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Research on the Sustainable Development System of the Low-Altitude Economy Industry from the Perspective of New Quality Productive Forces

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Abstract

This paper systematically examines the core of new quality productive forces underpinning the sustainable development of the low-altitude economy industry. Based on the Triple Bottom Line theory, it analyzes the interrelationships among various factors of new quality productive forces and reveals the underlying mechanism through which new quality productive forces drive sustainable development in this sector. By employing an integrated Fuzzy Decision-Making Trial and Evaluation Laboratory—Interpretive Structural Modeling (Fuzzy-DEMATEL-ISM) approach, this study establishes a hierarchical structure for sustainable development in the low-altitude economy industry grounded in the logical framework of new quality productive forces. The findings indicate that: (1) the strategic origin layer represents the prerequisite and most critical task for the emergence of the low-altitude economy industry; (2) the technological breakthrough layer constitutes the core competitive strength enabling its development; (3) the resource guarantee layer provides essential resource support for operational sustainability; (4) the institutional synergy layer enhances industrial efficiency through coordinated governance; and (5) the value realization layer signifies the ultimate form of industrial evolution. These research outcomes offer significant forward-looking insights for advancing sustainable development in the low-altitude economy industry.

Keywords: low-altitude economy; new quality productive forces; sustainable development; Fuzzy-DEMATEL; ISM

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1. Introduction

Driven by the dual forces of the global sustainable development agenda and technological innovation, the development models and pathways of emerging industries have become critical issues for countries seeking economic transformation and enhanced competitiveness. As resource constraints intensify and climate change challenges grow increasingly severe, traditional high-consumption and low-efficiency production methods urgently require reform. Strategic emerging industries, characterized by breakthroughs in cutting-edge technologies, are gradually becoming a key force driving high-quality economic development. Within this context, China, based on its developmental stage and domestic and international circumstances, has explicitly proposed the strategically for-

ward-looking concept of new quality productive forces (NQPF). NQPF represent an advanced form of productive forces led by scientific and technological innovation. Their core characteristics are reflected in high technology, high efficiency, and high quality, while their core components include technological innovation, factor reconfiguration, industrial upgrading, institutional support, and green transformation [1]. Cultivating and guiding NQPF can help support the sustainable development of economic, social, and environmental systems [2]. Therefore, NQPF not only provide technological momentum for the development of emerging industries, but also offer a theoretical basis for analyzing industrial sustainability from economic, social, and environmental dimensions. Following this logic, the low-altitude economy (LAE), as a strategic emerging industry, serves as an important carrier and representative application field of NQPF [3]. According to the definition of the Civil Aviation Administration of China, the LAE is a comprehensive economic system supported by low-altitude airspace and based primarily on general aviation [4]. It deeply integrates frontier technologies such as electronic information, intelligent manufacturing, advanced materials, and artificial intelligence. Relevant algorithmic studies have shown that intelligent recognition and human–computer interaction technologies can improve intelligent service capabilities in complex scenarios [5,6]. These technologies provide useful references for the intelligent expansion of LAE application scenarios, such as unmanned aerial vehicle inspection, low-altitude logistics, emergency rescue, and urban governance. As a transformative force in future transportation and logistics systems and a new engine for spatial resource utilization and economic growth, the LAE perfectly aligns with the core characteristics of NQPF.

However, challenges such as inadequate infrastructure, imperfect regulatory policies, and weak integration between technological innovation and application scenarios persist in the development of the LAE, hindering the formation of a systematic sustainable development framework. Therefore, exploring sustainable development pathways for the LAE from the perspective of NQPF not only enriches the theoretical framework of emerging industries but also represents an inevitable choice for the LAE to address current challenges and achieve long-term stable growth. Based on the above analysis, this study examines the underlying productivity logic and action pathways of sustainable development in the LAE industry from the perspective of NQPF, with the aim of providing theoretical explanations and practical references for the sustainable development of the LAE industry. Compared with existing studies, this study does not focus solely on individual influencing factors or partial development pathways of the LAE. Instead, it regards NQPF as a systematic driving mechanism for the sustainable development of the LAE industry. Specifically, based on the Triple Bottom Line theory and the existing literature, this study first identifies the key factors influencing the sustainable development of the LAE industry from the perspective of NQPF across economic, social, and environmental dimensions. Subsequently, the Fuzzy Decision-Making Trial and Evaluation Laboratory method (Fuzzy-DEMATEL) is employed to analyze the degree of influence, causal relationships, and key roles among these factors. Since the LAE industry involves multiple stakeholders, multiple factors, and multi-level relationships, Fuzzy-DEMATEL is suitable for dealing with such complex factor relationships. Compared with general comprehensive evaluation methods or single weight-measurement approaches, Fuzzy-DEMATEL places greater emphasis on the interactions and causal relationships among factors. At the same time, the introduction of fuzzy set theory helps reduce the uncertainty and subjectivity of expert linguistic evaluations, thereby improving the robustness of the analytical results [7]. On this basis, this study further adopts Interpretive Structural Modeling (ISM) to construct a multi-level structural framework. ISM was proposed by J. N. Warfield in 1973 and can reveal the hierarchical structure and logical relationships among factors in complex systems [8], thereby addressing the limitation of Fuzzy-DEMATEL in presenting the internal

hierarchical structure of a system. Compared with single-method approaches, the integrated Fuzzy-DEMATEL-ISM method has certain advantages in terms of the systematicity and robustness of result interpretation, and has been widely applied in studies analyzing influencing factors in complex systems [9,10]. Based on this method, this study further reveals the action mechanism, hierarchical relationships, and construction logic of NQPF in the LAE industry, and constructs a systematic analytical framework for the sustainable development of the LAE industry, providing more explanatory and operational decision-making support for policy formulation and industrial practice.

By integrating NQPF with the Triple Bottom Line theory, this study constructs a Fuzzy-DEMATEL-ISM integrated model to systematically analyze the key influencing factors of sustainable development in the LAE. Its primary contributions are as follows: (1) Methodologically, it innovatively provides an empirical tool for quantifying the complex influencing factors in this industry; (2) theoretically, it constructs a systematic analytical framework that integrates technology-driven and sustainable multidimensional objectives; (3) practically, it reveals the industrial hierarchical structure spanning from strategic origins and technological breakthroughs to value realization, offering clear decision-making bases with distinct stages and pathways for policy formulation and industrial development.

The paper is structured into seven main sections. Section 1 introduces the research background and objectives. Section 2 reviews the literature. Section 3 explains the methodology. Section 4 presents the results. Section 5 discusses sustainable development pathways for the LAE industry. Section 6 constructs the NQPF-driven sustainable development system. Section 7 concludes the study.

2. Literature Review

Although the LAE industry has shown strong development momentum, its long industrial chain and extensive cross-sectoral influence have also generated multiple economic, social, and environmental challenges during its development. Therefore, from the perspective of integrating NQPF with sustainable development, this study systematically reviews the relevant literature and identifies 15 key NQPF-related factors that influence the sustainable development of the LAE industry.

To classify these factors, this study adopts the Triple Bottom Line theory as the theoretical basis for factor categorization. The Triple Bottom Line theory emphasizes that sustainable industrial development should not be evaluated solely by economic performance, but should also consider social responsibility and environmental impact [11]. Its core connotation includes three dimensions: the economic dimension emphasizes industrial efficiency and value creation, the social dimension focuses on social well-being and responsibility fulfillment, and the environmental dimension highlights resource-use efficiency and ecological impacts [12]. In typical applications, this theory is often used to construct sustainability evaluation frameworks by identifying key factors from economic, social, and environmental perspectives and analyzing the synergies and potential trade-offs among these dimensions [13]. This framework is well aligned with the attributes of the LAE industry. The LAE industry is characterized by a long industrial chain, high technological intensity, strong dependence on airspace resources, strict public safety requirements, and increasing demand for green transformation. Therefore, this study integrates NQPF into the economic, social, and environmental dimensions of the LAE industrial chain, thereby constructing a holistic analytical framework to explore pathways for achieving sustainable development in this emerging industry.

2.1. Economic Dimensions

2.1.1. New Demand Drivers in the LAE (C1)

NQPF represent a novel paradigm of productivity centered on fostering new demand, which drives high-quality economic development in the LAE through three key mechanisms. First, consumer demand serves as a foundational force: as a strategic emerging industry, the LAE must continuously innovate to stimulate consumer interest in low-altitude products and services, thereby creating and satisfying high-quality demand. This process not only expands market potential but also generates spillover effects across related sectors, fueling broader economic growth [14]. Second, investment demand acts as a critical engine: investment serves as a primary driver of economic expansion, and by injecting fresh capital into the LAE, new investments strengthen supply-side dynamics by accelerating technological innovation (e.g., drone development, air traffic management systems), enhancing production efficiency through scale economies and advanced manufacturing, and optimizing resource allocation to high-potential subsectors. These effects collectively solidify the material foundation for sustainable industry growth [15]. Third, global demand functions as a dynamic enabler: expanding international openness allows the LAE to identify and cater to niche market demands across regions (e.g., urban air mobility in Southeast Asia, agricultural drone services in Africa), integrate global best practices and cutting-edge business models (e.g., UAM partnerships between Chinese firms and European aerospace companies), and diversify export markets, reducing reliance on domestic demand cycles.

