patients in flight were analyzed to be of relatively high importance, whereas FMS (navigation) errors or failures and flight route unavailability were analyzed to be of relatively low importance.

Table 15. Importance of sub-factors of contingency

Classification	External shocks (bird, etc.)	Emergency patients in flight	FMS (navigation) errors or failures	Flight route unavailability
Weight	0.371	0.360	0.153	0.116

The importance evaluation for the sub-factors of emergency under the off-nominal situation revealed weights of 0.454 for engine failure, 0.389 for fire, and 0.157 for aircraft damage. The effect of engine failure was found to be the greatest, which seemed to reflect the risk that an accident of an unpredictable scale might occur due to a power cut.

Table 16. Importance of sub-factors of emergency

Classification	Engine failure	Fire	Aircraft damage
Weight	0.454	0.389	0.157

4.5 Comprehensive importance of urban rotorcraft operations

Figure 4 shows the results listed in order of importance after synthesizing the results of relative importance for each sub-class element. As a result, the importance of safety and emergencies (engine failure, fire) that require direct and immediate action was the highest, and overall, the importance of items affecting operational safety was high.

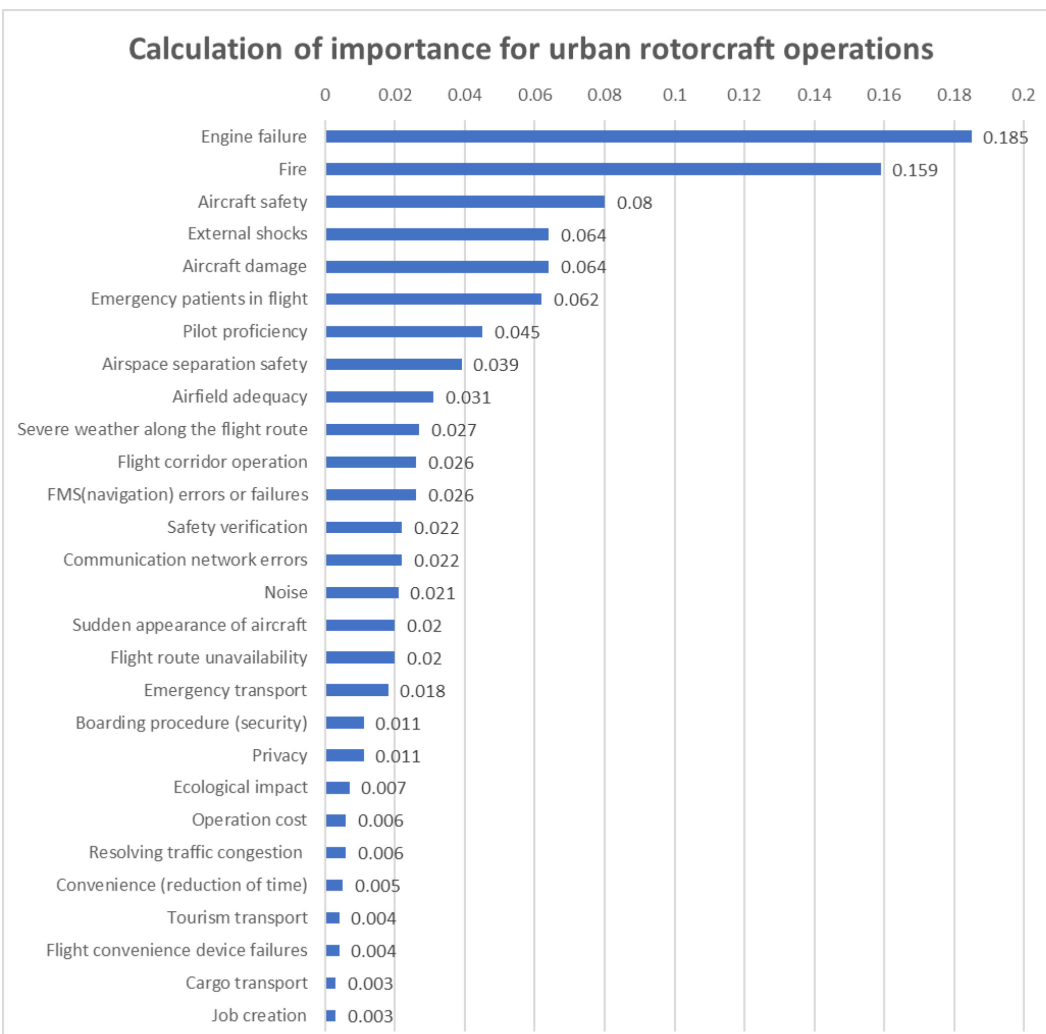

Figure 4. Comprehensive importance of urban rotorcraft operations

5. CONCLUSION

This study used AHP to calculate the importance of urban rotorcraft operations. In order to derive various factors that can affect urban rotorcraft operations, they are divided into nominal and off-nominal situations. In order to derive the sub-factors, the list of missions for each institution that operates rotorcraft was analyzed, and factors that could affect urban operations were organized based on various domestic and foreign documents. Using AHP, the factors affecting the urban rotorcraft operations were reviewed, and the items with high impact were analyzed.

In the field of aviation in three-dimensional space, there are many cases in which various factors work in combination due to the characteristics of the special operating environment compared to ground transportation. Due to this specificity, there are risk factors that are difficult to predict, with a high possibility and risk of an accident. For urban rotorcraft operations, various factors, such as operational safety, must be verified before prioritizing urban operations to secure aviation safety.

In this study, the factors influencing the importance of urban rotorcraft operations were examined by configuring detailed factors that may affect actual operations. Among these sub-factors, those analyzed as having high importance included the engine failure, fire, and aircraft damage factors under the off-nominal situation that have an absolute impact on aviation safety. In addition, factors that directly or indirectly influence urban operation, such as the airspace separation, flight corridor operation, and noise factors under the nominal situation, were identified as important.

This study analyzed the factors that can affect a rotorcraft, which is a superordinate concept of flight that is most similar to eVTOL operated in an urban environment. The results of this study can be used as a reference for research on the urban operation of eVTOL, which will be commercialized in the near future, as well as urban air traffic management.

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