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An AHP-TOPSIS Framework for Evaluating the Compatibility of Aircraft Engine Component Technology Schemes

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Abstract

Evaluating the compatibility of technology schemes for advanced aircraft engine components presents significant challenges, especially when comparing schemes derived from identical top-level specifications but varying in design implementation due to different tools or standards. This paper introduces a structured decision-support framework employing the Analytic Hierarchy Process (AHP) combined with the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), specifically tailored for assessing the compatibility of aircraft engine component technology schemes. The expert-driven AHP is utilized to systematically derive priority weights for a multi-dimensional evaluation criteria set reflecting engine technology compatibility requirements. Subsequently, the TOPSIS algorithm ranks the candidate solutions based on their relative performance against these weighted criteria, calculating their Euclidean distance from conceptually ideal and anti-ideal benchmarks. The proposed framework is applied in a detailed case study involving three front fan schemes for an advanced dual variable cycle engine, demonstrating the framework's practical utility and discriminatory power in identifying the most suitable technical scheme. The results demonstrate the framework's capability to effectively discriminate between complex technical alternatives, providing robust quantitative support for critical technology selection decisions, thereby enhancing resource allocation efficiency and accelerating the development pathway for future superior aircraft engines.

Keywords: aircraft engine; decision-support framework; analytic hierarchy process; Technique for Order of Preference by Similarity to Ideal Solution; compatibility evaluation; collaborative airframe-engine design



Academic Editor: Jichao Li

Received: 7 May 2026

Revised: 23 July 2026

Accepted: 27 July 2026

Published: 29 July 2026

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1. Introduction

The development of advanced aircraft engines represents a cornerstone of modern aviation, driving the improvements in aircraft engine performance and design. The critical design principle is ensuring compatibility among the design solutions for engine components, such as compressors, turbines, and combustors, that must function collaboratively, as their interdependencies affect the engine's overall performance, efficiency, and reliability. As early as the propeller era, designers recognized strong performance interdependencies between aircraft motion and engine performance, underscoring the critical importance of compatibility between high-speed rotating propellers and the engine [1]. In 2019, the U.S. Air Force initiated the development of next-generation fighter aircraft, exploring the

compatibility relationships among components of advanced engine systems [2]. The stealth performance requirements of advanced fighter aircraft demand collaborative design efforts to further reduce the radar and infrared signatures of propulsion systems for enhanced compatibility [3–5]. The interdependency between various components within a new generation of aeroengine in thermodynamic principles is increasingly intricate, and each new generation of engines strives to enhance the compatibility between these components. This synergy maximizes overall performance by ensuring that all parts, including combustion chambers, turbochargers, fuel injectors, and cooling systems, work seamlessly together to optimize key performance metrics. Therefore, the selection and integration of these component-level technology schemes are far from isolated decisions; their interdependencies determine critical system outcomes, including power output and operational longevity.

Advanced aircraft with wide-speed-range, cross-domain, and long-endurance capabilities hold significant value in modern aviation. To address these demanding technical requirements, the Aeroengine and Gas Turbine Science Center (referred to as “the Center”) was established in 2018 [6], and in 2020, the Center initiated the Future Aeroengine & Turbine Innovation Project (FATIP) plan to develop a new generation of engines capable of operating across a wide range of altitudes and speeds. Under the FATIP plan, the design of next-generation dual variable cycle engines (as shown in Figure 1) has prioritized component compatibility to meet these ambitious performance goals. Unlike conventional variable cycle engines, the proposed dual variable cycle engine features an innovative large-scale outer bypass combined with a small-scale core architecture, coupled with a three-stream variable-function bypass system and a dual-variable combustor. This highly complex thermodynamic layout enables the synchronous and continuous adjustment of both the bypass ratio (ranging from 0 to 4) and the pressure ratio (modulating from 5% to 100%), while sustaining extreme turbine inlet temperatures up to 2420 K. The pursuit of these ambitious performance goals necessitates a holistic design approach where the overall engine scheme (or overall performance targets) dictates the design objectives for individual component schemes, such as those for the fan, compressor, combustor, and turbine. As illustrated conceptually in the proposed system architecture (refer to Figure 2), each component undergoes a rigorous development process where multiple alternative technology schemes may be generated. The critical challenge then lies in evaluating and selecting component schemes that not only meet their individual design objectives but, more importantly, exhibit a high degree of compatibility and synergy with other components when integrated into the overall engine system. The harmonious matching of these component schemes is paramount, as their collective interactions and interdependencies directly translate to the enhancement of the overall engine’s performance, efficiency, and reliability. Poorly matched component schemes, even if individually optimized, can lead to suboptimal system performance or even detrimental interactions, underscoring the need for a systematic framework to assess and ensure this crucial compatibility.

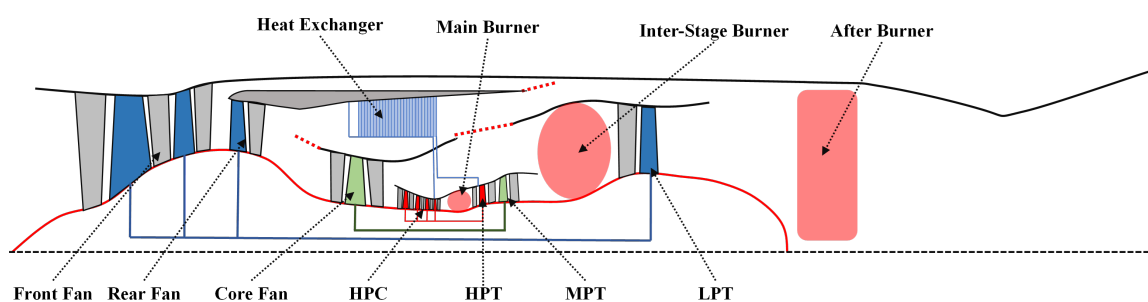


Figure 1. Principle Configuration of Dual Variable Cycle Engine.

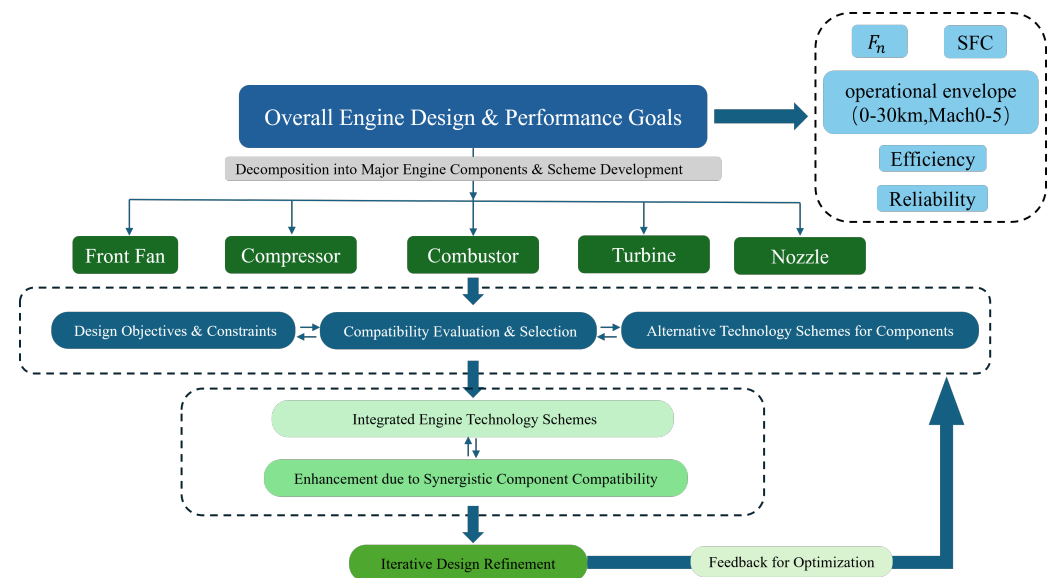


Figure 2. System Architecture of Overall-Component Scheme Interaction and Performance Synergy.

During the initial design phase of the new-generation dual variable cycle engine, the overall engine design team, in collaboration with multi-component and multidisciplinary design teams, developed low-dimensional overall performance models and low-dimensional component performance models, respectively. The overall design team then integrated the component performance models, followed by the verification and calibration of the overall performance. In the forward design process of the engine, the earliest design objectives and constraints for the component teams are typically proposed by the aerodynamic–thermodynamic overall design team and the structural overall design team. Subsequently, the integration process involves matching different components. Given that a variable-cycle engine operates in multiple modes, at the design point, the parameters of the engine’s operating processes are mutually independent. However, at off-design points, the engine’s performance deviates from the design point operation. The performance at off-design points depends on the collective operation of all components, meaning that the operating condition of any single component affects the others. The FATIP plan emphasizes addressing these matching relationships at off-design points to ensure robust engine performance across diverse operating conditions. Since the engine’s components operate in a coordinated, interdependent, and mutually constraining manner, the impact of these interrelationships must be quantified, which is a critical aspect of studying the compatibility between different engine components.

Under the same design requirements by the FATIP plan, the derived technical specifications led to the formulation of the project guidelines at the Center. However, under the guidance of the same technical specifications, variations in the precision of design tools and differences in tool standards used by different design entities resulted in distinct final design schemes for the same technical specifications. Consequently, this necessitated the development of a technical consistency evaluation method to assess the technical schemes derived under the same technical specifications, ensuring a standardized and reliable evaluation process.