2.1.2. Low-Altitude Technological Innovation (C2)

NQPF emphasize the central role of technological innovation and regard breakthroughs in key technologies as an important driver for improving production efficiency, cultivating emerging industries, and promoting industrial transformation and upgrading [16]. Accelerating the cultivation of NQPF can effectively enhance the resilience and security of the LAE industrial and supply chains, thereby enabling the industry to gain greater initiative in its development. Driven by NQPF, LAE-related technologies continue to iterate and upgrade [17], promoting the continuous optimization of flight equipment, intelligent control, communication and navigation, and operational services. This process further facilitates the transformation and upgrading of the LAE system and improves production efficiency. The deep integration of technological innovation and industrial application can accelerate the transformation of technological achievements into practical application scenarios [18], promote the coordinated upgrading of low-altitude equipment, operational services, and application scenarios, and further advance the intelligent development of the LAE industry. On one hand, advancing core technological innovations across the low-altitude industrial chain—including R&D and critical component manufacturing, complete aircraft production and system integration, as well as operations and services—supports targeted technological breakthroughs. On the other hand, the large-scale application of cutting-edge technologies such as 5G communication, artificial intelligence, and quantum navigation in unmanned aerial vehicles and electric vertical takeoff and landing (eVTOL) aircraft enables digital transformation of traditional low-altitude industries. This reduces reliance on manual operations, lowers operational costs, and provides sustained momentum for the industrial development.

2.1.3. Financial Innovation (C3)

Financial innovation refers to innovation in financial products, financial service models, and financial technology tools, which can optimize the allocation of financial resources and improve the efficiency of financial services. Existing studies have shown that financial

innovation can strengthen the financial system's capacity to support long-term sustainable economic development by promoting risk sharing and alleviating credit constraints [19]. For technology-intensive emerging industries such as the LAE, financial innovation can also reduce information asymmetry, improve financing efficiency, and enhance the ability of low-altitude enterprises to obtain external financing [20]. Specifically, establishing a robust financial support system enables the LAE to access greater resources, meeting its capital demands across R&D, production, and market expansion phases. Given the industrial characteristics—technology intensity, large-scale investment requirements, long payback periods, and high market demand uncertainty—it necessitates tailored financial support distinct from traditional industries. Through innovative financial instruments, leveraging the guiding role of policy-driven finance, and strengthening credit and financing support for low-altitude enterprises, financial innovation not only encourages venture capital inflows into the sector but also incentivizes firms to increase R&D investment while reducing financing costs and risks. Ultimately, financial innovation aims to optimize investment structures and enhance capital efficiency, channeling funds, talent, and technology toward the LAE to unlock its growth potential.

2.1.4. Policy-Driven Development (C4)

A well-developed policy system helps optimize resource allocation, promote factor mobility, and strengthen the role of industrial policy in supporting the development of emerging industries [21]. In the LAE industry, policy-driven development is mainly reflected in government top-level design, low-altitude airspace management reform, fiscal investment, infrastructure construction, and the cultivation of an industrial ecosystem [22]. The development of low-altitude enterprises largely depends on policy recognition and administrative support. Their access to key resources, such as subsidies, land, demonstration opportunities, and operating permits, is often closely related to government policy priorities [23]. Strong industrial policies can also reduce entry and operating costs, improve market expectations, and promote the agglomeration of capital, talent, and technology in the LAE sector through fiscal investment, infrastructure construction, and industrial chain support. Formulating and refining relevant policies and regulations help standardize market order in low-altitude consumption, prioritize consumer rights protection, strengthen market supervision, and mitigate risks associated with low-altitude activities. Policy-driven development manifests in two primary ways: First, by leveraging pilot experiences from low-altitude airspace management reforms to progressively optimize airspace governance and general aviation approval systems, enhancing operational service quality. Second, by focusing on low-altitude economic growth, policies refine fiscal, tax, financial, land-use, and market access regulations to stimulate market vitality. Additionally, strengthening safety oversight for low-altitude applications and improving policy frameworks are critical to sustainable development.

2.1.5. Airspace Resource Utilization (C5)

Airspace resources refer to the spatial regions above Earth's surface within defined altitudes, serving as intangible economic assets distinct from traditional resources. They provide essential operational space for aircraft and air routes, forming the foundational condition for low-altitude economic activities. As application scenarios like low-altitude logistics and tourism expand, the LAE has emerged as a pivotal domain for airspace resource development [24]. However, rapid growth in low-altitude aircraft numbers risks creating conflicts between limited airspace capacity and escalating flight demands [25]. Currently, low-altitude airspace utilization remains in its infancy, with surging drone numbers intensifying urban air traffic management complexity. Against this backdrop, the development of NQPF aligns with the urgent need for intelligent airspace planning in

the LAE. Intelligent allocation and efficient management of airspace resources hold critical practical and strategic significance for sustainable flight operations [26], creating a safer, more efficient environment for low-altitude economic growth. Safe and efficient airspace utilization enhances flight efficiency, reduces operational costs, and fosters emerging sectors like low-altitude logistics, thereby generating new growth drivers and economic value for the industry.

2.2. Social Dimensions

2.2.1. Regulatory Innovation (C6)

Regulatory systems influence market operations and firm behavior through policy guidance, market supervision, and resource allocation [27]. For the LAE industry, which is highly sensitive to safety risks, regulatory innovation not only affects the orderly entry of market participants, but also shapes the allocation efficiency of key resources, including low-altitude airspace, data, technology, and application scenarios. A favorable institutional environment optimizes regional business conditions, attracts relevant enterprises to local markets, and further influences regional development [28]. The prosperity of the LAE industry relies not only on breakthroughs in aircraft technology but also on an open, inclusive, and adaptable regulatory framework that meets development needs while addressing safety risks [29]. Comprehensively deepening regulatory reforms for the LAE requires establishing a conducive regulatory environment and new production relations aligned with industrial growth. Focused on the LAE, regulatory innovation should address four dimensions: airspace management, operational oversight, market access, and data security. These dimensions correspond to the logic of “liberation, regulation, activation, and trust” and serve as the “four pillars” of sustainable industrial development. Innovating airspace management systems can unlock low-altitude resources, providing physical space for urban air mobility and logistics in remote areas, thereby empowering rural revitalization and equitable public service delivery. Innovations in operational oversight reduce risks of unauthorized flights (“black flights”) while enhancing public trust in emerging technologies, injecting resilience into social governance. Market access reforms lower barriers, stimulate market vitality, create novel employment opportunities (e.g., drone maintenance, airspace coordination), and promote balanced regional economic development. Data security innovations define boundaries for technological applications, prevent societal ethical crises from low-altitude surveillance misuse, and safeguard citizen rights.

2.2.2. LAE Concept (C7)

NQPF emphasize not only technological innovation and efficiency improvement, but also green development and social sharing. Existing studies have shown that NQPF can significantly promote inclusive green growth, as reflected in their role in coordinating economic development, social equity, and ecological protection [30]. This connotation is consistent with the industrial philosophy of the LAE, which pursues safe, green, convenient, and inclusive services. Public trust in the safety, environmental friendliness, and convenience of low-altitude activities is essential for industrial growth. However, as an emerging industry, public awareness and acceptance of the LAE remain low, limiting market vitality for low-altitude consumption [31]. Thus, scientifically disseminating the LAE concept is critical to reducing public skepticism toward technological applications. By fostering societal consensus, engaging the public in discussions, and addressing concerns in real time, the convenience of low-altitude activities can reach more people, dismantling traditional notions that “airspace belongs solely to aviation transport.” Popularizing this concept highlights its broad applications in logistics, agriculture, emergency response, and tourism. Only when low-altitude technologies integrate into daily life and

deliver tangible value can societal endorsement become a lasting driver of sustainable industrial development.

