

Article

Analyzing Determinants of Aircraft Used Serviceable Material's Value Using Fuzzy Analytic Hierarchy Process

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Abstract

Using used serviceable material (USM), recycled and upcycled, for aircraft is environmentally and financially beneficial in helping the aviation industry achieve sustainability. This study aims to identify determinants of aircraft USM value and assess their significance using the Fuzzy Analytic Hierarchy Process (FAHP) to gain insights for making the USM market more active. Sixteen factors in four categories are selected based on literature and focus group interviews. A survey to analyze factor priority is conducted with 118 industry experts. The results show that maintenance requirements, airworthiness directive status, and maintenance status from the technical category are the most critical determinants of aircraft USM value, followed by traceability, former operator, and former aviation authority from the operational category and new part value. The technical category corresponds to “must-be” traits in the Kano model, requiring compliance by sellers, whereas new part value information can help buyers’ decisions. The implementation of an internationally agreed mutual accreditation system for approved maintenance organizations and a standard for aircraft dismantling is proposed to improve technical and operational determinants to achieve fewer uncertainties in USM valuation. This study aims to offer a new guideline for evaluating USM value to market participants. Price modeling of USM is left for future studies.

Keywords: used serviceable material; fuzzy analytic hierarchy process; aircraft; valuation; sustainability; circular economy



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1. Introduction

More companies are recognizing the importance of nonfinancial aspects owing to changing perceptions regarding climate change and corporate social responsibility. In particular, ESG, an umbrella term for environmental, social, and governance, is becoming a new standard that companies and governments must pursue and achieve for sustainability. As market demand for ESG continues to grow, the aviation industry has also been steadily seeking to implement ESG in management. Airlines are utilizing used serviceable materials (USMs) in aircraft, in an effort to be more eco-friendly. Moreover, USM is an option worthy of consideration from a financial perspective, as it is less expensive than new materials [1].

As COVID-19 adversely impacted the entire aviation industry by interrupting global spatial mobility and restricting intercontinental travel, airlines sought various strategies to survive this devastating era. In addition to increasing operational outsourcing [2–4] and passenger-to-freighter aircraft conversions [5], airlines made a concerted effort to reduce fixed costs through aircraft sale-and-leaseback and/or retirement. Using refurbished parts

is a cost-effective alternative to using new parts; therefore, the demand for USM has been increasing. Utilizing USM enables airlines to have financial flexibility because of its price advantage and simultaneously allows them to achieve nonfinancial goals by choosing an eco-friendly alternative. Many international organizations and corporations, including the International Air Transport Association (IATA), are facilitating the trade of USM for aircraft by building platforms for refurbished parts [6,7].

However, the majority of USM is still traded via auction, and despite the increased importance of identifying factors determining the value of USM, research in this field has been relatively neglected. This study aims to propose a systematic method to identify factors influencing USM valuation and evaluate their significance. A three-phase research framework is introduced. In the first phase, factors determining the value of USM are identified. For this purpose, we identified the areas where USM transactions are active, such as the automobile and shipbuilding industries, and analyzed their cases. We also analyze previous studies on the basic demand in the aviation industry to secure the integrity of valuation. The identified factors are then selected based on industry expert focus group interviews. In the second phase, factor significance is evaluated to confirm factor influence on aircraft USM valuation. For this, the fuzzy analytic hierarchy process (FAHP) is applied to determine factor priority. FAHP is extensively used in aviation industry studies, helping assign weights to each factor systematically. This structured multi-criteria methodology evaluates the relative importance among factors by pairwise comparison to confirm determinants of USM valuation and their characteristics. In the last phase, important factors impacting aircraft USM valuation are examined, and implications are drawn for USM transactions and airline carriers' strategies for operating aircraft parts. To our knowledge, this framework represents the first systematic attempt to apply FAHP to USM valuation.

The goal of this study is to identify determinants of aircraft USM value and demonstrate the relative importance of these factors as a reference in USM transactions. Since the COVID-19 pandemic, USM transaction volume has decreased, whereas the volatility of transaction prices has increased, thereby compromising the safety of USM transactions and delaying market growth [8]. This study aims to contribute to making the USM market more liquid and active by providing market participants with a standard for determining the value of used aircraft parts, thereby reducing transaction uncertainties. This study also seeks to propose a method to achieve sustainability in the aviation industry by helping invigorate the USM market and facilitate the market circulation of goods that have not been actively explored in the industry to date.

2. Literature Review

2.1. Circular Economy in the Aviation Industry

The International Civil Aviation Organization (ICAO) has proposed and implemented the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) in line with the emergence of global eco-friendly policies [9]. The organization strives to systematically introduce a system for reducing and controlling greenhouse gas emissions and promoting the mid- to long-term environmental competency of the industry. CORSIA focuses on reducing greenhouse gas emissions in airport operations through various measures, including replacing old aircraft, managing air traffic control and airport operations, and streamlining aircraft operations for better efficiency [9]. Such measures aim to minimize greenhouse gas emissions, particularly during the operation phase of the life cycle of aircraft, which consists of four stages: development, production, operations, and retirement [10–13].

However, these measures focus primarily on reducing emissions during aircraft operations and tend to overlook the end-of-life phase, including recycling and reusing parts [14], which are key concepts in eco-friendly policies [15,16]. Reusing parts can be an effective, eco-friendly strategy in the aviation industry, as it can simultaneously provide environmental protection and cost reduction [17–19]. As the consumption of resources and the discharge of potential wastes are expected to increase in the global aviation industry, recycling and reusing can not only help achieve nonfinancial benefits such as environmental protection but also contribute to the financial advantage of cost reduction [15] and present the possibility of “Green Recovery” [20]. New parts, either directly produced or manufactured by the original equipment manufacturer (OEM) [1,21], are more expensive compared to USM. The order-to-delivery time for OEM-produced parts is long, resulting in increased costs and/or increased inventory costs. Using USM can reduce the overall cost by up to 40% [21] and it can shorten the delivery time. Reusing and recycling at the end-of-life stage of transportation assets have been researched widely thanks to their cost advantage [22–28]. In the automobile and shipping industries, where the reuse of parts is relatively common, research on parts evaluation by assessing the conditions and remaining lifespan of used batteries has been conducted [29–36]. However, direct comparison with the aviation sector remains limited, as aircraft consist of multiple high-value components, such as engines, auxiliary power units, and landing gears, that differ significantly in function, lifestyle, and certification standards. This structural diversity underscores the challenge of developing a comprehensive valuation framework reflecting the heterogeneous nature of aircraft USM and the strict regulatory environment of the aviation industry.