Addressing this gap, the core novelty of this study lies in formulating a comprehensive evaluation framework tailored specifically to the operational compatibility of dual variable cycle engines. Traditionally, it has been exceedingly difficult to quantify the weighting of disparate off-design points, such as balancing subsonic cruise efficiency against high-altitude supersonic acceleration, and to systematically trade off conflicting top-level indicators like Thrust and Specific Fuel Consumption. By mapping rigorous

decision-making mathematical logics onto this novel aircraft engine cycle matching problem, our approach successfully translates subjective aerothermodynamic expertise into a standardized, quantitative ranking, providing solid theoretical support for next-generation propulsion system integration.

Crucially, this framework fundamentally differs from conventional engine evaluation methods. Traditional approaches typically focus on performance assessments at a single design point, which struggle to quantitatively aggregate a component's holistic contribution across a wide and complex flight envelope. For a dual variable cycle engine, operational requirements at different flight states often conflict—for example, maximizing thrust during ground takeoff versus minimizing specific fuel consumption during subsonic cruise. The proposed AHP-TOPSIS framework overcomes this limitation by enabling a systematic, multi-point evaluation. By rigorously assessing how different front fan schemes contribute to the overall engine performance across four critical state points (ranging from 0 km/Mach 0 to 23 km/Mach 3.2), this method successfully translates conflicting off-design aerodynamic demands into a standardized, comprehensive compatibility ranking, ensuring the selected scheme provides the optimal performance trade-off across the entire operational spectrum.

The paper is organized into five sections: The Section 1 offers an introduction to the research context and objectives. Section 2 delivers a thorough review of the existing literature on aircraft engine components compatibility and related evaluation methods. Section 3 elucidates the proposed methodology, encompassing the development of a compatibility evaluation indicator system, the formulation of the Analytic Hierarchy Process (AHP) for criteria weighting, and the integration of the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for ranking technology schemes. Section 4 applies the AHP-TOPSIS methodology to a representative case study for the front fan of dual variable cycle engine, providing detailed insights into its effectiveness in assessing component technology compatibility. Section 5 consolidates the study's conclusions, articulates its theoretical and practical contributions, and discusses limitations alongside directions for future research.

2. Related Works

Evaluation methods for the compatibility of technical schemes can be broadly classified into qualitative and quantitative approaches. Qualitative evaluation methods emphasize a descriptive and interpretive approach, focusing on understanding the characteristics, contexts, and implications of technical schemes without relying on numerical data. Such methods often involve detailed investigations through techniques like expert interviews, observational studies, or case analyses to gain a comprehensive insight into the compatibility and feasibility of schemes, beyond mere numerical assessments. Common qualitative techniques include peer review and the Delphi method. Peer review, frequently employed in technical scheme assessments, typically uses a scoring system where experts provide quantitative ratings based on their evaluations, and final decisions are made by ranking these scores after integrating comprehensive feedback from reviewers [7]. The Delphi method is a structured process that iteratively collects and synthesizes expert opinions through multiple rounds of anonymous surveys and feedback, aiming to achieve consensus on the compatibility of technical schemes or to predict their potential for successful integration [8].

Quantitative evaluation methods, in contrast, involve a systematic process of gathering and analyzing numerical data to measure, assess, and compare the compatibility of technical schemes. These methods employ statistical, mathematical, or computational tools to convert data into objective, measurable outcomes, facilitating the testing of hypotheses,

performance comparisons, or decision-making processes. Examples of quantitative techniques include bibliometric analysis [9], principal component analysis [10], the analytic hierarchy process (AHP) [11], and fuzzy comprehensive evaluation [12]. Furthermore, hybrid approaches, which integrate qualitative and quantitative strategies, provide a more nuanced and accurate assessment of technical scheme compatibility by leveraging the strengths of both methodologies [13].

Recent studies have aligned with the shift toward structured, multi-criteria quantitative frameworks in advanced propulsion systems. In component-level optimization, Davari et al. [14] utilized hybrid multi-objective strategies to balance efficiency and emissions in gas turbine combustors. For system-level evaluations, Şahin et al. [15] proposed a hybrid Interval Type-2 Fuzzy AHP-VIKOR-TOPSIS framework for helicopter engines, validating the efficacy of distance-based methods in resolving conflicting aviation criteria. Furthermore, Xu et al. [16] investigated synergistic optimization and intelligent decision-making for managing intricate interdependencies in engine rotor assembly. While these works demonstrate the utility of multi-criteria decision-making (MCDM) in aerospace applications, a systematic methodology to evaluate internal component compatibility under the tight, non-linear thermodynamic coupling of a dual variable cycle engine remains an unaddressed gap that this paper aims to bridge via a targeted AHP-TOPSIS approach.

Given the limited research on the compatibility of aircraft engine component schemes, the evaluation of weapon equipment R&D projects can serve as a technical reference. In such projects, the assessment of technical performance often takes precedence over the evaluation of economic benefits. Therefore, it is critical to focus on the top-level technical indicators of the aircraft engine's overall performance scheme and its systemic attributes within the operational and usage systems. Qu, G. et al. [17] developed an evaluation system for frontier fundamental research projects, integrating AHP and fuzzy comprehensive evaluation (FCE) to balance innovation potential and technical risks. Ilachinski, A. [18] proposed several evaluation criteria for autonomous capability levels, as well as a classification of levels based on task complexity, environmental complexity, and dependency on humans, with the aim of establishing a unified Autonomy Levels For Unmanned Systems (ALFUS) framework.

While existing MCDM methods, such as FAHP, MAUT, and Monte Carlo-based approaches, provide robust frameworks for performance evaluation across diverse engineering domains, they often fail to address the intricate compatibility challenges specific to aircraft engine component schemes, where subtle differences arise from identical top-level specifications implemented through varied design toolchains. The AHP-TOPSIS framework, as developed under the FATIP plan, is uniquely suited to this context, particularly for dual variable cycle engines operating across a wide envelope (0–30 km, Mach 0–5). AHP systematically decomposes hierarchical compatibility criteria (e.g., mass flow balance, pressure balance, power balance, and rotational speed equality), assigning precise weights to reflect their critical interdependencies in the tightly coupled engine system, as validated by expert judgments from the Aeroengine and Gas Turbine Science Center. TOPSIS complements this by ranking schemes based on their Euclidean proximity to an ideal compatibility profile, effectively balancing quantitative metrics (e.g., thrust, specific fuel consumption) with qualitative integration factors (e.g., technological maturity, risk exposure) across key operational states (e.g., 0 km/0 Ma, 23 km/3.2 Ma). This dual approach excels in quantifying the nuanced interplay of component interactions under off-design conditions, critical for variable-cycle engines, ensuring holistic compatibility evaluation across the engine's lifecycle. By enabling iterative refinement of design toolchains and component technologies within the FATIP plan's framework, AHP-TOPSIS directly supports the development of next-generation engines with enhanced efficiency, reliability, and

adaptability to wide-speed-range and cross-domain demands, as demonstrated in the front fan case study.

3. Methodology

In this section, we develop a comprehensive methodology to evaluate the compatibility of technology schemes for aircraft engine components, integrating the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The proposed AHP-TOPSIS framework aims to systematically assess the interdependencies and mutual constraints among components, ensuring alignment with performance objectives and strategic goals [19]. The methodology unfolds in four primary stages: the establishment of an evaluation indicator system, establishment of component characteristic compatibility for dual-variable cycle engines, the application of AHP to determine criteria weights, and the implementation of TOPSIS to rank technology schemes.

3.1. Principles for Establishing the Evaluation Indicator System

Since comprehensive evaluation refers to the assessment of a complex system influenced by multiple factors simultaneously, the collaborative operation of different component schemes within the overall engine design environment is ultimately mapped to component technology compatibility through the overall performance metrics. When verifying compatibility, it is imperative to recognize that certain indicators mutually influence and constrain one another. Therefore, the establishment of evaluation indicators for engine compatibility should strictly adhere to the following principles:

1. Representativeness principle

The indicators must capture the core attributes directly impacting the engine's overarching performance goals (e.g., thrust, fuel efficiency). By focusing on these representative traits, the evaluation avoids peripheral metrics and ensures the selected technology schemes contribute meaningfully to system-level targets.

2. Practicality principle

The data required for each indicator should be feasibly obtainable through standard computational simulations, experimental test results, or expert assessments without prohibitive resource expenditure, ensuring the evaluation remains actionable within real-world engineering constraints.

3. Simplicity Principle

Data sources underpinning the indicators must be clear, transparent, and manageable. This simplicity facilitates effective cross-functional data interpretation, which is crucial when dealing with interdependent components designed by multiple multidisciplinary teams (e.g., aerothermal and structural teams).

4. Independence principle

The indicators must exhibit minimal statistical correlation to prevent redundancy. In highly coupled aircraft engine systems, ensuring independence prevents the overemphasis of a single physical dimension (e.g., thermal limits) at the expense of others, thereby maintaining a balanced and objective compatibility assessment.

By selecting evaluation indicators in accordance with these general principles, a credible and practical evaluation model can be established.

Beyond the general statistical principles, the specific selection of evaluation criteria—encompassing critical operational state points and top-level performance metrics—must strictly align with the extreme aerothermodynamic matching bottlenecks inherent to the engine's physical envelope. In our methodology, the criteria selection dictates that: (1) Operational State Points (Criteria Layer): Selected flight states must represent the absolute boundary conditions of the thermodynamic cycle, such as maximum

mass flow limits (e.g., ground takeoff) or maximum inlet total temperature constraints (e.g., high-altitude supersonic flight). These extreme boundaries act as the most rigorous stress tests for internal component compatibility. (2) Performance Metrics (Sub-criteria Layer): Instead of utilizing internal localized parameters (e.g., adiabatic efficiency or pressure ratios), macroscopic output metrics—specifically Net Thrust (F_n) and Specific Fuel Consumption (SFC)—are selected. This is because any internal component mismatch (e.g., pressure or mass flow imbalance) fundamentally forces the numerical solver to shift the global operating point, causing the engine to operate at sub-optimal cycle conditions. Macroscopically, this friction manifests directly as degraded F_n and elevated SFC. Thus, these two unrestricted metrics are strategically positioned as the ultimate proxy indicators for evaluating systemic compatibility cost.