2.2.3. New Production Factors (C8)

New production factors refer to a composite set of factors oriented toward innovative production activities, mainly including innovation-related factors such as technology, knowledge, and data [21]. They are characterized by intangibility, high added value, and dynamic adaptability. For the LAE industry, new production factors are specifically reflected in low-altitude intelligent equipment technologies, flight data, digital platforms, and information infrastructure. The prerequisite for NQPF to drive industrial development lies in the transition from traditional to new production factors. This involves cultivating novel labor forces and means of production aligned with industrial evolution, thereby laying the foundation for NQPF formation [32]. The integration of new production factors, through innovation and optimized resource allocation, fosters emerging industries while facilitating the transformation and upgrading of traditional sectors. This process not only injects robust momentum into the modernization of the LAE but also creates new drivers and value for societal development. Specifically, from the perspective of emerging industries, the infusion of new production factors has spurred the development of low-altitude manufacturing, flight services, infrastructure construction, and other new sectors, generating substantial employment opportunities. Regarding traditional industrial transformation, the essence of industrial upgrading resides in technological advancement [33]. The application of technology, data, and other new production factors enables traditional industries to enhance production efficiency through intelligent and automated renovations. Concurrently, the deep integration of traditional and emerging industries has given rise to low-altitude new business formats such as unmanned aerial vehicle insurance services and supply chain financial services. This industrial convergence not only provides traditional sectors with novel development pathways but also expands application domains for emerging industries.

2.2.4. Talent Development (C9)

The healthy advancement of emerging and future industries relies fundamentally on intellectual support from highly skilled professionals. Within the LAE industry, this reliance has manifested as a critical shortage of qualified technical talent [34]. As industries undergo structural transformation, cultivating workforce capabilities that align with both technological evolution and economic development needs has become an immediate priority [35]. Sustainable high-speed growth in this domain necessitates dynamic synchronization between industrial chains and talent pipelines, as this alignment forms the cornerstone for enhancing regional competitiveness. The LAE's complexity demands particular attention. Spanning multiple sectors with an extended value chain, it encompasses R&D, manufacturing, operational services, and airspace safety regulation. This situation creates an urgent need for professionals who possess both technical proficiency and cross-disciplinary integration capabilities. Consequently, academic institutions must take proactive measures to establish specialized talent development frameworks [29]. These systems should focus on developing individuals with comprehensive knowledge of low-altitude economic principles, thereby creating a robust talent reservoir to support industry expansion. The strategic value of such talent development manifests through two primary channels. First, these professionals accelerate technology commercialization by bridging the gap between academic research and industrial application. Their ability to rapidly translate theoretical breakthroughs into operational solutions shortens innovation cycles and enhances market responsiveness. Second, cultivating high-caliber talent in this field

strengthens national competitiveness on the global stage. In an era of intensifying international rivalry, countries with well-structured talent ecosystems gain decisive advantages in shaping industry standards and capturing market leadership.

2.2.5. Scenario Innovation (C10)

Scenarios refer to the concrete contexts where new technologies, carrier equipment, and business models in the low-altitude domain achieve practical application, constituting the environment for creating economic and social value. These manifest as “LAE +” industrial clusters. Scenario innovation, serving as the core driver of low-altitude economic development, not only propels technological and business model breakthroughs but also generates positive societal impacts. In public service scenarios, technological empowerment enables efficient operations in infrastructure inspection, police aviation, and firefighting rescue [36]. This significantly enhances social governance efficacy while strengthening public safety guarantees, forming a robust backbone for social stability and civilian well-being. In market-driven scenarios, the commercial applications of LAE continue to expand—from streamlined logistics distribution [37] and novel tourism experiences to modernized agricultural pest control [38]. These developments not only stimulate economic vitality but also create substantial employment opportunities, driving industrial upgrading and coordinated regional economic development. The sustained advancement of scenario innovation has positioned the LAE as a critical engine for high-quality societal development. By providing foundational support for constructing smarter, more efficient, and sustainable social operation systems, this industry demonstrates immense value in advancing social progress and improving quality of life.

2.2.6. Collaboration and Sharing (C11)

Collaboration and sharing facilitates optimal resource allocation, cultivates societal cooperative consciousness and culture, and drives holistic social innovation. In R&D activities, enterprises achieving information, knowledge, and technology sharing through collaboration demonstrate significantly higher innovation quality compared to independent R&D efforts [39]. Similarly, in low-altitude flight scenarios, efficient inter-aircraft coordination constitutes the key to unlocking full application potential [40]. For LAE enterprises, first, they must enhance international market participation through global collaboration. By engaging in in-depth exchanges with leading general aviation enterprises worldwide, Chinese firms can absorb and integrate advanced technologies and management models, thereby strengthening China’s competitive positioning in the global low-altitude economic value chain. Second, even greater emphasis should be placed on forging synergies among military aviation, civil aviation, and local governments. This requires deepening the “government-industry-academia-research-application-finance” integration model, promoting comprehensive participation from governmental bodies, industrial players, and research institutions in low-altitude economic development [29]. Through this collaborative paradigm, enterprises can effectively resolve multifaceted challenges in low-altitude industry development, achieving mutually beneficial outcomes while maximizing public welfare. Such an approach forms the cornerstone for sustainable advancement in China’s LAE industry.

2.3. Environmental Dimensions

2.3.1. Digital Information Environment (C12)

The advent of the information age has driven various types of organizations to transform into information-driven institutions [41], enabling them to create value by fully leveraging information resources. With the continuous integration of the LAE and NQPF, the

information environment for low-altitude economic activities has been significantly optimized, and the LAE is rapidly evolving towards intelligence, interconnection, and collaboration [24]. On one hand, digital technology-empowered flight management platforms have greatly enriched the types of low-altitude flight intelligence, significantly enhancing the timeliness and accuracy of flight support information, thereby effectively reducing low-altitude flight risks [42]. On the other hand, the networked nature of low-altitude flight services has significantly enhanced information interaction capabilities among cross-regional flight service stations, improving the efficiency and quality of information sharing, and consequently increasing the efficiency of transit flights. Internet platforms have effectively improved information sharing efficiency from both operational management and service support perspectives, reducing the probability of low-altitude flight accidents and information barriers during low-altitude transit flights, thereby minimizing resource waste and pollutant emissions generated by flight activities and facilitating the green development of the LAE industry.

2.3.2. Green Energy Support (C13)

NQPF are guided by the concept of green development, oriented towards achieving the “dual carbon” goals, and driven by new momentum and elements. Actively promoting the application of green energy in low-altitude aircraft helps reduce atmospheric and noise pollution, providing a foundational guarantee for integrating low-altitude flight activities into urban life and achieving social value reconstruction. Firstly, traditional fuel-driven aircraft have high pollutant emissions and strong noise pollution, which can easily provoke resistance from residents and limit service scenarios. To address this issue, clean, environmentally friendly, and renewable green energy has been widely applied [43], giving rise to new types of aircraft such as eVTOLs [44] and hydrogen-powered drones [45]. The tailpipe emissions and noise pollution of new aircraft using green energy have been significantly reduced, fundamentally eliminating the Not-In-My-Backyard effect. Secondly, in-depth research on the optimal application scenarios and suitability of different energy types in the LAE industry, particularly improving the production capacity of green energy and expanding the applicability of energy carriers, helps enhance the utilization rate of green energy. By using green energy and expanding energy carriers, the pollution of the atmospheric environment caused by flight activities can be mitigated, the level of green development in the LAE can be elevated, positive contributions can be made to environmental protection, and the sustainable development of the LAE industry can be promoted.

2.3.3. Green Product Innovation (C14)

As low-altitude flight activities extend into urban transportation, logistics distribution, and public service scenarios, the environmental externalities they generate, such as noise, energy consumption, and ecological disturbance, have gradually attracted public concern and affected the social acceptance of the LAE industry [46]. Therefore, green product innovation is not only an important way for enterprises to respond to environmental constraints, but also a key pathway for enhancing the market recognition of low-altitude products and improving industrial sustainability. At the consumer level, consumers' preference for the green attributes of products (such as carbon reduction) [47] drives low-altitude enterprises to increase innovation efforts in product design, manufacturing, and logistics to meet market demand for green products. At the government level, many countries provide diverse green subsidies to incentivize enterprises to increase investment in green product research and development [48]. Through policy guidance, financial support, and promotional activities, low-altitude enterprises can be encouraged to optimize design and materials, develop intelligent management systems, and enhance the green

content and competitiveness of products throughout the LAE supply chain. Meanwhile, focusing on the development and implementation of green standards enables the LAE industry to protect the ecological environment while meeting the needs of economic and social development, achieving a win-win situation of economic and social benefits, and facilitating the sustainable development of the LAE industry.

2.3.4. Green Lifestyle (C15)

The 20th National Congress of the Communist Party of China report proposed promoting the formation of green and low-carbon production and lifestyles to facilitate harmonious coexistence between humans and nature. A green lifestyle is defined as a mode of living that actively practices environmental protection concepts in daily life, reduces environmental impact, and promotes sustainable development [49]. It is also an important component of achieving a comprehensive green transformation of economic and social development [50]. The green development of the LAE industry requires enhancing public awareness of green consumption, encouraging the public to choose environmentally friendly low-altitude services and products, and use low-altitude services reasonably to reduce resource waste in the operation of the LAE industry. The promotion of a green lifestyle sends clear signals of green production to the supply market, prompting low-altitude enterprises to pay more attention to green production, reduce resource consumption and pollutant emissions during the production process, and guide enterprises towards green production transformation. Meanwhile, corporate participation in environmental activities and sustained sustainable development policies further stimulate green consumption behavior [51]. This virtuous cycle between the public and enterprises contributes to the achievement of sustainable development goals.