2.2. USM in Practice

The concept of a circular economy varies slightly depending on the industry, but it usually includes “reuse” and “recycle” as its main principles [37]. In a circular economy, by linking the end of the product life back to the beginning, products in the disposal stage are recycled as resources, and the resources are put back into production [38]. By designing the product life cycle as circular, firms can reduce pollution, use resources efficiently, and improve sustainability [37]. The circular economy concept and guidelines have been introduced in the aviation industry for these benefits. In particular, the aviation industry has developed and implemented a process for decommissioning aircraft as shown in Figure 1 [38–40]. First, operators park and store the aircraft and remove the valuable parts from the aircraft. The removed components can be returned to service after being inspected or repaired by approved maintenance organizations. After removing all valuable parts from the aircraft, the aircraft permanently loses its airworthiness and enters the waste management stream by deregistration. This process involves extracting materials from recyclable parts and disposing of non-recyclable parts.

Building on this process-oriented perspective, recent market trends highlight both the vulnerability and potential of USM in practice. During the COVID-19 crisis, the USM market experienced a sharp contraction: in 2020, overall parts and materials spending fell to USD 26 billion from a pre-COVID estimate of USD 60 billion, with the USM segment shrinking to about USD 2.8 billion compared to USD 4.7 billion in 2019 [8,41]. This reflects both the steep decline in transaction volumes and the heightened price volatility triggered by grounded fleets and global travel restrictions [8,41]. Recent evidence illustrates the market scale and growth prospects of USM. According to KPMG International Limited, certified USM parts are typically 20–40% cheaper than new components, creating a strong cost advantage for airlines, lessors, and aircraft maintenance, repair, and overhaul (MRO) companies [42]. The global aircraft disassembly, dismantling, and recycling market is

projected to grow to more than USD 14 billion by 2032, reflecting both the economic urgency and sustainability relevance of USM [42].

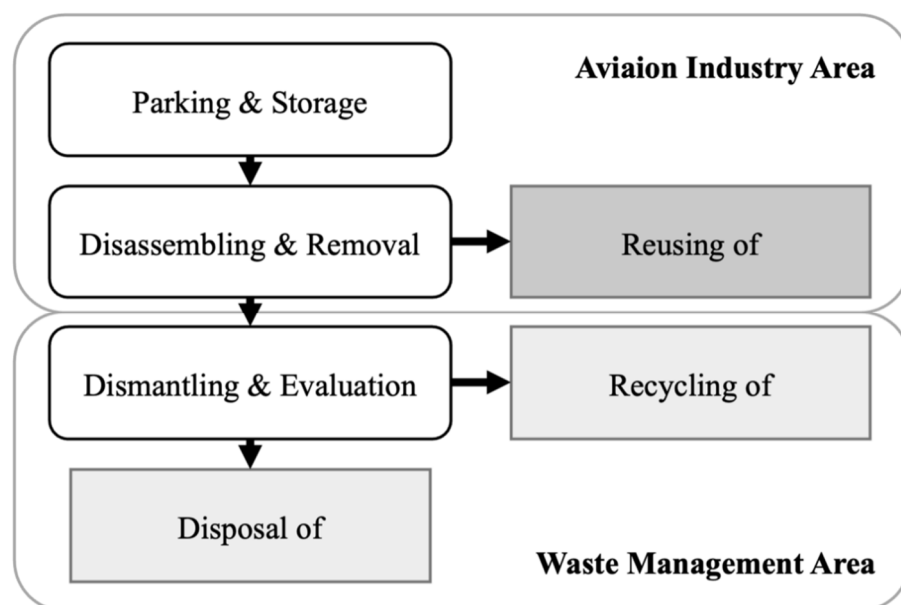


Figure 1. The end-of-life process of aircraft.

2.3. Factors Influencing USM's Value

Four properties of USM for aircraft are extracted from previous studies on USM valuation analysis. Safety is the number one priority in the aviation industry as aviation accidents are usually catastrophic. Therefore, aircraft manufacturers provide maintenance manuals and civil aviation authorities impose legal restrictions to secure airworthiness, which serves as a reference for safety in the industry, upon which operational activities of airlines and aircraft maintenance companies are based. Maintenance requirements [6,43,44], airworthiness directive status [6], maintenance status [6,43,44], and aircraft eligibility [6,44] are technical requirements for airworthiness, which should impact the value of USM. These factors are classified as the technical category, representing mandatory compliance items that underpin airworthiness and form the baseline for USM value.

Second, the aviation industry has been developed based on globally agreed standards, i.e., standards and recommended practices (SARPs), as it deals with international transportation among countries. These standards are proposed by the industry's representative organizations, such as ICAO for civil aviation authorities, and IATA for airline companies. However, they can only provide minimal outlines, as there are differences among countries in terms of the size and maturity of their industry. Each country implements its individual policies and regulations at its discretion accordingly. In this sense, the value of USM is influenced by its past operational environments, including its former operators [6,40], standards of previous aviation authorities [21,40], traceability [6,21,40,43,44], and accident/incident status [6,40,44]. These factors are grouped into the operational category, reflecting historical operating conditions and documentation status that directly shape buyer confidence.

Third, the value of USM can change with market supply and demand since it is ultimately determined by transactions. Price is the most important factor when determining market value. USM is usually traded at around 60–80% of the price of newly produced parts [1,42], while indirect costs such as tariffs and delivery costs [6,7,44] also need to be considered, as transactions are often inter-regional or international. In addition, entry into this relatively closed market, which is not open to the public, is limited, as market liquidity [6] differs depending on the part. Recently, with the help of advances in IT

technology, online trade platforms are introduced with major stakeholders (ICAO, IATA and OEMs) participating [21,45]. These factors correspond to the market category, capturing transaction-related aspects such as pricing, liquidity, and costs that define the commercial attractiveness of USM.