3.2. Establishment of Component Characteristic Compatibility for Dual-Variable Cycle Engines

The compatibility assessment of dual-variable cycle engines relies on the conditions of collaborative operation within the engine. When the engine operates under specific flight conditions, maintaining constant fuel flow and other geometric parameters ensures that the engine remains in a steady state, where the rotational speed and airflow parameters at each section remain unchanged. Consequently, for the engine to operate stably from design-point to off-design-point conditions, the components must adhere to mutually constraining conditions, collectively referred to as collaborative operating conditions.

1. Balance of engine mass flow

This condition stipulates that the mass flow rate must remain continuous and balanced across all engine components, accounting for bypass and bleed air. Maintaining this continuity prevents aerodynamic instabilities like flow separation or stall, which is especially critical during the dynamic mode transitions of a dual-variable cycle engine.

2. Pressure balance at key engine sections

Pressure profiles at critical component interfaces (e.g., compressor exit to combustor inlet) must match seamlessly. Consistent pressure distribution is essential to prevent aerodynamic inefficiencies and structural stress, ensuring stable operation across wide-ranging flight regimes and mode shifts.

3. Power balance between turbines and compressors components

This condition mandates a strict equilibrium where the work generated by the turbines is sufficient to drive the compressors and accessory mechanisms. Carefully matching turbine power output with compressor power demands is vital for maintaining system efficiency and stability, particularly under off-design conditions.

4. Rotational speed equality constraint for rotating components

Components sharing the same spool must operate at synchronized rotational speeds to ensure mechanical integrity and prevent excessive vibration. Crucially, this constraint acts as an absolute binary physical boundary rather than a relative evaluation indicator; any scheme failing to meet synchronized speed limits is automatically rejected by the numerical solver prior to the multi-criteria scoring process. Importantly, rotational speed equality functions as a binary physical boundary rather than a relative evaluation indicator. Unlike performance metrics that offer a continuous degree of merit for comparison, rotational limits act as absolute pre-evaluation eligibility filters. Any scheme violating these synchronous speed constraints is automatically disqualified by the numerical solver. Consequently, this mechanical constraint is strictly enforced as a simulation prerequisite and is deliberately excluded from the subsequent multi-criteria scoring process.

The mentioned constraint relationships can be described through balance equations. The overall performance model of a dual-variable cycle engine satisfies the constraints of

mass flow balance, power balance, and pressure balance, with the corresponding equations expressed as follows.

To enhance mathematical conciseness, the mass flow and static pressure conservation constraints across all engine stations (formerly treated as isolated equations) are aggregated into generalized vector notations.

The global mass flow conservation across the multi-component flow path is defined as

$$\mathbf{E}_m = \left[\frac{m_k - m'_k}{m_k} \right]_{k \in \mathbf{K}} \rightarrow \mathbf{0} \quad (1)$$

where $\mathbf{K} = \{FF, RF, CF, HPC, HPT, MPT, LPT\}$ represents the set of all core and bypass components, m_k and m'_k denote the theoretical inlet and actual outlet mass flow rates for component k , and $\mathbf{E}_m$ is the mass flow error vector.

Similarly, the static pressure balance at key mixing chambers is generalized as

$$\mathbf{E}_p = \left[\frac{P_{Mix,v} - P'_{Mix,v}}{P_{Mix,v}} \right]_{v \in \{1,2,3\}} \rightarrow \mathbf{0} \quad (2)$$

where $P_{Mix,v}$ and $P'_{Mix,v}$ are the design and measured static pressures at mixing plane v , and $\mathbf{E}_p$ is the relative static pressure deviation vector.

The following power balance equations (Equations (3)–(5)) are derived directly from the fundamental aerothermodynamics and First Principles of gas turbine propulsion [20]. These equations represent the mechanical equilibrium constraints based on the conservation of angular momentum, where the expansion work produced by the turbines must exactly offset the compression work consumed by the fan and compressor spools. The variables η_{FF} , η_{CF} , and η_{HPC} denote the mechanical efficiencies of the respective shaft power transfers. Rather than serving as flexible evaluation criteria, these equations act as rigid physical boundaries within the integrated numerical platform; any candidate scheme that violates these power conservation laws results in an unphysical thermodynamic cycle and is strictly rejected by the convergence solver. Low-pressure shaft power balance equation is given by

$$\frac{L_{LPT} - \frac{L_{FF}}{\eta_{FF}} - \frac{L_{RF}}{\eta_{RF}}}{L_{LPT} + L_{FF} + L_{RF}} = e_{LL} \quad (3)$$

where L_{LPT} represents the power generated by the low-pressure turbine. L_{FF} represents the power consumed by the component. L_{RF} represents the power consumed by the rear fan. η_{FF} represents the mechanical efficiency of component drive system. η_{RF} represents the mechanical efficiency of rear fan drive system. e_{LL} represents the power imbalance error.

Medium-Pressure Shaft Power Balance Equation is given by

$$\frac{L_{MPT} - \frac{L_{CF}}{\eta_{CF}}}{L_{MPT} + L_{CF}} = e_{LM} \quad (4)$$

where L_{MPT} represents the power output from medium-pressure turbine. L_{CF} represents the actual compression work of core fan. η_{CF} represents the mechanical efficiency of power transfer between MPT and CF. e_{LM} represents the normalized power imbalance coefficient.

High-Pressure Shaft Power Balance Equation is given by

$$\frac{L_{HPT} - \frac{L_{HPC}}{\eta_{HPC}}}{L_{HPT} + L_{HPC}} = e_{LH} \quad (5)$$

where L_{HPT} represents the power output from high-pressure turbine. L_{HPC} represents the actual compression work of high-pressure compressor. η_{HPC} represents the mechanical efficiency of power transfer between HPT and HPC. e_{LH} represents the normalized power imbalance coefficient.

The collaborative operating conditions and their governing non-linear balance equations (Equations (1)–(5)) underscore the intrinsic aerodynamic, thermodynamic, and mechanical coupled constraints within the engine system. When alternative technology schemes for a specific component (e.g., individual front fan designs) are integrated into the overall engine architecture, the internal flow capacities, efficiency maps, and pressure ratios alter locally. To satisfy the stringent multi-spool mass conservation, statics pressure matching, and power equilibria under off-design points, the solver of the integrated performance platform must iteratively shift the global joint operating points on the component characteristic maps.

Consequently, any internal compatibility discrepancy or technological mismatch among components manifests macroscopically as a multi-dimensional deviation in the engine's external thermodynamic output parameters. Therefore, net thrust (F_n) and Specific Fuel Consumption (SFC) at critical operational state points are not arbitrary metrics; they serve as optimal structural proxy indicators that comprehensively map and quantify how successfully a component scheme synergizes with the rest of the engine environment while satisfying the baseline equilibrium balance equations. These metrics directly reflect the component scheme's contribution to the engine's ability to meet overall performance targets while maintaining stable, balanced operation as described by the equations in Section 3.2. The AHP framework (Section 3.4) is then used to structure the evaluation based on these critical indicators.

3.3. Conceptual Framework, Simulation Platform, and Definition of Technical Compatibility

To establish a rigorous mathematical and physical foundation for the evaluation, it is critical to formally distinguish between standalone performance evaluation and component technical compatibility within a tightly coupled multi-spool propulsion architecture. A conventional performance evaluation focuses primarily on maximized, decoupled boundary outputs at localized operational design points. In contrast, component technical compatibility within the FATIP framework is defined as the multi-dimensional capability of a specific technological scheme alternative to minimize systemic matching mismatch errors and aerodynamic/thermodynamic cycle degradation across a wide operational envelope (0–30 km, Mach 0–5), while completely satisfying the rigid geometric, mechanical, and flow boundary constraints imposed by neighboring components.

The quantitative indicators (F_n , SFC) subsequently processed by our evaluation model are calculated directly using an advanced engine integrated performance simulation platform. This numerical platform utilizes a 0 D/1 D component-matching method for steady-state aerothermal performance simulation. Thermodynamically, the physical matching constraints are formulated as a high-dimensional non-linear algebraic equation system. The simulation model couples a set of independent numerical trial variables with the 13 residual checking equations (Equations (1)–(5)) representing mass, pressure, and power balances. The resulting non-linear mathematical system is iteratively solved using an advanced Broyden-based multi-variable quasi-Newton numerical solver. The convergence criteria requires residual errors to fall strictly below 10^{-5} .

Under this platform, component compatibility is formulated as a constrained functional mapping, where the engineering validity of the alternative performance profiles is

rigidly bounded by the numerical convergence of the simulation residuals. This compatibility state is expressed as

$$\mathbf{D}_i = \Psi \left(\mathbf{Z}_{w,i} \mid \mathbf{E}_{res} = \{e_{mFF}, e_{mRF}, e_{mCF}, e_{mHPC}, e_{mHPT}, e_{mMPT}, e_{mLPT}, e_{P_{Mix1}}, e_{P_{Mix2}}, e_{P_{Mix3}}, e_{L_L}, e_{L_M}, e_{L_H}\} \rightarrow 0 \right) \quad (6)$$

where $\mathbf{D}_i$ denotes the comprehensive compatibility closeness score for the candidate component scheme i , $\mathbf{Z}_{w,i}$ represents the weighted standardized profile matrix derived via the AHP hierarchy, and $\mathbf{E}_{res} \rightarrow 0$ signifies the vector of absolute algebraic residuals compiled from Equations (1)–(5) that must be driven below the 10^{-5} threshold.