3. Methodology

3.1. Fuzzy-DEMATEL

The Fuzzy-DEMATEL method not only retains the practical and effective advantages of the traditional DEMATEL method [52] in factor identification but also replaces the original precise values with triangular fuzzy numbers. This approach can more comprehensively reflect the true circumstances of the problem, enhancing the credibility of the analysis results and providing more valuable references for managers in decision-making [53]. Fuzzy mathematics, based on fuzzy set theory, is suitable for analyzing problems with vague correlations among elements. It simulates the human brain's processing of fuzzy information by introducing fuzzy set theory and triangular fuzzy numbers to quantify experts' subjective judgments, thereby eliminating subjectivity in expert scoring.

Step 1: Through a combination of literature review, mutual understanding, and consultation with relevant experts, 15 main influencing factors for the sustainable development of the LAE industry based on the core of NQPF were identified and numbered as C1, C2, ..., C15.

Step 2: Seven experts in the field of the LAE were invited to evaluate the interrelationships among the aforementioned 15 factors. As shown in Table 1, linguistic operators were introduced to score the effects of each influencing factor, with "0" representing no influence, "1" representing weak influence, "2" representing moderate influence, "3" representing strong influence, and "4" representing extremely strong influence.

Step 3: After collecting the expert scoring questionnaires, the linguistic operators in the experts' original evaluations were converted into triangular fuzzy numbers using a semantic conversion table and Formula (1).

$$w_{ij}^k = (a_{1ij}^k, a_{2ij}^k, a_{3ij}^k) \quad (1)$$

Table 1. Semantic conversion table.

Linguistic Operators in Experts' Original Evaluations	Meaning	Corresponding Triangular Fuzzy Numbers
0	No impact	(0, 0, 0.2)
1	Weak impact	(0, 0.2, 0.4)
2	Moderate impact	(0.2, 0.4, 0.6)
3	Strong impact	(0.4, 0.6, 0.8)
4	Extremely strong impact	(0.8, 1, 1)

Step 4: Utilize the CFCS (Converting the Fuzzy data into Crisp Scores) method to defuzzify the initial expert scores, thereby obtaining an n-order direct influence matrix **Z** that represents the direct influences among the influencing factors [54]. The defuzzification process is as follows:

- (1) Standardize the triangular fuzzy numbers:

$$xa_{1ij}^k = (a_{1ij}^k - \min a_{1ij}^k) / \Delta_{\min}^{\max} \quad (2)$$

$$xa_{2ij}^k = (a_{2ij}^k - \min a_{1ij}^k) / \Delta_{\min}^{\max} \quad (3)$$

$$xa_{3ij}^k = (a_{3ij}^k - \min a_{1ij}^k) / \Delta_{\min}^{\max} \quad (4)$$

- (2) Standardize the left-hand and right-hand values:

$$xls_{ij}^k = xa_{2ij}^k / (1 + xa_{2ij}^k - xa_{1ij}^k) \quad (5)$$

$$xrs_{ij}^k = xa_{3ij}^k / (1 + xa_{3ij}^k - xa_{2ij}^k) \quad (6)$$

- (3) Calculate the crisp values after defuzzifying the expert scores:

$$x_{ij}^k = [xls_{ij}^k(1 - xls_{ij}^k) + xrs_{ij}^k xrs_{ij}^k] / [1 - xls_{ij}^k + xrs_{ij}^k] \quad (7)$$

- (4) Calculate the average crisp values:

$$z_{ij} = (z_{ij}^1 + z_{ij}^2 + \dots + z_{ij}^k) / n \quad (8)$$

$$z_{ij}^k = \min a_{1ij}^k + x_{ij}^k \times \Delta_{\min}^{\max} \quad (9)$$

- (5) Derive the direct influence matrix:

$$Z = [z_{ij}]_{n \times n} \quad (10)$$

Step 5: Standardize the direct influence matrix **Z** to obtain the normalized matrix **G**.

$$\mu = 1 / \max_{1 \leq i \leq n} \sum_{j=1}^n z_{ij} \quad (11)$$

$$G = \mu Z \quad (12)$$

Step 6: Let **E** be an n-order identity matrix. Calculate the comprehensive influence matrix **T** using the inverse matrix.

$$T = G(E - G)^{-1} = [t_{ij}]_{n \times n} \quad (13)$$

Step 7: Analyze the comprehensive influence matrix **T** to understand the internal structure and interactions among the influencing factors. First, calculate the influencing degree and influenced degree of each factor. The influencing degree represents the sum

of each influencing factor by row, while the influenced degree represents the sum by column. The calculation formulas are as follows:

$$E_i = \sum_{j=1}^n t_{ij} \quad (i = 1, 2, 3, \dots, n) \quad (14)$$

$$E_i' = \sum_{j=1}^n t_{ji} \quad (i = 1, 2, 3, \dots, n) \quad (15)$$

The centrality represents the magnitude of the role played by an influencing factor within the entire collaborative influencing factor system, while the causality represents the causal relationship of interactions among influencing factors within the entire collaborative influencing factor system. If the causality of a factor is greater than 0, it indicates that the factor has a significant effect on other factors and is referred to as a causal factor. Conversely, if the causality is less than 0, it indicates that the factor is greatly influenced by other factors and is referred to as a resultant factor. The calculation formulas for centrality and causality are as follows:

$$P_i = E_i + E_i' \quad (i = 1, 2, 3, \dots, n) \quad (16)$$

$$Q_i = E_i - E_i' \quad (i = 1, 2, 3, \dots, n) \quad (17)$$

3.2. ISM

The DEMATEL method can calculate the importance of a specific factor within the influencing factor system, but it cannot determine the internal associations and hierarchical structure of the factors, making it difficult to effectively manage and control the factors. Therefore, the ISM method is also required to grade the system structure, transforming vague ideas and viewpoints into an intuitive model with a well-structured relationship [54].

Step 1: Calculate the overall influence matrix **F**.

$$F = I + T = \begin{bmatrix} f_{ij} \end{bmatrix}_{n \times n} \quad (18)$$

Step 2: Introduce a threshold value λ to eliminate redundant information and obtain the most streamlined matrix. Based on trial calculations, the threshold calculation model that best fits this study is derived as follows:

$$\lambda = \alpha + \beta \quad (19)$$

where α and β are the mean and standard deviation, respectively, of all elements in the comprehensive influence matrix **T**.

Step 3: Use the threshold value to remove redundant factors and obtain the reachability matrix **M**.

Here, 1 indicates a direct influence between two factors, while 0 indicates no direct influence.

$$m_{ij} = \begin{cases} 1, & f_{ij} \geq \lambda \\ 0, & f_{ij} < \lambda \end{cases} \quad (i = 1, 2, 3, \dots, n) \quad (20)$$

Step 4: Perform hierarchical processing to obtain the reachability set R_i , the antecedent set S_i , and the common set C_i (where C_i is the intersection of S_i and R_i).

$$R_i = \{a_j \mid a_j \in A, k_{ij} \neq 0\}, \quad (i = 1, 2, \dots, m) \quad (21)$$

$$S_i = \{a_j \mid a_j \in A, k_{ji} \neq 0\}, \quad (i = 1, 2, \dots, m) \quad (22)$$

Step 5: Cross out the rows and columns corresponding to the factors included in the intersection of sets R_i and S_i in matrix M .

Step 6: Repeat Steps 4 and 5 until the factor sets for each level are obtained and all factors in the reachability matrix M have been crossed out.

Step 7: Based on the matrix obtained in Step 6, draw a hierarchical structure diagram of the influencing factors.

4. Result Analysis

To design the questionnaire and collect primary data for analysis, we selected seven experts, each with at least 10 years of working experience in their respective fields. The panel comprised two experts from the aircraft R&D sector, two from the government's department of industry and information technology, two from academia specializing in industrial economics, and one from the Civil Aviation Administration.

The draft of the questionnaire was developed through literature review and analysis, and then sent to the 7 experts. If any one of the experts disagrees with the proposed measures in the questionnaire, the authors re-discussed the disputed points with the panel until a unanimous consensus was reached. This refinement process went through several iterations. Finally, one-on-one questionnaire surveys were conducted for data collection to ensure accuracy and prevent potential peer influence.

- (1) We summarized the responses and made corrections to obtain a fuzzy direct influence matrix, which was then processed using the CFCS method to handle the raw data.
- (2) After calculations, we derived the direct influence matrix Z among the influencing factors, as shown in Table 2.