Finally, USM for aircraft is not generally manufactured but generated as a byproduct of aircraft retirement [21]. This indicates that factors related to the pre-supply stage should be considered to evaluate USM in addition to market supply and demand for parts. Known factors related to aircraft retirement include passenger demand [6,41,46,47], fuel price [6,46,47], aircraft age [6,46,47] and environmental regulations [6,47]. These factors have direct and indirect impacts on the value of USM as they influence the volume of retired aircraft. These factors are classified as the supply category, highlighting external conditions—demand cycles, fuel prices, fleet age, and regulations—that set the effective supply base of USM.

3. Methodology

3.1. Research Framework

This study aims to identify factors that influence the value of aircraft USM, review their priorities with industry experts and practitioners, and gain insights to invigorate the USM market. To this end, this study proposes a three-phase research framework (identification of factors, analysis of their priorities, and derivation of insights), as shown in Figure 2.

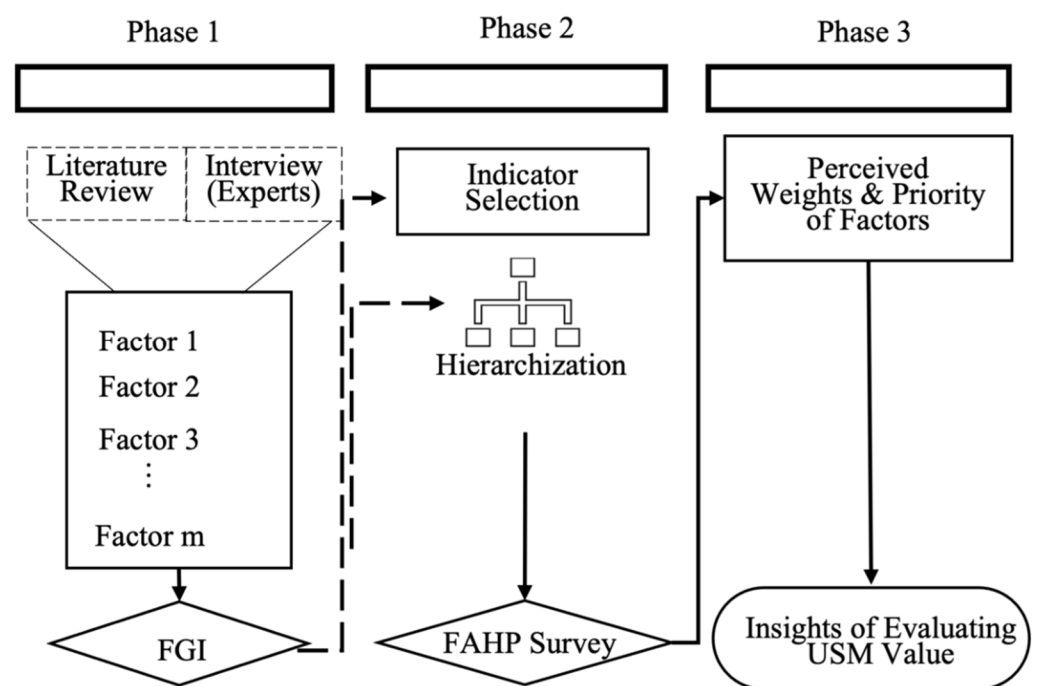


Figure 2. Research framework.

In the first phase, we identify factors that influence the value of USM in aircraft. Factors were initially shortlisted based on the literature review (Section 2.3 “Factors Influencing USM’s Value”) and refined and validated via extensive focus group interviews with twelve industry experts (over ten years of professional experience), and ultimately, sixteen factors in four categories (technical, operational, market, and supply) were selected. Selected factors and categories are described in Table 1.

Table 1. Selected categories and factors of USM value.

Category of Factors		Factors	Description	References
Technical (T)	T1	Maintenance Requirements	Compliance with manufacturer maintenance manuals and mandatory programs, showing whether inspections and repairs have been properly performed	[6,43,44]
	T2	Airworthiness Directive Status	Regulatory directives issued to correct safety issues; compliance confirms the part is free from unresolved safety concerns	[6]
	T3	Maintenance Status	Recorded results of work performed by operators or approved maintenance organizations, reflecting the current technical condition of the part	[6,43,44]
	T4	Aircraft Eligibility	Certification of whether a part can be legally and technically installed on different aircraft types, indicating its applicability	[6,44]
Operational (O)	O1	Former Operator	Information on the previous owner or airline, which signals operational environment and management practices	[6,40]
	O2	Former Aviation Authority	Oversight history from the national or supranational authority that previously regulated the aircraft, affecting reliability of compliance	[21,40]
	O3	Traceability	Documentation proving the complete lifecycle history of the part, ensuring authenticity and regulatory acceptance	[6,21,40,43,44]
	O4	Accident/ Incident Status	Records of involvement in accidents or incidents; parts may remain usable but require additional verification and certification	[6,40,44]
Market (M)	M1	New Part Value	Price of an equivalent new part from the OEM, often serving as the baseline reference for USM valuation	[1,42]
	M2	Market Liquidity	The ease with which a part can be bought or sold, reflecting supply–demand balance and inventory turnover	[6]
	M3	Trade Difficulty	Practical barriers to transactions, including market accessibility and platform availability for buyers and sellers	[21,45]
	M4	Indirect Cost	Extra expenses such as shipping, tariffs, and handling fees, which influence the final cost of transactions	[6,7,44]
Supply (S)	S1	Passenger Demand	Overall air transport demand that drives fleet utilization and retirement	[6,41,46,47]
	S2	Fuel Price	Global jet fuel price, influencing airline operating costs and decisions on fleet replacement or retirement	[6,46,47]
	S3	Aircraft Age	The elapsed time since manufacture	[6,46,47]
	S4	Environmental Regulation	National or international policies requiring eco-friendly operations or retirements	[6,47]

In the second phase of this study, we evaluated the selected factors' priorities for the value of USM. The FAHP methodology was used to assess the importance of key factors and to show how these factors influence the value of USM. FAHP is an extension of the Analytic Hierarchy Process (AHP) multi-criteria-decision-making (MCDM) method that helps decision-makers find the best alternative among multiple options based on different criteria. Despite the widespread use of AHP, this method is often criticized for

its inability to adequately handle the uncertainty and imprecision inherent in translating a decision-maker's perceptions into exact numbers [48,49]. FAHP was developed as an advanced method incorporating fuzzy set theory to address AHP's limitations in dealing with uncertainty and imprecision in decision-makers' judgments [48,50]. The methodology is widely used in the aviation industry across various fields such as aircraft selection, service quality, and environmental assessment [49,51–53] where problems are complex, involving multiple, often conflicting, criteria, both quantitative and qualitative.