By tying the quantitative decision metrics directly to the numerical convergence of the physical cycle continuity laws, the framework evaluates the synergistic alignment and technical relief that a component alternative provides to the entire operational thermodynamic cycle, rather than relying on isolated localized optimization. Within the scope of this paper, this technical compatibility is tracked through aerodynamic flow capacity matching, thermochemical energy balance, and steady operating stability margins. Other highly coupled multi-disciplinary interactions, including transient mechanical rotor dynamics, closed-loop control system response times, and full-lifecycle fatigue degradation, are explicitly decoupled from the current model and established as contextual boundary parameters reserved for future extensions.

It is crucial to clarify how internal compatibility constraints (mass, pressure, and power balances detailed in Section 3.2) are mathematically mapped into the final evaluation indicators. In our integrated engine simulation platform, internal balance equations do not act as flexible evaluation metrics; rather, they serve as rigid physical boundaries. The Newton-Raphson numerical solver enforces these continuity equations (Equations (1)–(5)). When a specific component technology scheme (e.g., a front fan) is integrated, any inherent aerodynamic mismatch forces the global operating point to shift along the component characteristic maps to satisfy these rigid internal balances. Consequently, poor internal compatibility directly manifests as degraded thermodynamic cycle efficiency at the system level. Therefore, Net Thrust (F_n) and Specific Fuel Consumption (SFC) are selected not merely as standard performance outputs, but as ultimate macroscopic proxy indicators that quantitatively encapsulate the systemic cost of satisfying internal component equilibrium.

3.4. Establishment of the Analytic Hierarchy Process

We employ the Analytic Hierarchy Process (AHP), a systematic methodology originally developed by Thomas L. Saaty in the 1970s [21], to evaluate the compatibility of aircraft engine component technology schemes within the framework of the FATIP plan. AHP is uniquely suited to the complex decision-making demands of dual variable cycle engine design, as it structures the intricate interdependencies of component compatibility criteria, ranging from mass flow balance, pressure balance, power balance, and rotational speed equality, into a hierarchical framework of criteria, sub-criteria, and indicators. Through pairwise comparisons informed by expert judgments from the Aeroengine and Gas Turbine Science Center, AHP quantifies the relative importance of performance metrics (e.g., thrust, specific fuel consumption) and integration factors (e.g., technological maturity, risk exposure) across critical operational states (e.g., 0 km/0 Ma, 23 km/3.2 Ma). This structured approach ensures precise weight assignment that reflects the tightly coupled nature of engine systems, particularly under off-design conditions critical to variable-cycle engines, enabling a rigorous and transparent assessment of component schemes' contributions to overall engine performance.

The detailed computational procedure of AHP, tailored to prioritize compatibility in this context, is outlined as follows:

Step 1. Construction of the Compatibility AHP Hierarchical Model

In the analysis of the decision problem, the objectives, influencing factors, and decision alternatives are systematically categorized into a hierarchical structure based on their interrelationships, comprising three primary levels: the topmost layer, intermediate layers, and the bottommost layer. The topmost layer represents the overarching goal of the decision-making process, such as achieving optimal compatibility among aircraft engine component technology schemes. The intermediate layers consist of criteria and sub-criteria, such as performance synergy, technological maturity, and risk exposure, which mediate the relationship between the goal and the alternatives. The bottommost layer includes the specific technology schemes or measures under evaluation, such as advanced turbine blade materials or novel combustor cooling designs. The Analytic Hierarchy Process (AHP) addresses the challenge of quantifying the relative weights of the bottommost layer elements with respect to the topmost layer goal. By deriving these relative weights through pairwise comparisons, AHP facilitates the ranking of alternatives at the bottommost layer, enabling a structured and principled approach to either select the most suitable scheme from among the alternatives or formulate a prioritized set of options. This process ensures that the decision aligns with the overarching objective while accounting for the complex interdependencies among factors, thereby providing a robust foundation for decision-making in aircraft engine technology compatibility assessments.

Step 2. Construction of Pairwise Comparison Matrix

Within each level of the AHP hierarchy, the relative importance of the elements is evaluated by constructing a pairwise comparison matrix. This matrix is developed based on expert assessments, where the element A_{ij} represents the relative priority of element i over element j with respect to a specific criterion C_m . The criteria at a given level, denoted as $I_1, I_2, \dots, I_n$ are systematically compared to determine their relative significance in contributing to the overarching objective. Experts provide their judgments using a 1–9 scale, as proposed by Saaty, where a value of 1 indicates equal importance, and a value of 9 signifies extreme dominance of one element over another. The resulting pairwise comparison matrix for each criterion is presented in Table 1, with the corresponding scale of relative importance detailed separately in Table 2. This structured comparison ensures that the prioritization of indicators reflects expert consensus while maintaining consistency across the evaluation process.

A critical methodological contribution of this framework is how qualitative engineering expertise is rigorously translated into the quantitative elements (a_{ij}) of the pairwise comparison matrices. Firstly, to ensure authority and mitigate subjective bias, a Delphi-inspired consensus mechanism is employed. An expert panel (comprising senior engineers and chief designers with extensive propulsion integration experience) independently evaluates the criteria. In cases of significant divergence or a Consistency Ratio (CR) exceeding 0.1, anonymous feedback loops are triggered to mathematically refine judgments until convergence is achieved. Secondly, the experts' assignment of Saaty's 1–9 scale is not arbitrary; it is strictly anchored in the physical mission profiles of the engine. For instance, when constructing the sub-criteria matrix comparing Thrust vs. SFC under a takeoff boundary condition, experts rely on the physical consensus that overcoming aircraft inertia dictates maximizing thrust redundancy over fuel optimization. This physical necessity logically translates into a strong quantitative preference score (e.g., 7) for Thrust over SFC. Conversely, under a sub-cruise economic condition, the physical priority strictly inverts to favor SFC. This translation mechanism ensures that the resulting AHP weights are precise numerical reflections of the engine's highly coupled thermodynamic operational logic.

Table 1. Pairwise comparison matrix.

C_m	I_1	I_2	I_3	$\dots$	I_n
I_1	1	A_{12}	A_{13}	$\dots$	A_{1n}
I_2	$1/A_{12}$	1	A_{23}	$\dots$	A_{2n}
I_3	$1/A_{13}$	$1/A_{23}$	1	$\dots$	A_{3n}
$\dots$	$\dots$	$\dots$	$\dots$	1	$\dots$
I_n	$1/A_{1n}$	$1/A_{2n}$	$1/A_{3n}$	$\dots$	1

Table 2. Importance score of element A_{ij} .

Score	Implicature
1	Both indicators contribute equally to the criterion.
$A_{ij} = 3$	The former element indicator is slightly more important than the latter.
$A_{ij} = 5$	One indicator is significantly more important than the other.
$A_{ij} = 7$	One indicator is strongly favored over the other.
$A_{ij} = 9$	One indicator is overwhelmingly more important than the other.
$A_{ij} = 2, 4, 6, 8$	Used to represent intermediate levels of importance between the main scales.
$A_{ij} = 1/2, \dots, 1/9$	If I_i has a score of A_{ij} over I_j , then I_j has a score of $1/A_{ij}$ over I_i .

Step 3. Calculation of weights and Consistency Check

For each pairwise comparison matrix constructed in the previous step, the weights of the indicators are computed by determining the principal eigenvector, and the consistency of the expert judgments is verified through a consistency check.

The computational procedures for the Analytic Hierarchy Process (AHP) follow established operations research methodologies. For brevity, the standard mathematical derivations—including the principal eigenvector estimation via the geometric mean method, maximum eigenvalue (μ_{max}) determination, and the consistency index (CI) and consistency ratio (CR) verifications—are omitted here. These algorithmic steps are rigorously executed according to the foundational frameworks established by Saaty [22]. Within the context of the FATIP plan, the primary focus is not the replication of these standard operations, but rather utilizing the validated expert-driven weights to rigorously map physical aerothermodynamic priorities into the standardized decision matrix.

3.5. Order of Preference by Similarity to Ideal Solution Method

Following the determination of indicator weights through the Analytic Hierarchy Process (AHP), the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), originally proposed by Hwang and Yoon in 1981 [23], is employed to rank candidate aircraft engine component technology schemes for compatibility within the FATIP plan. TOPSIS is uniquely suited to the complex compatibility assessment of dual variable cycle engines, as it ranks schemes by measuring their Euclidean distances from an ideal compatibility profile and a negative-ideal benchmark, effectively balancing quantitative performance metrics (e.g., thrust, specific fuel consumption) with qualitative integration factors (e.g., technological maturity, risk exposure) across critical operational states (e.g., 0 km/0 Ma, 23 km/3.2 Ma). This geometric approach excels in capturing the nuanced trade-offs among interdependent component constraints (namely mass flow balance, pressure balance, and power balance) under off-design conditions critical to variable-cycle engines, ensuring the selected scheme optimizes overall engine performance across a wide operational envelope (0–30 km, Mach 0–5). By leveraging AHP-derived weights to prioritize engine-specific criteria, TOPSIS provides a robust and objective ranking mechanism, as demonstrated

in the front fan case study in Section 4, supporting the development of next-generation engines with enhanced efficiency and adaptability.

Once the criteria weights are derived via the expert-driven AHP pairwise comparisons, TOPSIS is employed to measure the multidimensional distances of each candidate aircraft engine component technology scheme. To ensure methodological reproducibility in evaluating the specific engine performance metrics, the core execution steps are streamlined as follows:

Step 1. Data Normalization and Matrix Construction.