Table 2. Direct influence matrix Z .

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1	0.000	0.410	0.410	0.410	0.136	0.000	0.498	0.145	0.131	0.145	0.000	0.000	0.461	0.169	0.159
C2	0.011	0.000	0.387	0.000	0.410	0.169	0.000	0.447	0.424	0.011	0.206	0.169	0.373	0.011	0.021
C3	0.000	0.373	0.000	0.011	0.424	0.169	0.000	0.410	0.424	0.000	0.155	0.169	0.373	0.000	0.000
C4	0.498	0.424	0.350	0.000	0.136	0.032	0.424	0.136	0.122	0.145	0.021	0.021	0.498	0.169	0.159
C5	0.021	0.000	0.000	0.020	0.000	0.373	0.020	0.322	0.336	0.196	0.359	0.387	0.000	0.145	0.155
C6	0.000	0.011	0.000	0.000	0.031	0.000	0.011	0.045	0.000	0.350	0.424	0.387	0.011	0.350	0.350
C7	0.424	0.373	0.387	0.410	0.131	0.021	0.000	0.145	0.247	0.145	0.011	0.011	0.424	0.169	0.159
C8	0.020	0.000	0.011	0.011	0.322	0.373	0.041	0.000	0.336	0.247	0.387	0.387	0.000	0.145	0.155
C9	0.020	0.000	0.000	0.031	0.336	0.373	0.011	0.336	0.000	0.145	0.387	0.387	0.000	0.159	0.155
C10	0.011	0.011	0.011	0.000	0.011	0.021	0.011	0.000	0.011	0.000	0.000	0.000	0.000	0.424	0.424
C11	0.000	0.011	0.056	0.000	0.000	0.313	0.000	0.011	0.000	0.350	0.000	0.350	0.011	0.387	0.387
C12	0.000	0.000	0.011	0.000	0.011	0.387	0.000	0.000	0.000	0.387	0.424	0.000	0.000	0.350	0.387
C13	0.000	0.461	0.461	0.000	0.373	0.169	0.000	0.336	0.359	0.021	0.169	0.169	0.000	0.021	0.021
C14	0.000	0.011	0.011	0.000	0.011	0.011	0.032	0.011	0.011	0.387	0.000	0.000	0.000	0.000	0.424
C15	0.011	0.000	0.000	0.000	0.011	0.011	0.000	0.000	0.000	0.322	0.000	0.000	0.011	0.387	0.000

- (3) Using the formula from Step 6, we calculated the comprehensive influence matrix T , as presented in Table 3.

Table 3. Comprehensive influence matrix T .

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1	0.061	0.259	0.260	0.170	0.213	0.162	0.200	0.215	0.216	0.217	0.168	0.163	0.274	0.225	0.227
C2	0.012	0.048	0.162	0.008	0.233	0.209	0.011	0.241	0.235	0.162	0.227	0.212	0.151	0.158	0.165
C3	0.009	0.153	0.051	0.011	0.234	0.205	0.011	0.230	0.232	0.152	0.210	0.208	0.150	0.148	0.153

C4	0.199	0.264	0.247	0.055	0.213	0.172	0.183	0.212	0.212	0.221	0.176	0.170	0.284	0.229	0.231
C5	0.014	0.012	0.015	0.012	0.039	0.208	0.016	0.132	0.134	0.200	0.211	0.213	0.011	0.188	0.195
C6	0.003	0.010	0.009	0.002	0.021	0.047	0.008	0.024	0.011	0.209	0.171	0.157	0.009	0.214	0.218
C7	0.176	0.241	0.246	0.167	0.206	0.167	0.059	0.209	0.238	0.217	0.170	0.165	0.255	0.225	0.227
C8	0.015	0.013	0.019	0.011	0.134	0.210	0.022	0.041	0.136	0.218	0.221	0.215	0.013	0.193	0.200
C9	0.014	0.012	0.015	0.015	0.137	0.209	0.014	0.136	0.038	0.188	0.220	0.215	0.012	0.192	0.195
C10	0.005	0.007	0.008	0.002	0.010	0.014	0.007	0.006	0.009	0.043	0.007	0.007	0.004	0.167	0.169
C11	0.002	0.011	0.024	0.001	0.013	0.131	0.004	0.015	0.011	0.201	0.044	0.140	0.010	0.216	0.220
C12	0.002	0.005	0.010	0.001	0.012	0.153	0.004	0.008	0.007	0.216	0.166	0.042	0.005	0.213	0.226
C13	0.009	0.182	0.186	0.007	0.225	0.204	0.010	0.215	0.220	0.158	0.213	0.207	0.050	0.154	0.159
C14	0.003	0.008	0.008	0.002	0.010	0.012	0.012	0.010	0.010	0.152	0.007	0.007	0.005	0.047	0.168
C15	0.005	0.003	0.003	0.001	0.007	0.008	0.003	0.004	0.004	0.129	0.004	0.004	0.006	0.149	0.041

- (4) We further computed the influencing degree, influenced degree, centrality, and causality, with the results shown in Table 4. Column 4 and 5 of Table 4 present the centrality (P) and causality (Q) values for each of the 15 factors respectively, which are crucial for understanding their roles within the sustainable development system of the Low-Altitude Economy (LAE).

On the one hand, centrality indicates the overall importance of a factor within the system. As shown in the table, New Demands (C1, $P = 3.559$), Policy Drivers (C4, $P = 3.534$), and LAE Concept (C7, $P = 3.531$) exhibit the highest centrality values. This suggests that these three factors are the most critical and influential elements in the entire system. They act as the core hubs, connecting and affecting numerous other factors. In contrast, factors like Green Lifestyle (C15, $P = 3.165$) and Green Product Innovation (C14, $P = 3.178$) have relatively lower centrality, implying they are more peripheral or are end-result factors that are influenced by the core drivers.

On the other hand, factors with positive Q values are the primary drivers of the system. Policy Drivers (C4, $Q = 2.603$), New Demands (C1, $Q = 2.498$), and LAE Concept (C7, $Q = 2.402$) have the highest positive causality. This confirms their role as fundamental, initiating forces. Changes in these areas will have a significant ripple effect on the entire system. Low-Altitude Technological Innovation (C2, $Q = 1.005$) and Financial Innovation (C3, $Q = 0.894$) also act as strong drivers, pushing the industry forward. Factors with negative Q values are primarily influenced by others. Green Lifestyle (C15, $Q = -2.421$), Green Product Innovation (C14, $Q = -2.253$), and Scenario Innovation (C10, $Q = -2.218$) show the strongest negative causality. This indicates that they are the ultimate outcomes or goals of the system. Their development is heavily dependent on the successful implementation and interaction of the cause factors in the upper layers. For instance, a widespread green lifestyle (C15) can only be realized after technological breakthroughs (C2), supportive policies (C4), and scenario implementations are in place.

Table 4. Analysis of comprehensive influence matrix.

	D	R	P	Q
C1	3.028	0.530	3.559	2.498
C2	2.234	1.229	3.463	1.005
C3	2.157	1.263	3.420	0.894
C4	3.069	0.465	3.534	2.603
C5	1.599	1.706	3.305	−0.106
C6	1.111	2.111	3.222	−1.000
C7	2.966	0.564	3.531	2.402
C8	1.659	1.697	3.356	−0.037
C9	1.612	1.712	3.324	−0.101
C10	0.464	2.682	3.147	−2.218

C11	1.043	2.214	3.257	−1.172
C12	1.070	2.123	3.193	−1.053
C13	2.197	1.238	3.435	0.959
C14	0.463	2.716	3.178	−2.253
C15	0.372	2.793	3.165	−2.421

The DEMATEL cause-and-effect results are shown in Figure 1, illustrating the centrality and causality of the 15 influencing factors. The diagram is divided into four quadrants. The factors in the upper-right quadrant, including New Demands (C1), Policy Drivers (C4), and LAE Concept (C7), possess both high centrality and high causality. This positions them as the core driving forces of the entire system. Any strategic initiatives should prioritize these factors, as they have the most significant influence on all other aspects of LAE development.

Conversely, the factors in the lower-left quadrant, such as Scenario Innovation (C10), Green Product Innovation (C14), and Green Lifestyle (C15), exhibit low causality and relatively lower centrality. These represent the ultimate outcome factors. They are heavily influenced by the system but have little direct influence on other factors. This confirms that achieving these desirable outcomes is dependent on first addressing the core drivers in the upper-right quadrant.