This phase was conducted in four steps: defining the problem and decisions to be made; setting up derived factors within control hierarchies; performing pairwise comparisons of the matrix of factor clusters; and calculating the overall ranked weights and priorities.

In the final phase, implications and suggestions were discussed based on the results. This study seeks to offer theoretical and empirical grounds for making strategic decisions; for example, when a USM supplier seeks a higher price or when a buyer of used aircraft parts sets up a purchasing strategy. In addition, the survey results were analyzed to offer insights into how governments or civil aviation authorities should approach policy development to establish and promote the USM market.

3.2. Fuzzy Analytical Hierarchy Process (FAHP)

This study used the FAHP based on Chang's extent analysis method [50] and MATLAB version 2022 function developed by Catak [54]. Let $M \in F(R)$ be a fuzzy number, if following hold:

- (1) There exists $x_0 \in R$ such that $\mu_M(x_0) = 1$
- (2) For any $0 \leq \alpha \leq 1$, $A_\alpha = [x, \mu_{A_\alpha}(x) \geq \alpha]$ is a closed interval.

Here, $F(R)$ denotes a family of all fuzzy sets defined on R (the real numbers).

A Triangular Fuzzy Number (TFN) is represented as $M = (l, m, u)$ where l denotes the lower value, m the most likely value, and u the upper bound. Its membership function $\mu_{M(x)} : R \rightarrow [0, 1]$ is defined as:

$$\mu_{M(x)} = \begin{cases} 0, & x < l \\ \frac{x-l}{m-l}, & l \leq x \leq m \\ \frac{u-x}{u-m}, & m \leq x \leq u \\ 0, & x > u \end{cases} \quad (1)$$

Let $X = \{x_1, x_2, \dots, x_n\}$ be the set of objects (e.g., criteria or alternatives) and $U = \{U_1, U_2, \dots, U_n\}$ the set of goals. For each object x_i and each goal u_i , let

$$M_{g_i}^1, M_{g_i}^2, \dots, M_{g_i}^m, i = 1, 2, \dots, n \quad (2)$$

denote the extent analysis value expressed as a triangular fuzzy number (TFN). And the fuzzy synthetic extent with respect to i th object defined as:

$$\tilde{S}_i = \sum_{j=1}^m M_{ij} \otimes \left(\sum_{i=1}^n \sum_{j=1}^m M_{ij} \right)^{-1} \quad (3)$$

where ' $\oplus$ ' (addition), ' $\otimes$ ' (multiplication), and ' $(\cdot)^{-1}$ ' (reciprocal) are the standard TFN operations.

For two TFNs $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$, the degree of possibility is defined as follows:

$$V(M_1 \geq M_2) = \sup_{x \geq y} [\min(\mu_{M_1}(x), \mu_{M_2}(y))] \quad (4)$$

$$V(M_2 \geq M_1) = \begin{cases} 1, & m_2 \geq m_1 \\ 0, & l_1 \geq u_2 \\ \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}, & \text{otherwise} \end{cases} \quad (5)$$

The degree of possibility that M is not smaller than all M_i is defined by

$$V(M \geq M_1, M_2, \dots, M_K) = V(M \geq M_1) \wedge (M \geq M_2) \wedge \dots \wedge (M \geq M_K) = \min_{1 \leq i \leq K} V(M \geq M_i) \quad (6)$$

Assume $d'(A_i) = \min_{k \neq i} V(\tilde{S}_i \geq \tilde{S}_k)$ for $k = 1, 2, \dots, n$ then the unnormalized weight vector is given by:

$$W = (d'(A_1), d'(A_1), \dots, d'(A_n))^T \quad (7)$$

where and $A_i (i = 1, 2, \dots, n)$ are n elements. After normalization, we obtain the weight vectors.

$$W = (d(A_1), d(A_1), \dots, d(A_n))^T \quad (8)$$

The overall priority weights and ranks were obtained by first mapping linguistic judgments to TFNs via Table 2 and then applying the above equations.

Table 2. FAHP scale.

Linguistic Scale	Triangular Fuzzy Scale	Triangular Fuzzy Reciprocal Scale
Just Equal	(1,1,1)	(1,1,1)
Equally Important	(1/2,1,3/2)	(2/3,1,2)
Weakly Important	(1,3/2,2)	(1/2,2/3,1)
Strongly Important	(3/2,2,5/2)	(2/5,1/2,2/3)
Very strongly important	(2,5/2,3)	(1/3,2/5,1/2)
Absolutely more important	(5/2,3,7/2)	(2/7,1/3,2/5)

3.3. Data Collection

Access to information on USM trades is limited for non-participants in the market, as used aircraft parts are mostly traded in a relatively closed market. Therefore, surveys were conducted by former and incumbent market professionals. Survey participants were given in advance the overview of USM valuation and this study's objectives, as well as basic information on survey questions. Data were collected from 1 July 2022, to 5 August 2022, through an open survey of 118 aviation industry experts and practitioners. Survey questions can be found in Appendix A.

Although fuzzy AHP is used to capture vagueness in judgments, the consistency of pairwise comparisons was still evaluated using Saaty's Consistency Ratio (CR). Following standard AHP practice, we calculated the CR for all responses; 104 responses with $CR < 20\%$ were retained for analysis, while those with higher CR values were excluded as inconsistent. As a result, 14 out of 118 survey samples were discarded due to low consistency. Table 3 reports the demographics of respondents. 45.2% of the respondents had more than 20 years of industry experience. More than half reported working for airlines, where they buy and use aircraft parts. 24% of the respondents worked for government, government agencies, or research institutions related to the aviation industry.