The raw thermodynamic indicators exhibit conflicting preferences. Thrust (F_n) acts as a benefit-type indicator (maximal), while Specific Fuel Consumption (SFC) acts as a cost-type indicator (minimal). The raw decision matrix is transformed using reciprocal mapping for cost-type metrics ($\hat{x}_{ij} = 1/x_{ij}$) and direct mapping for benefit-type metrics ($\hat{x}_{ij} = x_{ij}$). The values are then vector-normalized to eliminate scale discrepancies:

$$z_{ij} = \frac{\hat{x}_{ij}}{\sqrt{\sum_{i=1}^n \hat{x}_{ij}^2}} \quad (7)$$

where x_{ij} denotes the original evaluation value of the i -th candidate scheme under the j -th criterion, $\hat{x}_{ij}$ signifies the transformed benefit-type attribute value, z_{ij} represents the standardized normalized value, and n is the total number of candidate component technology schemes under evaluation ($i = 1, 2, \dots, n$).

The weighted normalized decision matrix Z_w is subsequently constructed by applying the AHP-derived weights to each normalized metric: $Z_w = [z_{ij} \cdot V_j]$, where V_j represents the comprehensive weight of the j -th criterion calculated from the AHP hierarchy ($j = 1, 2, \dots, m$), and m is the total number of sub-criteria indicators.

Step 2. Ideal and Negative-Ideal Solutions.

The optimal compatibility profile (Z^+) and the worst-case profile (Z^-) are geometrically defined by extracting the maximum and minimum values across all candidate schemes for each weighted criterion:

$$Z^+ = [z_1^+, z_2^+, \dots, z_m^+], \quad Z^- = [z_1^-, z_2^-, \dots, z_m^-] \quad (8)$$

where the coordinate elements of the positive-ideal and negative-ideal vectors are defined as $z_j^+ = \max_i(z_{ij} \cdot V_j)$ and $z_j^- = \min_i(z_{ij} \cdot V_j)$, respectively.

Step 3. Comprehensive Distance Calculation and Closeness Coefficient.

The weighted Euclidean distances of each candidate scheme i from the ideal (d_i^+) and negative-ideal (d_i^-) solutions are calculated as

$$d_i^+ = \sqrt{\sum_{j=1}^m (z_j^+ - z_{ij} \cdot V_j)^2}, \quad d_i^- = \sqrt{\sum_{j=1}^m (z_{ij} \cdot V_j - z_j^-)^2} \quad (9)$$

where d_i^+ represents the geometric separation measure from the target scheme to the absolute ideal compatibility boundary, and d_i^- signifies the separation measure to the anti-ideal baseline.

Ultimately, the candidate schemes are evaluated and ranked according to their comprehensive closeness coefficient (D_i), calculated as

$$D_i = \frac{d_i^-}{d_i^+ + d_i^-} \quad (10)$$

where D_i denotes the final relative closeness score bounding between 0 and 1. A higher value of D_i (approaching 1) indicates that the component scheme is geometrically closer to the optimal compatibility profile, thereby representing a superior and highly synergistic match within the tightly coupled multi-spool engine system.

4. Case Study

In this case study, we evaluate the compatibility of component technology schemes for a dual variable cycle engine, a cornerstone of advanced aerospace research under the FATIP plan. Specifically, we focus on the front fan, a critical component that governs mass flow balance, pressure balance, and aerodynamic efficiency. From an aerothermodynamic perspective, a major bottleneck in high-Mach flight (e.g., Mach 3.5–5.0) is the severe attenuation of the engine's mass flow capacity. The sharp increase in inlet total temperature at these speeds drastically escalates the power demand on the fan while suppressing its corrected rotational speed. Therefore, the front fan must be designed with an extraordinary “full-speed-range large mass flow” capacity to prevent high-speed thrust degradation. This extreme physical requirement makes it the ideal candidate for assessing compatibility across the engine's wide operational envelope (0–30 km, Mach 0–5). The front fan's pivotal role in modulating airflow and ensuring performance stability under diverse conditions, spanning subsonic (0 km/0 Ma) and supersonic (23 km/3.2 Ma) states, underscores its selection for this analysis. Designed with a highly adjustable bypass ratio, adaptive supercharger ratio, and optimized turbine inlet temperature, the dual variable cycle engine demands components that integrate seamlessly to achieve superior efficiency and adaptability. As shown in Figure 3, by applying the AHP-TOPSIS methodology, a comprehensive technical implementation pipeline is executed. To visually bridge the theoretical matching formulations with the practical execution steps, the engineering assessment is systematically partitioned into three sequential modules: Phase 1 registers the steady-state multi-spool system outputs under aerodynamic constraints; Phase 2 aggregates the expert consensus to populate the hierarchical criterion matrix; Phase 3 channels the standard profiles into the positive transformation, vector normalization, and Euclidean geometric boundary loops to calculate the ultimate compatibility ranking. This process integrates expert insights from the Aeroengine and Gas Turbine Science Center with a structured evaluation indicator system to assess front fan technology schemes, demonstrating the methodology's effectiveness in identifying optimal solutions.

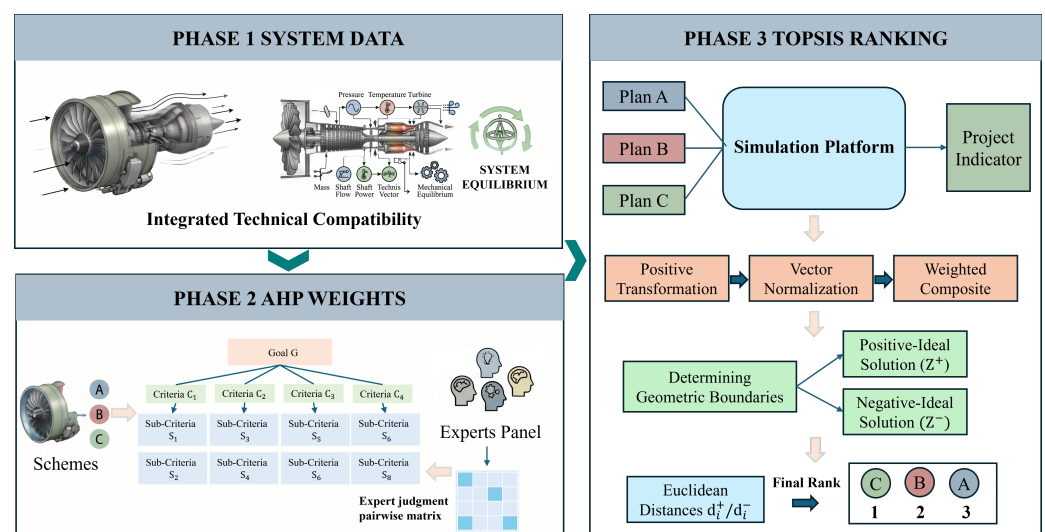


Figure 3. Detailed multi-phase operational data-flow and implementation framework for the aircraft engine front fan scheme compatibility evaluation case study.

4.1. Establishment of the Evaluation Indicator System for Front Fan Component Matching

In evaluating the compatibility of front fan technology schemes across the wide operational envelope (0 to 30 km, Mach 0 to 5), the selection of evaluation indicators is bounded by the underlying numerical simulation platform. Given the conceptual nature of this study, which focuses on baseline cycle matching and performance boundary mapping, the integrated aeroengine model utilized herein relies on the nonlinear algebraic component method for steady state aerothermal balancing. Therefore, rather than incorporating dynamic or transient phenomena, which require detailed inertia parameters, volume dynamics, and predefined control schedules, this research strictly limits its analysis to steady state conditions. Structured within this steady state spectrum, specific operational state points and performance metrics serve as proxy indicators mapping internal component balances.

(1) 0 km/0 Ma (Ground Takeoff State): This state represents the design point for engine initialization, characterized by maximum pressure and temperature conditions due to high thrust demands during takeoff. It is critical for evaluating the front fan's structural integrity and aerodynamic performance under extreme thermal and mechanical loads, ensuring safety and reliability at the onset of flight. Its inclusion as an evaluation basis reflects its role as a fundamental benchmark for engine decision-making, directly influencing the compatibility of front fan designs with the engine's overall performance requirements.

(2) 11 km/0.8 Ma (Economic Sub-Cruise State): Corresponding to long-duration cruise conditions at typical commercial altitudes, this state is pivotal for assessing the front fan's contribution to fuel efficiency and operational economy. It aligns with the top-level technical requirements of the "New Generation Aircraft Engine Aerothermodynamics Configuration" project, emphasizing optimized bypass ratios and airflow management to minimize specific fuel consumption. The front fan's performance in this state ensures sustained efficiency, making it a key evaluation point for compatibility with the engine's economic objectives.

(3) 23 km/3.2 Ma (High-Altitude High-Speed State): This state marks a critical transition point before mode switching in the dual variable cycle engine, where the front fan must adapt to rapid changes in airflow and pressure to support the engine's transition to high-speed, high-altitude operation (up to 30 km/5 Ma). Its selection as an evaluation basis stems from its direct impact on the engine's ability to maintain aerodynamic stability and performance during mode shifts, ensuring compatibility with the engine's wide-envelope capabilities.

(4) 11 km/1.5 Ma (Low-Altitude Supercruise State): Achievable by many modern supersonic engines, this state is essential for evaluating the front fan's performance during low-altitude, high-speed flight, a common operational mode for dual variable cycle engines. It tests the front fan's ability to manage increased dynamic pressures and maintain compatibility with subsequent mode conversion schemes, ensuring robust performance across subsonic-to-supersonic transitions. This state's inclusion reflects its role in validating the front fan's adaptability to diverse flight regimes.