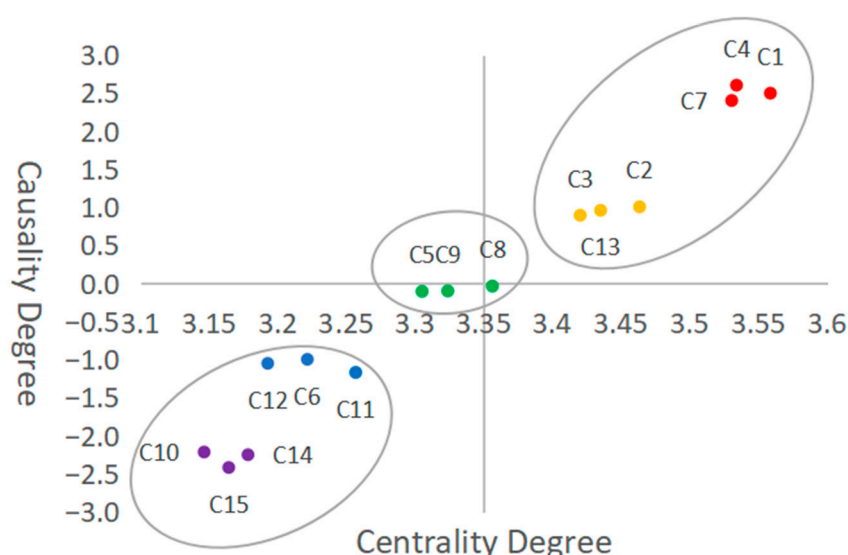


Figure 1. DEMATEL causal diagram.

- (5) Based on the ISM calculation procedures, the reachability matrix M was obtained, as shown in Table 5. In this matrix, “1” indicates a strong relationship between two factors, while “0” denotes the absence or weakness of such a relationship. Taking the first-priority partitioning results as an example, the reachability sets and antecedent sets of the factors are presented in Table 6.

Table 5. Reachability matrix M.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1	1	1	1	0	1	0	0	1	1	1	0	0	1	1	1
C2	0	1	0	0	1	1	0	1	1	0	1	1	0	0	0
C3	0	0	1	0	1	0	0	1	1	0	1	1	0	0	0
C4	0	1	1	1	1	0	0	1	1	1	0	0	1	1	1
C5	0	0	0	0	1	1	0	0	0	0	1	1	0	0	0

C6	0	0	0	0	0	1	0	0	0	1	0	0	0	1	1
C7	0	1	1	0	0	0	1	1	1	1	0	0	1	1	1
C8	0	0	0	0	0	1	0	1	0	1	1	1	0	0	0
C9	0	0	0	0	0	1	0	0	1	0	1	1	0	0	0
C10	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
C11	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1
C12	0	0	0	0	0	0	0	0	0	1	0	1	0	1	1
C13	0	0	0	0	1	0	0	1	1	0	1	1	1	0	0
C14	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
C15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Table 6. First priority classification results.

	Reachable Set R_i	Predecessor Set S_i	$R_i \cap S_i$
C1	C1, C2, C3, C5, C8, C9, C10, C13, C14, C15	C1	C1
C2	C2, C5, C6, C8, C9, C11, C12	C1, C2, C4, C7	C2
C3	C3, C5, C8, C9, C11, C12	C1, C3, C4, C7	C3
C4	C2, C3, C4, C5, C8, C9, C10, C13, C14, C15	C4	C4
C5	C5, C6, C11, C12	C1, C2, C3, C4, C5, C13	C5
C6	C6, C10, C14, C15	C2, C5, C6, C8, C9	C6
C7	C2, C3, C7, C8, C9, C10, C13, C14, C15	C7	C7
C8	C6, C8, C10, C11, C12	C1, C2, C3, C4, C7, C8, C13	C8
C9	C6, C9, C11, C12	C1, C2, C3, C4, C7, C9, C13	C9
C10	C10	C1, C4, C6, C7, C8, C10, C12	C10
C11	C11, C14, C15	C2, C3, C5, C8, C9, C11, C13	C11
C12	C10, C12, C14, C15	C2, C3, C5, C8, C9, C12, C13	C12
C13	C5, C8, C9, C11, C12, C13	C1, C4, C7, C13	C13
C14	C14	C1, C4, C6, C7, C11, C12, C14	C14
C15	C15	C1, C4, C6, C7, C11, C12, C15	C15

- (6) Finally, a hierarchical pathway depicting the interactive relationships among indicators can be constructed from the ISM model, as illustrated in Figure 2. In this diagram, red arrows indicate adjacent-level influences, while green arrows represent cross-level influences. The influencing factors are categorized into five priority tiers: C1, C4, and C7 occupy the highest priority tier; C2, C3, and C13 form the second tier; C5, C8, and C9 constitute the third tier; C6, C12, and C11 belong to the fourth tier; with C14, C10, and C15 positioned at the lowest tier. The construction of a sustainable development system for the LAE industry necessitates a sequential approach starting from the highest priority tier, with meticulous attention to inter-tier connections and transitions, ultimately achieving the value objectives of the final tier.

Figure 2 reveals a clear five-level hierarchical structure, illustrating the logical pathway for achieving sustainable development in the LAE industry. This structure is not arbitrary; rather, it demonstrates a clear dependency chain.

The Strategic Origin Layer (Level 1), containing C1, C4, and C7, serves as the foundation. This implies that before any technological or operational progress can be made, the fundamental issues of market demand, policy support, and public perception must be addressed. These act as the absolute prerequisites.

The arrows pointing from Level 1 to Level 2 (Technological Breakthrough Layer) indicate that strong policy and market demand drive and enable technological and financial innovation. For instance, it is difficult for C2 (Technological Innovation) to advance without the robust support of C4 (Policy Drivers).

This cascading effect propagates upward through the hierarchy. The Value Realization Layer (Level 5) is positioned at the top, signifying that outcomes like green products

(C14) and innovative scenarios (C10) are the final results of a well-functioning system. They can only be realized after the strategic, technological, resource, and institutional layers below them are properly established. Ultimately, this hierarchical model provides a clear, step-by-step roadmap for policymakers and industry practitioners.

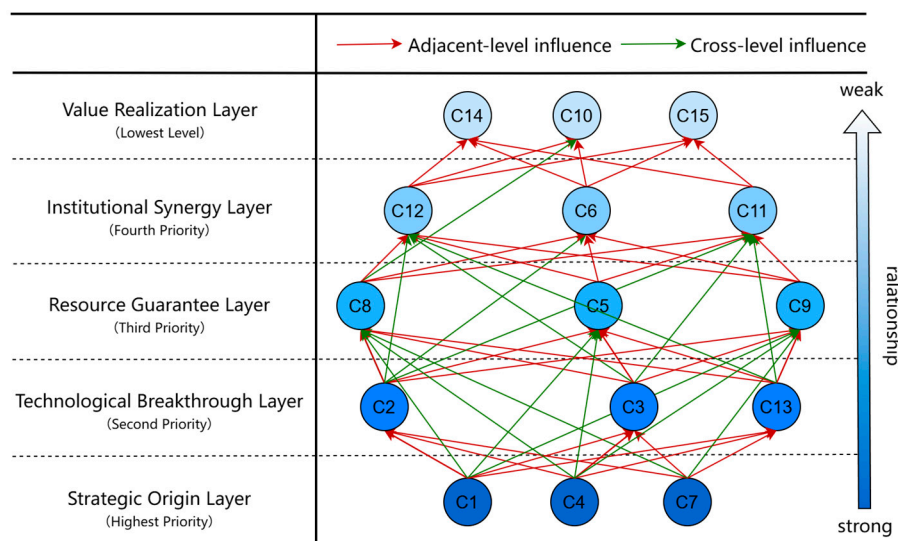


Figure 2. Hierarchical structure result diagram of the ISM model.

5. Discussion

From the perspective of NQPF, this study systematically analyzes the influencing factors of sustainable development in the LAE industry across economic, social, and environmental dimensions. The results show that these factors do not exist in isolation, but have profound structural relationships. These relationships reflect the construction logic of the core of NQPF within the LAE industry and provide actionable pathway support for building a sustainable development system for the LAE industry.

From the perspective of industrial economics, the role of NQPF in promoting the sustainable development of the LAE industry is mainly reflected in a continuous process involving strategic guidance, technological capability enhancement, resource factor allocation, institutional synergy, and industrial value transformation. Specifically, market demand, policy support, and the LAE concept provide demand traction, institutional supply, and cognitive foundations for industrial development. Low-altitude technological innovation, financial innovation, and green energy support enhance the capabilities of low-altitude aircraft manufacturing, sensing and communication, airspace management, and operational services. The optimized allocation of airspace resources, new production factors, and professional talent improves the factor supply structure of the industrial chain. Regulatory innovation, the digital information environment, and collaboration and sharing reduce institutional costs, safety risks, and coordination costs among stakeholders. Ultimately, these capabilities are transformed into sustainable development outcomes of the LAE industry through green product innovation, scenario innovation, and green lifestyles.