Table 3. Demographics of respondents.

	Characteristics	Observations	Frequency
Work Experience	Less than 5	35	33.7%
	5–9	9	8.7%
	10–14	5	4.8%
	15–19	8	7.7%
	Over 20	47	45.2%
Workplace	Airline	58	53.8%
	Approved Maintenance Organization	21	20.2%
	Others	25	26.0%
Age	20–29	18	17.3%
	30–39	29	27.9%
	40–49	18	17.3%
	50–59	34	32.7%
	Over 60	5	4.8%

4. Results and Discussion

Priorities were calculated based on the survey results. Pairwise comparison matrices were constructed with a fuzzy scale from the closest value to the average of the respondents' answers (see Table 4). Detailed FAHP results, including category priorities, are reported in Tables 4 and 5. Low-level hierarchy factors (sub-category) priorities are calculated in the same way. Factor global priorities are calculated by multiplying each factor priority with the category (high-level hierarchy) priority and are reported in Table 5.

Each category has distinct characteristics in terms of its contribution to the value of USM. The technical category emerged as the most fundamental component in deciding the value of USM. Failure to meet the requirements of the technical category prevents any USM trades from being completed, thus impacting USM value negatively. However, meeting the requirements does not contribute to additional value. On the other hand, the operational category is closely related to a part's condition, most notably how and under what circumstances it was used. Therefore, the degree of satisfaction of operational factors is proportional to the value of USM. The market and supply categories have different characteristics from the first two in that they are linked to market supply and demand of the market and are linked to the macroenvironment. These factors help increase the value of USM; however, they do not have adverse impacts on the value because they cannot affect the essential demand in the USM market.

The Kano model [55], originally developed to classify customer requirements into distinct categories, is employed as a framework to analyze and interpret the FAHP-derived priorities of USM evaluation factors to provide insights into how different attributes influence industry decision-making. By mapping the criteria into Kano categories, we highlight which factors represent essential baseline requirements, which have a proportional impact on perceived value, and which create additional value when present. The characteristics of the four categories are shown in Figure 3 to demonstrate the relationship between the degree to which each category is satisfied and the change in the value of USM. The technical category can be matched to the “must-be,” the operational category to “one-dimensional,” and the market and supply categories to “attractive” in the Kano scale [55]. In the Kano model, “must-be” refers to qualities that cause no positive influence when met but negative influence when not met. It is the basic quality attribute that customers take for granted. If it is missing, it causes strong dissatisfaction, but having it does not greatly increase satisfaction. “One-dimensional” features refer to qualities where customer satisfaction

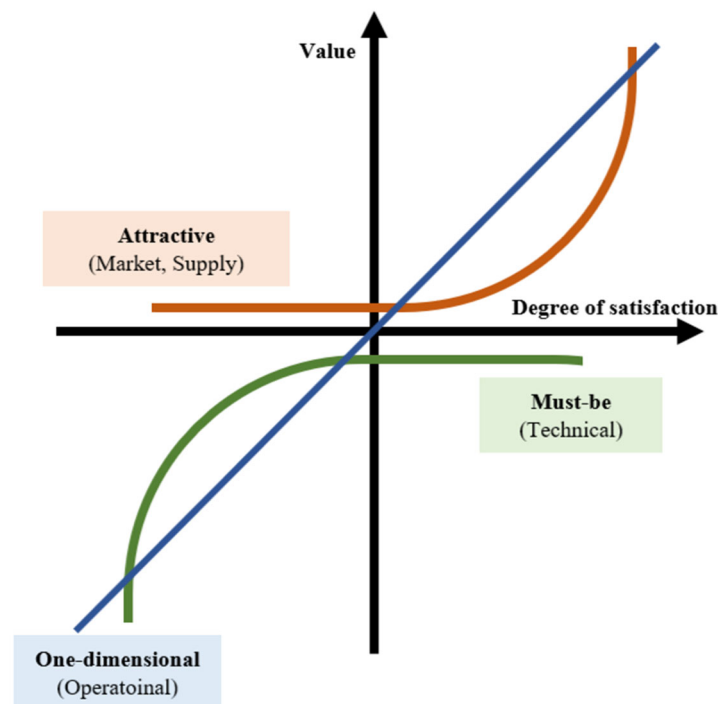
increases as performance improves, and dissatisfaction grows as performance worsens. These features have a linear relationship with satisfaction- meeting them results in positive responses, while failing to meet them leads to negative ones. In contrast, “attractive” qualities delight customers when present but cause little to no dissatisfaction when absent. These attributes do not follow a linear pattern; they create high satisfaction when fulfilled but are not expected by default, so their absence does not lead to disappointment. The Kano model considers “must-be” qualities the most important as they are essential, followed by “one-dimensional” and “attractive.” This priority order of qualities supports the results of this study and suggests that Kano-based implications can be applied as well.

Table 4. Detailed FAHP results by categories.