Thrust and specific fuel consumption (SFC) are selected as core performance metrics because they collectively capture the front fan's impact on engine performance, operational cost, and energy utilization, ensuring compatibility with mission requirements, sustainability goals, and system efficiency across the engine's operational spectrum. To further justify the exclusive selection of F_n and SFC over other component-level parameters, it is essential to consider the hierarchical nature of engine design. Because the present study is positioned at the "overall cycle parameter matching" level during the conceptual stage, localized component parameters (e.g., adiabatic efficiency, pressure ratios) are fundamentally treated as input design variables rather than output evaluation metrics. Conversely, critical opera-

tional safety parameters, including compressor surge margins, rotor vibration dynamics, and turbine temperature margins, function as strict physical constraints. The integrated simulation platform utilizes a “boundary filtering” strategy: any candidate scheme that violates these safety margins is deemed unfeasible and is automatically rejected by the numerical solver, thus never entering the TOPSIS evaluation matrix. Consequently, F_n and SFC remain as the ultimate, unconstrained top-level output responses that directly dictate the aircraft’s mission capability. Their macroscopic numerical values thermodynamically encapsulate and synthesize the coupled impacts of all underlying internal variables. This “target-driven, constraint-gatekeeping” strategy represents the most rigorous and appropriate evaluation method for assessing systemic compatibility at this specific phase of design.

After determining these indicators, the hierarchical evaluation model is constructed. This model ensures that both state points and performance metrics are systematically integrated into the evaluation process. The model is based on research into the front fan component design and compatibility studies conducted across different teams. Based on the above analysis, an engine hierarchical evaluation indicator system for front fan technology schemes was established using the AHP method, resulting in a three-level evaluation model, as shown in Figure 4.

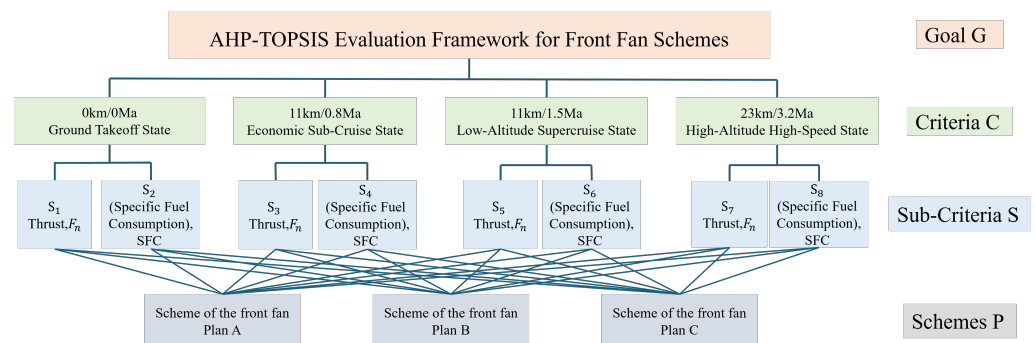


Figure 4. Hierarchical Evaluation Indicator System for the Front Fan Component Matching

The top level (goal layer G) uses the front fan compatibility indicators as the decision basis for front fan selection, while the middle level (criteria layer C) includes four states, which are used as the evaluation indicators for front fan compatibility. The sub-criterion layer (S) breaks down each criterion into two specific performance indicators: thrust (F_n Thrust) and specific fuel consumption rate (SFC fuel consumption rate). These indicators are applied across all four operational conditions, resulting in eight sub-criteria (S_1 to S_8). The plan layer (P) consists of three candidate front fan technology schemes (Plan A, Plan B, and Plan C). To establish a clear physical context for the technical compatibility evaluation, these schemes represent distinct evolutionary milestones in the aerodynamic layout and matching process of the dual variable cycle engine:

- **Plan A (Generic/Baseline Map Scheme):** Serves as the initial baseline configuration. It utilizes a standard generic aerodynamic performance map designed for conventional turbofan boundary matching, lacking variable geometry modulation features. It was primarily used to establish the lower bound of system performance.
- **Plan B (Integrated Down-Selection Scheme):** Serves as an intermediate integrated evaluation stage. It introduces simplified variable guide vane (VGV) tracking parameters tailored for basic multi-mode matching evaluations, bridging the gap between conventional schedules and highly variable cycles.
- **Plan C (Advanced Dedicated Scheme):** Represents the finalized specialized configuration optimized specifically for the unique three-spool driving constraints and multi-bypass architectures of the dual variable cycle engine. It incorporates an exten-

sive dedicated adjustable guide vane dataset. This allows for precise flow-matching and optimal throttling stability during the critical transition between the low-specific-thrust turbofan mode (for subsonic cruise) and the high-specific-thrust turbojet mode (for high-altitude supersonic acceleration).

Each plan is evaluated against the eight sub-criteria (S_1 to S_8), which collectively assess the front fan's performance across the four operational conditions (C_1 to C_4). The connections between the sub-criteria and plans indicate that each plan's performance is measured for thrust and fuel consumption under all conditions, forming the basis for the decision matrix in the TOPSIS evaluation.

4.1.1. Construction of Judgment Matrix for the Importance of State Points

The AHP hierarchy (as shown in Figure 4) includes four criteria (C_1 to C_4) representing operational conditions (e.g., 0 km, 0 Ma; 11 km, 0.8 Ma), each with two sub-criteria: thrust (S_1, S_3, S_5, S_7) and specific fuel consumption rate (SFC) (S_2, S_4, S_6, S_8). There are three front fan schemes (P_1, P_2, P_3), and for each of the eight sub-criteria (S_1 to S_8), a pairwise comparison matrix must be constructed to compare the schemes. Since there are three schemes, each matrix is a 3×3 matrix, resulting in eight such matrices (one for each sub-criterion).

The problem specifies that the pairwise comparison matrices for sub-criteria S_1 (thrust at 0 km, 0 Ma) and S_2 (SFC at 0 km, 0 Ma) will be constructed as Equations (11) and (12), with the remaining six matrices (S_3 to S_8) following a similar approach:

$$S_1 = \begin{bmatrix} 1 & \frac{p_{1S_1}}{p_{2S_1}} & \frac{p_{1S_1}}{p_{3S_1}} \\ \frac{p_{2S_1}}{p_{1S_1}} & 1 & \frac{p_{2S_1}}{p_{3S_1}} \\ \frac{p_{3S_1}}{p_{1S_1}} & \frac{p_{3S_1}}{p_{2S_1}} & 1 \end{bmatrix} \quad (11)$$

$$S_2 = \begin{bmatrix} 1 & \frac{p_{1S_2}}{p_{2S_2}} & \frac{p_{1S_2}}{p_{3S_2}} \\ \frac{p_{2S_2}}{p_{1S_2}} & 1 & \frac{p_{2S_2}}{p_{3S_2}} \\ \frac{p_{3S_2}}{p_{1S_2}} & \frac{p_{3S_2}}{p_{2S_2}} & 1 \end{bmatrix} \quad (12)$$

The proposed model incorporates four criterion layer elements, corresponding to four critical operational condition points, necessitating the construction of four pairwise comparison matrices. The order of each matrix is determined by the number of sub-criterion elements associated with the respective criterion layer element. Specifically, for the criterion C_1 (0 km, 0 Ma, Ground High-Thrust State Matching), the primary influencing factors are the sub-criteria S_1 (F_n Thrust) and S_2 (SFC Fuel Consumption Rate), resulting in two sub-criterion elements. Consequently, a 2×2 pairwise comparison matrix is established, as shown in Equations (13) and (14), to evaluate the relative importance of these sub-criteria with respect to the ground state matching condition. The remaining three pairwise comparison matrices for criteria C_2 (11 km, 0.8 Ma), C_3 (11 km, 1.5 Ma), and C_4 (23 km, 3.2 Ma) are constructed similarly, as each criterion is also associated with two sub-criteria (thrust and SFC).

$$C_1 = \begin{bmatrix} 1 & \frac{S_{1C_1}}{S_{2C_1}} \\ \frac{S_{2C_1}}{S_{1C_1}} & 1 \end{bmatrix} \quad (13)$$

$$C_2 = \begin{bmatrix} 1 & \frac{s_{1C_2}}{s_{2C_2}} \\ \frac{s_{2C_2}}{s_{1C_2}} & 1 \end{bmatrix} \quad (14)$$

Given that the assessment involves four critical operational condition points to evaluate the matching compatibility of component designs, the contribution of the criterion layer to the top-level goal of optimal matching compatibility requires the construction of a single 4×4 pairwise comparison matrix. This matrix quantifies the relative importance of the four criteria in the criterion layer (C) with respect to the goal layer (G) as shown in Equation (15), ensuring a structured evaluation of their impact on the overall objective of achieving optimal front fan compatibility for the dual variable cycle engine.

$$G = \begin{bmatrix} 1 & \frac{C_{2G}}{C_{1G}} & \frac{C_{3G}}{C_{1G}} & \frac{C_{4G}}{C_{1G}} \\ \frac{C_{1G}}{C_{2G}} & 1 & \frac{C_{3G}}{C_{2G}} & \frac{C_{4G}}{C_{2G}} \\ \frac{C_{1G}}{C_{3G}} & \frac{C_{2G}}{C_{3G}} & 1 & \frac{C_{4G}}{C_{3G}} \\ \frac{C_{1G}}{C_{4G}} & \frac{C_{2G}}{C_{4G}} & \frac{C_{3G}}{C_{4G}} & 1 \end{bmatrix} \quad (15)$$

Based on the established comprehensive evaluation indicator system, questionnaires were distributed to a rigorously selected expert panel to conduct the AHP pairwise comparisons. To ensure the highest level of professional authority and transparency, strict selection criteria were applied: all experts must hold Ph.D. degrees in Aerospace Engineering or Engineering Thermophysics and possess the title of Senior Engineer or higher. The panel comprised four accountable technical experts from the Aeroengine and Gas Turbine Basic Science Center. Their professional experience ranges from 15 to 28 years. The detailed demographic profile and specific areas of expertise for each panel member are explicitly summarized in Table 3, providing a profound engineering foundation for evaluating the dual variable cycle engine.