It should be noted that the hierarchical division of the ISM model mainly reflects the structural dependence and transmission relationships among factors. It is not a direct description of the chronological sequence of industrial development, nor does it represent a simple ranking of factor importance. Therefore, higher-priority factors mainly play preceding and guiding roles in the system, whereas outcome-oriented factors are more likely

to reflect the results of interactions among multiple driving conditions. In the LAE industry, the Strategic Origin Layer provides demand traction, policy support, and cognitive foundations; the Technological Breakthrough Layer transforms these strategic orientations into technological capabilities, financial support, and green energy conditions; the Resource Guarantee Layer supports airspace opening, data flow, and talent supply; the Institutional Synergy Layer reduces safety risks, institutional costs, and coordination costs through regulatory innovation, digital information environments, and collaboration; and the Value Realization Layer is ultimately manifested in green products, application scenarios, and green lifestyles. Meanwhile, the relationships among layers are not purely one-way. For example, policy support and market demand can directly promote scenario pilots such as low-altitude logistics, emergency rescue, and urban governance; technological innovation and green energy applications can also require improvements in regulatory rules, digital platforms, and collaborative mechanisms; and the supply of airspace resources, data elements, and professional talent directly affects whether LAE application scenarios can be implemented at scale. Thus, the five-layer structure reveals how different factors interact and jointly promote the sustainable development of the LAE industry.

Existing studies have provided valuable discussions on LAE development from the perspectives of policy support [22], airspace governance [24], technological innovation, infrastructure construction [23], application scenario expansion, and green transformation. However, most of these studies focus on specific dimensions or partial pathways of LAE development, while the internal logic through which NQPF systematically drive the sustainable development of the LAE industry across economic, social, and environmental dimensions still requires further clarification. Compared with existing studies, the contribution of this study does not lie merely in identifying a set of influencing factors. Rather, based on the Triple Bottom Line theory and the NQPF perspective, this study incorporates these factors into a unified analytical framework. More importantly, the Fuzzy-DEMATEL-ISM method reveals the causal relationships and hierarchical progression among these factors, thereby not only explaining which factors influence the sustainable development of the LAE industry, but also further clarifying how these factors interact and evolve into a systematic development pathway. Based on this logic, the following discussion is organized around the Strategic Origin Layer, Technological Breakthrough Layer, Resource Guarantee Layer, Institutional Synergy Layer, and Value Realization Layer.

5.1. Strategic Origin Layer

Within the framework, three indicators—New Demand Drivers in the LAE (C1), Policy-Driven Development (C4), and LAE Concept (C7)—constitute the first tier, the Strategic Origin Layer. These indicators, with the highest centrality, serve as prerequisites for the industry's emergence and primary tasks for achieving high-quality development. Actively cultivating new demands in the LAE through expanding consumer, investment, and international demands strengthens the foundational support, critical traction, and dynamic regulatory role of demand in economic development, thereby creating favorable market conditions, solidifying market foundations, and stimulating market vitality. Second, the industry's emergence and growth rely on policy drivers. Implementing a coordinated policy “toolkit” and formulating targeted policies are crucial for mitigating low-altitude consumption risks and nurturing industry leaders. Furthermore, rapid industry development requires societal recognition. Popularizing the concept of the LAE effectively dismantles cognitive barriers, fosters consensus, and provides a robust social foundation and public support for the industry's transition from R&D investment to product application. Thus, economic objectives (new demands and policy drivers) and social objectives (conceptual adoption) jointly form the Strategic Origin Layer. Economic goal attainment necessitates social recognition, while social recognition deepening depends on

economic outcomes from industrial development. These dimensions are interdependent and mutually reinforcing, highlighting the critical economic and social development priorities for the LAE industry. As the starting point of the hierarchical structure, the Strategic Origin Layer first transmits its influence to the Technological Breakthrough Layer by stabilizing market expectations, strengthening policy legitimacy, and improving social acceptance. Meanwhile, this layer also exerts cross-level effects on the Value Realization Layer, as policy support, market demand, and public cognition can directly influence the selection of pilot scenarios, the diffusion of green products, and public participation in low-altitude services.

5.2. Technological Breakthrough Layer

From the NQPF perspective, Low-Altitude Technological Innovation (C2), Financial Innovation (C3), and Green Energy Support (C13) constitute the Technological Breakthrough Layer, representing the industry's hard power. Technological innovation serves as the core driver of low-altitude economic development. Breakthroughs in key technologies accelerate application and industrial chain transformation, addressing "bottleneck" challenges, improving operational efficiency, reducing costs, and creating high-value-added sectors, thereby enhancing competitiveness and fostering new economic growth points. Financial innovation provides stable funding for R&D and industrial upgrading. By implementing financial innovation initiatives and strengthening financial services' role in supporting the real economy, the healthy development of "high-precision" technologies and upstream-downstream industrial chains in the LAE is promoted. Simultaneously, green energy support offers critical environmental backing for sustainable development. Clean energy adoption reduces carbon emissions and enables low-altitude flight integration into urban life, aligning economic and societal value creation. Therefore, while pursuing technological innovation and financial support, strengthening green energy support is essential to ensure synchronous progress in industrial development and ecological civilization construction, achieving organic unity between economic benefits and social value. Under the guidance of the Strategic Origin Layer, the Technological Breakthrough Layer transforms demand traction and policy support into technological capabilities, financial support, and green energy conditions, and further transmits these enabling conditions to the Resource Guarantee Layer. In addition, this layer also exerts cross-level effects on the Institutional Synergy Layer, since new aircraft technologies, digital platforms, and green energy applications require corresponding regulatory rules, information systems, and collaborative governance mechanisms.

5.3. Resource Guarantee Layer

Airspace Resource Utilization (C5), New Production Factors (C8), and Talent Development (C9) collectively form the Resource Guarantee Layer, providing spatial, production, and intellectual resources for industrial operations. Low-altitude flight activities, the industry's core business, depend heavily on scientific airspace allocation. Establishing dynamic, intelligent airspace management systems enables refined utilization, significantly lowering operational costs, improving efficiency, and supporting diverse applications like logistics, emergency response, and urban commuting. Input of new production factors drives industrial resource optimization and spurs innovative business models, improving production and lifestyle efficiency while introducing novel production elements (e.g., 5G, Beidou navigation, new energy materials, intelligent equipment). However, sustained input has exposed contradictions between talent structures and industry demands, revealing lagging talent development and supply shortages. Thus, sustainable development requires strengthening professional talent recruitment and training to build a skilled workforce. This tier demonstrates the critical roles of airspace, factorial, and human resources

in sustainable development, with airspace utilization (economic) and new production factors/talent development (social) underscoring their interdisciplinary importance. The Resource Guarantee Layer receives the enabling conditions formed by the Technological Breakthrough Layer and further converts them into operational resources, including airspace availability, data elements, intelligent equipment, and professional talent. These resources provide an important basis for the Institutional Synergy Layer, as the expansion of low-altitude operations requires stronger regulatory coordination, digital information support, and inter-organizational collaboration. At the same time, this layer also directly affects the Value Realization Layer, because the availability of key resources determines whether application scenarios such as low-altitude logistics, emergency rescue, and urban governance can be implemented at scale.

5.4. Institutional Synergy Layer

Regulatory Innovation (C6), Digital Information Environment (C12), and Collaboration and Sharing (C11) constitute the Institutional Synergy Layer, serving as soft connectors for enhancing industrial efficiency. Safety underpins low-altitude economic development, with risks spanning national, public, and data security. Healthy industry growth necessitates regulatory innovation to refine safety supervision philosophies, models, and systems. Leveraging internet and big data technologies improves information sharing and flight efficiency while reducing resource waste from information silos and accidents. Collaboration and sharing expands markets and drives development by enhancing openness to learn advanced Western technologies and management practices while capturing global consumer markets. It also fosters regional and enterprise-level collaboration, encouraging resource and technology sharing among low-altitude firms. This tier highlights the interplay of social (regulatory innovation, collaboration and sharing) and environmental (digital information) factors, emphasizing that institutional optimization, information flow, and ecological cooperation are vital for sustainable development. Based on the resources provided by the Resource Guarantee Layer, the Institutional Synergy Layer organizes low-altitude operations through regulatory innovation, the digital information environment, and collaboration and sharing, thereby transmitting its influence to the Value Realization Layer. This layer indicates that the LAE industry cannot rely solely on technology and resources for development. Given the safety-sensitive and multi-stakeholder nature of the LAE industry, technological capabilities and resource conditions must be transformed into safe, efficient, and trustworthy industrial operations through institutional coordination.