Global Categories						Priority	Rank
		T	O	M	S		
Global Category	T	(1, 1, 1)	(3/2, 2, 5/2)	(3/2, 2, 5/2)	(3/2, 2, 5/2)	51.96%	1
	O	(2/5, 1/2, 2/3)	(1, 1, 1)	(1, 3/2, 2)	(1, 3/2, 2)	27.64%	2
	M	(2/5, 1/2, 2/3)	(1/2, 2/3, 1)	(1, 1, 1)	(2/3, 1, 3/2)	10.20%	3
	S	(2/5, 1/2, 2/3)	(1/2, 2/3, 1)	(3/2, 1, 2/3)	(1, 1, 1)	10.20%	3
Technical Category (T)						Priority	Rank
		T1	T2	T3	T4		
Technical Category (T)	T1	(1, 1, 1)	(2/3, 1, 3/2)	(1, 3/2, 2)	(1, 3/2, 2)	32.03%	2
	T2	(3/2, 1, 2/3)	(1, 1, 1)	(3/2, 2, 5/2)	(3/2, 2, 5/2)	38.86%	1
	T3	(1/2, 2/3, 1)	(2/5, 1/2, 2/3)	(1, 1, 1)	(1, 3/2, 2)	19.43%	3
	T4	(1/2, 2/3, 1)	(2/5, 1/2, 2/3)	(1/2, 2/3, 1)	(1, 1, 1)	9.68%	4
Operational Category (O)						Priority	Rank
		O1	O2	O3	O4		
Operational Category (O)	O1	(1, 1, 1)	(2/3, 1, 3/2)	(1/2, 3/4, 1)	(2/3, 1, 3/2)	23.02%	3
	O2	(3/2, 1, 2/3)	(1, 1, 1)	(2/3, 1, 3/2)	(2/3, 1, 3/2)	24.88%	2
	O3	(1, 4/3, 2)	(3/2, 1, 2/3)	(1, 1, 1)	(1, 3/2, 2)	29.45%	1
	O4	(3/2, 1, 2/3)	(3/2, 1, 2/3)	(1/2, 2/3, 1)	(1, 1, 1)	22.64%	4
Market Category (M)						Priority	Rank
		M1	M2	M3	S		
Market Category (M)	M1	(1, 1, 1)	(2/3, 1, 3/2)	(1, 3/2, 2)	(1, 3/2, 2)	30.21%	1
	M2	(3/2, 1, 2/3)	(1, 1, 1)	(2/3, 1, 3/2)	(2/3, 1, 3/2)	24.77%	2
	M3	(1/2, 2/3, 1)	(3/2, 1, 2/3)	(1, 1, 1)	(2/3, 1, 3/2)	22.51%	3
	M4	(1/2, 2/3, 1)	(3/2, 1, 2/3)	(3/2, 1, 2/3)	(1, 1, 1)	22.51%	3
Supply Category (S)						Priority	Rank
		S1	S2	S3	S4		
Supply Category (S)	S1	(1, 1, 1)	(3/2, 2, 5/2)	(2/3, 1, 3/2)	(1, 3/2, 2)	33.57%	1
	S2	(2/5, 1/2, 2/3)	(1, 1, 1)	(2/3, 1, 3/2)	(2/3, 1, 3/2)	20.07%	3
	S3	(3/2, 1, 2/3)	(3/2, 1, 2/3)	(1, 1, 1)	(2/3, 1, 3/2)	24.52%	2
	S4	(1/2, 2/3, 1)	(3/2, 1, 2/3)	(3/2, 1, 2/3)	(1, 1, 1)	21.83%	4

Table 5. Category and factors' priority and rank.

Category of Factors	Priority	Rank	Factors	Global Priority	Global Rank
Technical (T)	51.96%	1	T1 Maintenance Requirements	16.64%	2
			T2 Airworthiness Directive Status	20.19%	1
			T3 Maintenance Status	10.10%	3
			T4 Aircraft Eligibility	5.03%	8
Operational (O)	27.64%	2	O1 Former Operator	6.36%	6
			O2 Former Aviation Authority	6.88%	5
			O3 Traceability	8.14%	4
			O4 Accident/Incident Status	6.26%	7
Market (M)	10.2%	3	M1 New Part Value	3.08%	10
			M2 Market Liquidity	2.53%	11
			M3 Trade Difficulty	2.29%	13
			M4 Indirect Cost	2.29%	13
Supply (S)	10.2%	3	S1 Passenger Demand	3.42%	9
			S2 Fuel Price	2.05%	16
			S3 Aircraft Age	2.50%	12
			S4 Environmental Regulation	2.23%	15

**Figure 3.** Kano model application.

The technical category was recognized as the most essential in determining the value of USM. The category includes four factors: maintenance requirements (T1), airworthiness directive status (T2), maintenance status (T3), and aircraft eligibility (T4). Table 5 summarizes the weight analysis and rank results for all factors.

T2 and T1 were identified as the most important determinants of USM value. Appropriate maintenance should be conducted according to related requirements such as regulations, procedures, and maintenance manuals [56,57]. Unexpected or accumulated defects can occur on aircraft or parts; in this case, aviation authorities issue airworthiness directives to eliminate the associated risks. Aircraft owners/users must implement notices within a specified time frame to ensure safety [56,57]. Survey participants, as industry professionals, assigned the highest significance to T2 and T1, as compliance with airworthiness

directives and maintenance requirements is a basic prerequisite for utilizing USM. In addition, the more complicated the requirements for maintenance or airworthiness directives are, the more managerial and technical resources are required. For the sustainability of the business, aircraft operators should try to minimize maintenance costs, and the same principle applies to the maintenance of aircraft parts. Therefore, it is necessary to review aircraft parts to determine whether maintenance costs are lower than replacement costs [58,59]. When maintenance costs exceed the expected costs of using replacement parts, consumers of aircraft parts must evaluate the value of acceptable alternatives. As for maintenance status (T3), one of the ways to measure aircraft value is through the maintenance status of high-value components (e.g., engine, auxiliary power unit, and landing gear) using the remaining life on life-limited parts or the time since the last overhaul in the aircraft leasing [43,44,60], which was assessed as the least significant factor in the technical category. Aircraft, as with other means of transportation, use some interoperable parts. In general, as the compatibility of a part increases, operators have more options for parts available; thus the value of USM is expected to decrease. However, in the case of aircraft, parts that have critical influence on safety or airworthiness have low eligibility due to certification issues or technical considerations. Parts with high eligibility usually do not impact airworthiness. They are simple and common, such as bolts and nuts, and their prices are unlikely to be very high for new products. As a result, aircraft operators prefer to use new products over USM for parts with high eligibility because they are inexpensive, and for parts with low eligibility because they are closely related to airworthiness. This can explain why T4 was perceived as less important in the technical category.