Table 3. Demographic profile and specific expertise of the selected expert panel.

Expert	Professional Title	Degree	Years of Exp.	Area of Expertise
Expert 1	Chief Designer	Ph.D.	28	Advanced Propulsion System Integration
Expert 2	Professor-level Senior Engineer	Ph.D.	22	Turbomachinery Aerothermodynamics
Expert 3	Professor-level Senior Engineer	Ph.D.	19	Engine Cycle Matching
Expert 4	Senior Engineer	Ph.D.	15	Multi-spool Rotor Dynamics

To guarantee data reproducibility and actively minimize cognitive variance and subjective bias, a Delphi-inspired consensus mechanism was implemented based on established forecasting frameworks [8,24]. In the initial round, each expert independently conducted blind evaluations of the criteria using Saaty's 1 to 9 fundamental scale (Table 2). To systematically handle disagreements and reduce subjective bias, an anonymous feedback loop was strictly enforced: if the Consistency Ratio (CR) of any individual matrix exceeded the mathematical threshold of 0.1, or if significant divergence existed among the experts' judgments, the statistical deviations were anonymously fed back to the panel for a subsequent round of independent refinement. Individual judgments were not combined until mathematical convergence ($CR < 0.1$) and expert consensus were verified across all evaluators. Once these rigid conditions were met, the individual responses were aggregated via the geometric mean method, effectively neutralizing isolated subjective extremes. Through this rigorous pairwise comparison process, the unified matrix G was constructed, as shown in Table 4, translating qualitative expert insights into robust quantitative entries.

Table 4. Comparison matrix of expert judgments of G.

Indicator of G	C ₁	C ₂	C ₃	C ₄
C ₁	1	1/2	3	1/3
C ₂	2	1	7	1/2
C ₃	1/3	1/7	1	1/5
C ₄	3	2	5	1

4.1.2. Weight Vector Derivation in AHP

Following the construction of the pairwise comparison matrix for the criterion layer C with respect to the goal layer G, the column vectors of the matrix are normalized using the sum method. This process transforms the pairwise comparison matrix G into a normalized judgment matrix G_1 as shown in Equation (16), which is a critical step in the AHP methodology for deriving the priority weights of the criteria.

$$G_1 = \begin{bmatrix} 0.1579 & 0.1373 & 0.1875 & 0.1639 \\ 0.3158 & 0.2745 & 0.4375 & 0.2459 \\ 0.0526 & 0.0392 & 0.0625 & 0.0984 \\ 0.4737 & 0.5490 & 0.3125 & 0.4918 \end{bmatrix} \quad (16)$$

Following the column vector normalization of the pairwise comparison matrix, the standardized weight vector G_2 for the criteria is obtained by summing the row vectors of the normalized judgment matrix and performing a normalization process:

$$G_2 = \begin{bmatrix} 0.16165 \\ 0.318425 \\ 0.063175 \\ 0.45675 \end{bmatrix} \quad (17)$$

To ensure the consistency of the pairwise comparison matrix in the AHP methodology, μ_{max} and CR are calculated by Saaty [22].

$$\mu_{max} = 4.096775 \quad (18)$$

$$CR = 0.03584 \quad (19)$$

Therefore, with $CR < 0.1$, the matrix is consistent, and the weights are reliable.

Through expert scoring and single-level hierarchical analysis, pairwise comparisons are conducted to construct the judgment matrices for the sub-criterion layer indicators (S) with respect to their corresponding criterion layer indicators (C):

$$C_1 = \begin{bmatrix} 1 & 7 \\ 1/7 & 1 \end{bmatrix}, \quad C_2 = \begin{bmatrix} 1 & 1/5 \\ 5 & 1 \end{bmatrix}, \quad C_3 = \begin{bmatrix} 1 & 1/3 \\ 3 & 1 \end{bmatrix}, \quad C_4 = \begin{bmatrix} 1 & 7 \\ 1/7 & 1 \end{bmatrix} \quad (20)$$

Since they are all second-order matrices, the consistency index $CI = 0$, which inherently satisfies the consistency test and meets the consistency requirements. After normalization, the maximum eigenvalue is obtained, and the weight vectors are as follows:

$$\begin{bmatrix} S_1 \\ S_2 \end{bmatrix} = \begin{bmatrix} 0.875 \\ 0.125 \end{bmatrix}, \quad \begin{bmatrix} S_3 \\ S_4 \end{bmatrix} = \begin{bmatrix} 0.1667 \\ 0.8333 \end{bmatrix}, \quad \begin{bmatrix} S_5 \\ S_6 \end{bmatrix} = \begin{bmatrix} 0.25 \\ 0.75 \end{bmatrix}, \quad \begin{bmatrix} S_7 \\ S_8 \end{bmatrix} = \begin{bmatrix} 0.875 \\ 0.125 \end{bmatrix} \quad (21)$$

The calculated $CR = 0.035603 < 0.1$, indicating that the consistency of the pairwise comparison matrix is acceptable. This suggests that the consistency level of the judgment

matrix G is considered within the allowable range. At this point, the eigenvector of G can be used to calculate the weight vector.

4.1.3. Overall Hierarchical Ranking

At this stage, the single-level sorting and consistency checks for the AHP hierarchy have been completed. Since the evaluation framework involves multi-level influence, hierarchical total sorting is performed to determine the final weights. The resulting comprehensive weights for the elements in the sub-criteria layer are detailed in Table 5.

Table 5. Comprehensive weight of elements in the sub-criteria layer

Indicator	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
Comprehensive weight	0.1414	0.0202	0.0531	0.2653	0.0158	0.0474	0.3997	0.0571

4.1.4. Quantification and Data Mapping for Alternative and Sub-Criteria Matrices

To address the opacity in the initialization of the hierarchical decision matrices and guarantee methodological reproducibility, this subsection explicitly demonstrates the mathematical tracking from the raw thermodynamic simulation data (listed in Table 6) and expert elicitation to the specific matrix entries. This explicitly resolves the consistency between physical parameters and algebraic terms.

Table 6. Aerodynamic and thermodynamic overall performance outputs of candidate front fan schemes under key operational state points.

Operational State/Metric	Plan A	Plan B	Plan C
0 km, 0 Ma (Ground Takeoff)			
Thrust F_n (N)	133,366.4529	133,371.5075	133,364.0501
SFC ($\text{kg}\cdot\text{h}^{-1}\cdot\text{N}^{-1}$)	0.210800337	0.210811652	0.210802488
11 km, 0.8 Ma (Subsonic Cruise)			
Thrust F_n (N)	10,843.32919	10,035.21393	10,645.28579
SFC ($\text{kg}\cdot\text{h}^{-1}\cdot\text{N}^{-1}$)	0.084922933	0.089327003	0.086502900
11 km, 1.5 Ma (Low-Altitude Supercruise)			
Thrust F_n (N)	50,543.42588	65,743.42781	49,563.52601
SFC ($\text{kg}\cdot\text{h}^{-1}\cdot\text{N}^{-1}$)	0.122786615	0.136814294	0.122633275
23 km, 3.2 Ma (High-Altitude Supersonic)			
Thrust F_n (N)	58,089.49120	62,566.29523	63,232.19708
SFC ($\text{kg}\cdot\text{h}^{-1}\cdot\text{N}^{-1}$)	0.193125342	0.202986805	0.202710532

1. Mapping from Physical Simulation Data to Alternative Layer Matrices

Let $M_{S_m} = [a_{ij}]_{3 \times 3}$ denote the pairwise comparison matrix of the three candidate front fan schemes under the sub-criterion S_m ($m = 1, 2, \dots, 8$). The entries within these matrices are systematically constructed from the converged aerothermal outputs shown in Table 6.

For the benefit-type (maximal) sub-criteria representing Thrust (S_1, S_3, S_5, S_7), the elements are calculated directly as the linear mathematical ratio of the propulsion outputs between Plan i and Plan j :

$$a_{ij}(S_m) = \frac{F_n(\text{Plan } i)}{F_n(\text{Plan } j)} \quad \text{for } m \in \{1, 3, 5, 7\} \quad (22)$$

Taking the Ground Condition (C_1) as an illustrative checkpoint, the thrust values (F_n) for Plan A and Plan B are 133,366.4529 N and 133,371.5075 N, respectively. Thus, the entry a_{12} within the S_1 judgment matrix is instantiated as

$$a_{12}(S_1) = \frac{F_n(\text{Plan A})}{F_n(\text{Plan B})} = \frac{133366.4529}{133371.5075} = 0.999962 \quad (23)$$

Conversely, for the cost-type (minimal) sub-criteria representing Specific Fuel Consumption (S_2, S_4, S_6, S_8), the matrix entries are formulated inversely to logically reflect the performance preference for a minimized fuel flow rate:

$$a_{ij}(S_m) = \frac{\text{SFC}(\text{Plan } j)}{\text{SFC}(\text{Plan } i)} \quad \text{for } m \in \{2, 4, 6, 8\} \quad (24)$$

Utilizing the identical takeoff boundary conditions (where SFC for Plan A is 0.210800337 and SFC for Plan B is 0.210811652), the entry comparing Plan A to Plan B under the S_2 block is rigorously populating as

$$a_{12}(S_2) = \frac{\text{SFC}(\text{Plan B})}{\text{SFC}(\text{Plan A})} = \frac{0.210811652}{0.210800337} = 1.000054 \quad (25)$$

2. Instantiation of Sub-criteria Layer Preference Matrices

The relative entries within the sub-criteria layer matrices (C_k for $k = 1, 2, 3, 4$) evaluate the relative scaling between performance dimensions (Thrust vs. SFC) under designated flight regimes. Under the Ground Takeoff regime (C_1), core structural limits and takeoff cycle matching dictate that fuel flow optimization carries a higher priority than peak thrust redundancy. Following the expert consensus loop using Saaty's 1–9 linear scale, the quantified pairwise comparison matrix for C_1 is given as

$$C_1 = \begin{bmatrix} 1 & 7 \\ 1/7 & 1 \end{bmatrix} \quad \text{with } a_{12}(C_1) = \frac{S_{1,C_1}}{S_{2,C_1}} = 7 \quad (26)$$

where the entry $a_{12}(C_1) = 7$ mathematically captures the strong relative preference assigned to raw thrust over specific fuel consumption at this critical takeoff state, validating the single-ranking local priority outputs of $[0.875, 0.125]^T$.