5.5. Value Realization Layer

Green Product Innovation (C14), Scenario Innovation (C10), and Green Lifestyle (C15) form the final Value Realization Layer, representing the industry's ultimate form. This layer reflects the cumulative outcomes of the preceding layers and shows how technological breakthroughs, resource allocation, and institutional optimization are ultimately translated into practical industrial value. Green product innovation drives sustainable development through eco-friendly R&D and production, aligning with global green transitions. Scenario innovation bridges technology application and societal needs by expanding low-altitude transport, logistics, and emergency response applications, meeting strategic demands and improving public services. Cultivating green lifestyles by promoting eco-conscious consumption and low-carbon travel establishes a virtuous cycle: market demand drives corporate innovation, corporate innovation leads to industrial upgrading, and industrial upgrading facilitates societal transformation. This tier prioritizes environmental and social solutions, urging the industry to meet economic goals while adhering

to triple value standards of environmental friendliness and social benefit. The Value Realization Layer receives the influence transmitted from the Institutional Synergy Layer and represents the final manifestation of the economic, social, and environmental values of the LAE industry. Green product innovation, scenario innovation, and green lifestyles are more likely to emerge when strategic guidance, technological capabilities, resource conditions, and institutional coordination are effectively aligned. Although scenario innovation is often regarded as an important driving force in the practical development of the LAE industry, its large-scale realization depends on upstream conditions such as policy support, technological maturity, airspace availability, regulatory coordination, digital platforms, and public acceptance. Therefore, in the ISM hierarchy, scenario innovation is positioned in the Value Realization Layer, which does not imply that it is unimportant, but rather indicates that it mainly serves as a direct carrier of industrial value and application transformation.

6. NQPF-Driven Sustainable Development System for the LAE Industry

To better understand the theoretical framework of this paper, we further construct a sustainable development system for the LAE industry based on NQPF from a stakeholder perspective, and explain the roles played by various stakeholders in the sustainable development of the LAE industry, as illustrated in Figure 3.

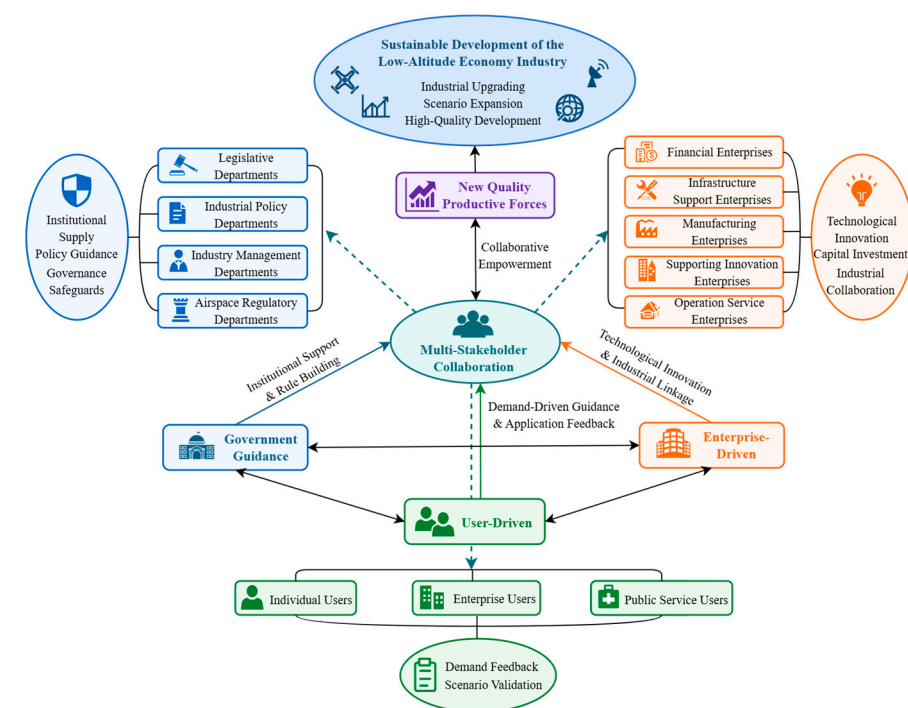


Figure 3. Stakeholder relationship diagram for LAE industry sustainable development. Blue, orange, and green distinguish the government, enterprise, and user dimensions, respectively. Black solid arrows indicate direct influence or interaction, teal dashed arrows indicate collaborative linkages with multi-stakeholder collaboration, single-headed arrows indicate directional influence, and double-headed arrows indicate mutual influence or dynamic feedback.

As shown in Figure 3, the government, enterprises, and users jointly promote industrial upgrading, scenario expansion, and high-quality development of the LAE, embedding NQPF throughout the entire process of sustainable development of the LAE industry.

First, at the government level, the government provides the foundational conditions for the development of the LAE industry through institutional guarantees and rule construction. Legislative departments and industrial policy-making bodies, via regulatory innovation and policy drivers, create a favorable industrial development environment. Industry management departments and airspace regulatory authorities aggregate various factor resources for industrial development. By regulating the behavior of market entities, the government effectively reduces institutional and security risks during the development of the LAE. Meanwhile, government policy support and regulatory rules further influence corporate decision-making and user preferences.

Second, at the enterprise level, enterprises enhance the development level of the LAE industry mainly through technological innovation and industrial collaboration. Various entities participate in industrial development by providing capital support, infrastructure guarantees, scenario operations, technology and product innovation, thereby promoting upstream and downstream synergy across the LAE industry chain and facilitating the transformation of technological achievements. In addition, enterprise practices provide empirical grounds for government institutional improvement, while continuously optimizing product functions, service models, and business paths to meet user needs.

Finally, at the user level, users drive the realization of industrial value of the LAE primarily through demand traction and application feedback. Individual users, enterprise users, and public service users put forward diverse demands from aspects such as daily consumption, production and operations, and public governance, thus promoting the implementation of LAE scenarios. User demand provides direction for enterprise technological innovation and service optimization, and also offers empirical evidence for the government to refine regulatory policies and optimize the allocation of public resources.

Thus, the three parties—government, enterprises, and users—do not function in isolation but rather work together to promote the development of the LAE industry through mutual influence and dynamic feedback. Relying on NQPF, and guided by government leadership, enterprise-driven innovation, and user-led demand, factor integration is achieved, ultimately reaching the goal of multi-stakeholder collaborative empowerment for the sustainable development of the LAE industry.

7. Conclusions

Currently, academic research on the LAE has increasingly recognized the pivotal role of NQPF in driving its development. However, systematic investigations into the sustainable development of the LAE industry remain superficial. This study systematically examines the core mechanisms of NQPF underpinning sustainable development in the LAE industry, analyzing the interrelationships among its economic, social, and environmental factors while elucidating their operational dynamics. By employing an integrated Fuzzy-DEMATEL-ISM methodology, this research constructs a hierarchical framework for sustainable development in the LAE industry based on the logic of NQPF. As a strategic emerging industry, the Strategic Origin Layer represents the foundational prerequisite and paramount task for the industry's inception. The Technological Breakthrough Layer constitutes the hard power driving industrial advancement, while the Resource Guarantee Layer provides essential resource support for operational sustainability. The Institutional Synergy Layer enhances industrial efficiency through systemic optimization, and the Value Realization Layer signifies the ultimate form of industrial development. Overall, the findings indicate that the sustainable development of the LAE industry is not driven by any single factor. Rather, under the logic of NQPF, it is jointly promoted by the hierarchical progression, interaction, and systemic coordination of multidimensional factors.

This study still has several limitations. First, although the Triple Bottom Line theory provides an analytical framework for the sustainable development of the LAE industry from economic, social, and environmental dimensions, it remains insufficient in explaining issues specific to emerging digital and general aviation-related industries, such as airspace safety, data governance, algorithm application, and multi-stakeholder coordination. At the same time, some influencing factors in the LAE industry have cross-dimensional attributes and cannot be fully classified into a single dimension. Second, the identification of influencing factors and the judgment of factor relationships in this study are mainly based on literature analysis and expert evaluation. Although fuzzy set theory and the CFCS defuzzification method can reduce the uncertainty of expert linguistic evaluations, the results may still be affected by differences in expert sample size, professional background, and practical experience. Third, the LAE industry is still in a stage of rapid development, and its technological system, policy environment, airspace management model, and application scenarios are continuously evolving. Therefore, the hierarchical structure constructed in this study mainly reflects the relative relationships among influencing factors at the current stage of development, and the importance of some factors and their interaction mechanisms may change as the industry evolves.

Future research can be further extended in the following aspects. First, dynamic data, longitudinal tracking studies, or system dynamics methods can be used to examine the dynamic evolution of the sustainable development system of the LAE industry. Second, regional data, typical cases, or empirical models can be further incorporated to verify the actual effects of different factors and compare the differences in sustainable development pathways of the LAE industry across regions. Meanwhile, as issues such as artificial intelligence, digital twins, intelligent airspace governance, and public acceptance become increasingly important, future studies can continue to optimize the indicator system to enhance the explanatory power and practical applicability of the proposed framework.

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