The operational category includes former operator (O1), former aviation authority (O2), traceability (O3), and accident/incident status (O4). The operational category factors showed no significant difference in importance. Before installing aircraft parts, their history and traceability should be evaluated to determine how credibly they were historically managed [6,60]. It is important to check the former operator (O1), former aviation authority of the aircraft (O2) and traceability (O3) to determine how well aircraft (or aircraft parts) were managed and assess their current condition. Accident/incident status (O4) ranked slightly less important than other factors in the category. Its relatively low importance can be attributed to the fact that aircraft parts can be reused even after an accident/incident if they receive certification through inspection [6]. Using parts from aircraft that were involved in an accident/incident affects USM value negatively, as it requires time and resources to obtain mandatory certification to ensure the safety of the parts.

The market category includes new part value (M1), market liquidity (M2), trade difficulty (M3), and indirect cost (M4). New part value (M1) was shown to be the most important market factor. This is because USM parts are evaluated based on the new part value once depreciation and other modifications are accounted for [43,61]. Market liquidity (M2) of USM supply and demand is a major factor in USM inventory management. Market liquidity should be managed to support an active market; market illiquidity leads to congestion in inventory and a subsequent decrease in USM value [21]. Trade difficulty (M3) and indirect costs in transactions (M4) ranked lower in terms of priority in the market category factors. Trade difficulties (M3) can have an indirect impact on USM value if trade environments are switched from face-to-face to online or mobile platforms; however, the influence will be somewhat limited. Indirect cost (M4) includes tariffs and delivery costs, but their impact is also small because most USM transactions are exempt from tariffs under international agreements such as the WTO Agreement on Trade in Civil Aircraft, and primary customers are usually air transport companies that handle their own delivery.

The priority of the supply category is the lowest among the four. The results placed passenger demand (S1) first, followed by fuel price (S2), aircraft age (S3), and environ-

mental concerns (S4). Passenger demand (S1) is closely related to air transport volume, which is determined by fleet volume. Therefore, changes in passenger demand affect aircraft operations. A decrease in passenger demand leads to increased aircraft retirements, increasing the overall supply in the USM market [21]. Moreover, it can negatively impact USM demand by increasing aircraft storage and ground time. Fuel price (S2) accounts for a significant portion of direct operating costs; therefore, changes in fuel price can impact the size of the budget allocated to purchase parts. However, S2's impact is not critical because most airlines hedge jet fuels through long-term contracts as a risk management practice. As for aircraft age (S3), older aircraft require more maintenance tasks with a broader scope [43]. Therefore, maintenance costs increase depending on the model year; however, as is predictable, the costs are already accounted for at the time of the introduction of the aircraft as fixed commitments. Finally, environmental regulations showed the lowest global priority of all the factors. The result indicates that industry professionals see little reduction in emissions even if airlines retire old aircraft and replace them with newer, more environmentally friendly ones to comply with environmental regulations (S4). This is consistent with a previous study showing that early peak retirement age of aircraft had no significant impact on carbon reduction [47].

The results provide insights and strategies for market participants. Part traders and owners, i.e., sellers, need to minimize the negative impact on aircraft USM value by putting top priority on managing maintenance requirements, airworthiness directives, and maintenance status. Then, they can focus on increasing USM value by providing better traceability. For buyers such as aircraft operators and approved maintenance organizations, they are required to check the general technical and operational aspects of parts first. They are expected to make an aircraft USM purchasing decision based on new part value after an economic and sustainable cost–benefit analysis.

5. Conclusions

This study identified and prioritized the key determinants influencing the valuation of aircraft USM by applying the Fuzzy Analytics Hierarchy Process (FAHP). Sixteen factors (maintenance requirements, airworthiness directive status, maintenance status, aircraft eligibility, former operator, former aviation authority, traceability, accident/incident status, new part value, market liquidity, trade difficulty, indirect cost, passenger demand, fuel price, aircraft age, environmental regulation) in four categories (technical, operational, market and supply) were derived through a literature review and expert focus group interviews. The results indicated that the technical category represents the most fundamental dimension, followed by operational, market and supply categories. The results were consistent with the value-satisfaction framework of the Kano model. The technical category corresponded to the “must-be” dimension, emphasizing its essentiality in USM valuation. The operational category aligned with “one-dimensional” features, while the market and supply categories were classified as “attractive” attributes, respectively. Maintenance requirements, airworthiness directive and maintenance status were identified as the most critical determinants, while traceability, former operator, former aviation authority, and new part value also play significant roles in shaping USM prices. Securing maintenance requirements, airworthiness directive and maintenance status is critical for sellers, whereas new part value information can assist buyers in making purchasing decisions.

This study demonstrated that maintenance is especially important in determining aircraft USM value. The findings emphasize the necessity of internationally harmonized accreditation systems for approved maintenance organizations and standardized aircraft dismantling procedures to reduce uncertainty and enhance transparency in USM transactions. The ICAO has presented a global roadmap to standardize the systems of approved

maintenance organizations globally by 2024 and is advising governments to revise related standards and recommendations accordingly [62,63]. If implemented as planned, this policy will help unify differing national regulations and reduce operational inconsistencies in USM valuation. In parallel, the global aviation industry is developing an approved maintenance organization management system to authorize qualified organizations for aircraft dismantling [64]. This initiative aims to establish international guidelines for dismantling, enhance traceability, and revitalize the circulation and trade of USM [64]. Once the ICAO's proposed accreditation framework is adopted, the operational category—previously “one-dimensional” in the Kano model—could evolve into an “attractive” attribute, improving market satisfaction and controllability of USM value. However, significant challenges remain due to differences in regulatory structures, budgets, technical capacity, and workforce quality across countries.

As evidenced by ICAO and CORSIA, this study ultimately supports the transition of airlines toward more environmentally responsible practices and aligns with the growing emphasis on Environmental, Social, and Governance (ESG) in the global aviation industry.

This study proposes a new guideline for evaluating the value of USM and aims to invigorate the USM market, which has been unstable in trade volume and price. Although this research provides structured decision criteria and weighted priorities, several limitations should be acknowledged. First, the derived factor weights are relative rather than absolute, making it difficult to apply the findings directly to USM price modeling. In addition, the respondent pool—primarily professionals from the South Korean aviation industry—may not fully represent global market participants, such as international lessors or dismantling firms.

Future studies should expand on this work by integrating quantitative transaction data with FAHP-derived weights to develop robust valuation models tailored to the diverse characteristics of aircraft components. Comparative analysis across regions or aircraft types could also help refine valuation frameworks. These efforts will enhance the practical applicability of USM valuation and contribute to a more transparent, standardized, and sustainable circular economy in the global aviation industry.

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Institutional Review Board Statement: This study is waived for ethical review by Institution Committee. According to the Bioethics and Safety Act of Korea (Article 15) and its Enforcement Rule (Article 13), certain categories of research are exempt from Institutional Review Board (IRB) review. Specifically, research conducted through surveys, interviews, or observation of public behavior may be exempt when: The research involves no more than minimal risk to participants, The study does not collect personally identifiable information, and The study does not address sensitive personal data (such as health, criminal, or sexual information). Our study was based solely on a professional survey, did not involve the collection of any sensitive or identifiable personal data, and posed no more than minimal risk to the participants. Therefore, it qualifies as IRB-exempt research under Korean law.

Informed Consent Statement: Informed consent for participation was obtained from all subjects involved in the study. The following statement was included at the beginning of the survey to inform participants and obtain their consent: Dear Participant, My name is Jaehyun Cho, a Master's student in Techno-Management at Korea Aerospace University. I would like to sincerely thank you for taking the time to participate in this survey despite your busy schedule. This survey aims to identify and

prioritize the key value factors of Used Serviceable Materials (USM) in the aviation industry. It will be conducted anonymously, and all responses will be used solely for research purposes in accordance with Articles 33 (Confidentiality Protection) and 34 of the Statistics Act. We assure you that your answers will not be used for any purpose other than academic research. Advisor: Woon-Kyung Song
 Researcher: Jaehyun Cho, Researcher, Korea Institute of Aviation Safety Technology (KIAST) Contact: +82-32-727-5761 / z5688@kiast.or.kr.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

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Appendix A. FAHP Survey

The purpose of this survey is to analyze Determining Factors of Aircraft Used Serviceable Material (USM)'s Value. Please answer by referring to the description of the categories and factors provided. Your responses will be confidential and will never be used for purposes other than research.

Questionnaires for demographic information

Please respond to the following demographic questions.

1. Age
 ① 20–29 ② 30–39 ③ 40–49 ④ 50–59 ⑤ Over 60
2. Work Experience
 ① Less than 5 years ② 5–9 years ③ 10–14 years ④ 15–19 years ⑤ Over 20 years
3. Work Place
 ① Airline ② Approved Maintenance Organization ③ Others ()

Questionnaires for Value Factors of USM

Please respond to the following to evaluate the importance of the 4 major factors and 16 sub-factors on the value of used aircraft parts. Please check the explanation of the factors presented in the question and check the evaluation scales and linguistic terms according to the table.

Evaluation scales	Linguistic terms
①	Equally important
③	Moderately important
⑤	Important
⑦	Very important
⑨	Absolutely important
② ④ ⑥ ⑧	Intermediate value

- (1) Please compare the importance of each category considering their impact on the USM value.

1. Technical Category (T)
 Category related to manufacturers and national requirements for airworthiness.
2. Operational Category (O)
 Category related to the operating environment, standards and reliability.
3. Market Category (M)
 Category related to characteristics of USM Market
4. Supply Category

Table A1. Category that influences the supply of used aircraft parts on the market.

Assessment	Poor←Medium→Good																	Assessment
T	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	O
T	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	M
T	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	S
O	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	M
O	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	S
M	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	S

(2) Please compare the importance of each factor considering their impact on the USM value.

Appendix A.1. Technical Category (T)

1. Maintenance Requirements (T1)

Requirements from maintenance manuals and maintenance programs

2. Airworthiness Directive Status (T2)

Issuing documents and direction for restoring an acceptable level of safety

3. Maintenance Status (T3)

Maintenance result from operator and Approved Maintenance Organization

4. Aircraft Eligibility (T4)

Table A2. Capable of being used or installed in another type of aircraft.

Assessment	Poor←Medium→Good																	Assessment
T1	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	T2
T1	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	T3
T1	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	T4
T2	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	T3
T2	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	T4
T3	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	T4

(3) Please compare the importance of each factor considering their impact on the USM value.

Appendix A.2. Operational Category (O)

1. Former Operator (O1)

Previously owner or user

2. Former Aviation Authority (O2)

Previously national or supranational organization for aircraft safety

3. Traceability (O3)

Documents or statements to prove part's history from back to birth

4. Accident/Incident Status (O4)

Table A3. Documents or statements related to accident/incident information during operation.

Assessment		Poor←Medium→Good																Assessment	
O1	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	O2	
O1	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	O3	
O1	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	O4	
O2	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	O3	
O2	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	O4	
O3	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	O4	

(4) Please compare the importance of each factor considering their impact on the USM value.

Appendix A.3. Market Category (M)

1. New Part Value (M1)

Value of condition “new” part form original equipment manufacturing

2. Market Liquidity (M2)

Part’s inventory management characteristics

3. Trade Difficulty (M3)

Markets are comfortable for traders and customer

4. Indirect Cost (M4)

Table A4. Additional costs for shipping, paying tax, etc.

Assessment		Poor←Medium→Good																Assessment	
M1	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	M2	
M1	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	M3	
M1	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	M4	
M2	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	M3	
M2	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	M4	
M3	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	M4	

(5). Please compare the importance of each factor considering their impact on the USM value.

Appendix A.4. Supply Category

1. Passenger Demand (S1)

Number or size of air transportation demand for traveling, freight age, etc.

2. Fuel Price (S2)

International price for jet fuel

3. Aircraft Age (S3)

The number of days elapsed from manufactured date

4. Environmental Regulation (S4)

Table A5. Policy or guideline affecting aviation industry, related to eco-friendliness and sustainability.

Assessment	Poor←Medium→Good																	Assessment
S1	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	S2
S1	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	S3
S1	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	S4
S2	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	S3
S2	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	S4
S3	⑨	⑧	⑦	⑥	⑤	④	③	②	①	②	③	④	⑤	⑥	⑦	⑧	⑨	S4

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