4.2. Simulation Experiment Based the Typical Project

To obtain the quantitative performance data required for the AHP-TOPSIS compatibility assessment framework, this study employed a model-based integrated aircraft engine simulation methodology. This approach aims to objectively evaluate the compatibility of various component technology schemes (such as Front Fan Plans A, B, and C in this case study), developed under identical top-level design requirements, with the overall engine system. The core concept involves utilizing an advanced aircraft engine system simulation platform to construct an overall engine performance model incorporating the component scheme under evaluation. A critical aspect is establishing consistent evaluation boundaries for technology schemes originating from different design processes or tools.

Specifically, the essential performance characteristics of component schemes (e.g., different front fan aerodynamic designs) generated by various teams or tools are first converted into a standardized input format acceptable to the simulation platform, such as standardized performance maps or component characteristic models. Subsequently, while keeping the overall engine architecture model, the performance characteristics of other components (e.g., compressor, combustor, turbine), and the control laws constant,

the component scheme being evaluated is integrated into the overall engine model. By executing simulations at the selected key operational state points (defined as criteria C_1 to C_4 in Section 4.1), the overall engine performance metrics—such as Thrust (F_n) and Specific Fuel Consumption (SFC)—are obtained for the configuration including the specific component scheme. Comparing these simulation results against a baseline performance (e.g., using generic component characteristics or theoretical design point data) allows the performance deviation to quantify the compatibility or synergistic contribution of the component scheme with the rest of the engine. This method effectively isolates the impact of the evaluated component variation on overall engine performance, providing reliable quantitative input for the subsequent compatibility assessment.

In the present case study focusing on the front fan, this model-based simulation methodology was applied to the three technology schemes: Plan A, Plan B, and Plan C. Overall engine performance simulations were conducted at the four key state points (C_1 to C_4). The resulting values for Thrust (indicators S_1, S_3, S_5, S_7) and Specific Fuel Consumption (indicators S_2, S_4, S_6, S_8) for each plan at the corresponding state points constitute the data presented in Table 7. This data forms the foundation for the subsequent TOPSIS analysis used to rank the schemes.

Table 7. Project indicator schemes.

Indicator	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
Plan A	133,366.453	0.210800	10,843.329	0.084923	50,543.43	0.122787	58,089.49	0.193125
Plan B	133,371.508	0.210812	10,035.210	0.089327	65,743.43	0.136814	62,566.30	0.202987
Plan C	133,364.050	0.210802	10,645.290	0.086503	49,563.53	0.122633	63,232.20	0.202711

4.3. TOPSIS Algorithm of the Typical Project

The AHP-based evaluation framework for component technical compatibility established the evaluation indicators $S_1 - S_8$. The specific values of these indicators, representing the performance of each front fan scheme (Plan A, B, C) under the corresponding metrics, were obtained through the simulation experiments described in Section 4.2. Table 8 presents these simulation results and specifies the type of each indicator. For example, thrust indicators S_1, S_5 , and S_7 are of the Maximization type (larger values are preferred), specific fuel consumption indicators S_2, S_4, S_6 , and S_8 are of the Minimization type (smaller values are preferred), and indicator S_3 is an Interval Type, with optimal performance within the range [10,000, 11,000]. The determination of indicator types is critical for the subsequent data normalization process in the TOPSIS method, ensuring that all indicators have a consistent preference direction during evaluation.

Table 8. Project indicator types and schemes.

Indicator	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
Plan A	133,366.453	0.210800	10,843.329	0.084923	50,543.43	0.122787	58,089.49	0.193125
Plan B	133,371.508	0.210812	10,035.210	0.089327	65,743.43	0.136814	62,566.30	0.202987
Plan C	133,364.050	0.210802	10,645.290	0.086503	49,563.53	0.122633	63,232.20	0.202711
Types	Max.	Min.	Int. [10 k, 11 k]	Min.	Max.	Min.	Max.	Min.

After positive normalization processing, the normalized matrix X is obtained as follows:

$$X = \begin{bmatrix} 133,366.453 & 4.74383 & 1 & 11.77537 & 50,543.43 & 8.14418 & 58,089.49 & 5.17799 \\ 133,371.508 & 4.74356 & 1 & 11.19482 & 65,743.43 & 7.30919 & 62,566.30 & 4.92642 \\ 133,364.050 & 4.74378 & 1 & 11.56029 & 49,563.53 & 8.15441 & 63,232.20 & 4.93313 \end{bmatrix} \quad (27)$$

Then, the standardized matrix formed is Z :

$$Z = \begin{bmatrix} 0.5773 & 0.5774 & 0.5774 & 0.5905 & 0.5232 & 0.5968 & 0.5468 & 0.5962 \\ 0.5774 & 0.5773 & 0.5774 & 0.5614 & 0.6805 & 0.5356 & 0.5889 & 0.5673 \\ 0.5773 & 0.5774 & 0.5774 & 0.5797 & 0.5130 & 0.5975 & 0.5952 & 0.5681 \end{bmatrix} \quad (28)$$

Since the evaluation weights of each indicator obtained through AHP analysis vary, as shown in Table 5 (Comprehensive Weights of Sub-criteria Layer Elements), it is necessary to consider the degree of influence of different indicators on the technical compatibility of components before calculating the comprehensive distance. This is achieved by multiplying the weights with the standardized values to obtain the weighted normalized matrix:

$$Z_w = \begin{bmatrix} 0.08167 & 0.01167 & 0.03065 & 0.15669 & 0.00826 & 0.02828 & 0.21852 & 0.03404 \\ 0.08167 & 0.01167 & 0.03065 & 0.14897 & 0.01075 & 0.02538 & 0.23536 & 0.03239 \\ 0.08167 & 0.01167 & 0.03065 & 0.15383 & 0.00810 & 0.02831 & 0.23787 & 0.03243 \end{bmatrix} \quad (29)$$

The ideal optimal solution vector Z^+ and the negative-ideal solution vector Z^- are calculated as follows:

$$Z^+ = [0.08167 \quad 0.01167 \quad 0.03065 \quad 0.15669 \quad 0.01075 \quad 0.02831 \quad 0.23787 \quad 0.03404] \quad (30)$$

$$Z^- = [0.08167 \quad 0.01167 \quad 0.03065 \quad 0.14897 \quad 0.00810 \quad 0.02538 \quad 0.21852 \quad 0.03239] \quad (31)$$

Finally, the comprehensive distance calculation and scoring are computed as shown in Table 9:

Table 9. Technical evaluation results of front fan scheme compatibility.

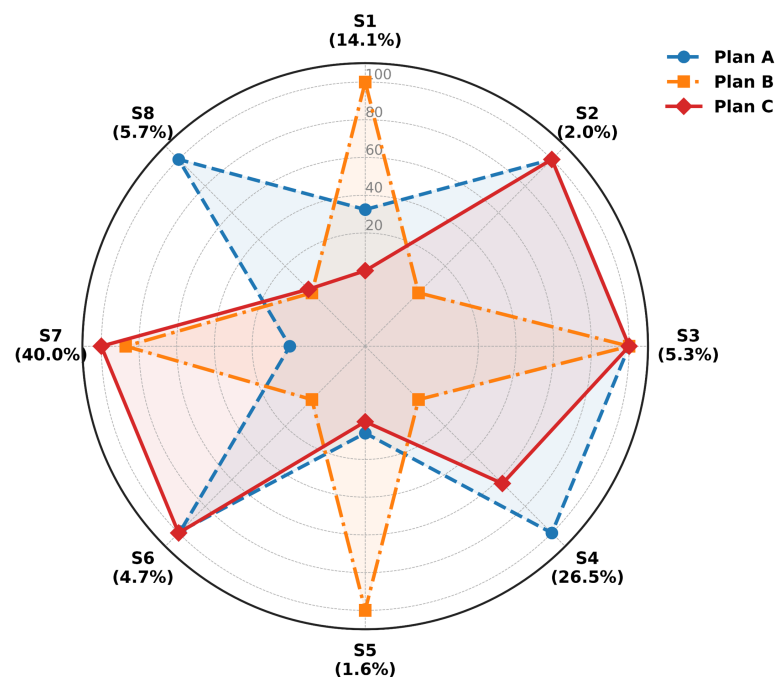
	Plan A	Plan B	Plan C
Optimal Distance	0.01951	0.00879	0.00422
Worst Distance	0.00841	0.01705	0.02016
Comprehensive Distance/Value	0.30145	0.65974	0.82704
Normalized Value	36.4	79.8	100
Ranking	3	2	1

Table 9 reveals that Plan C achieves the highest rank (Normalized Value 100, Rank 1), indicating it is the most compatible front fan scheme according to the AHP-TOPSIS evaluation. Its superior performance is reflected in the shortest distance to the ideal solution (0.00422) and the largest distance to the negative-ideal solution (0.02016). This outcome is likely driven by Plan C's strong performance relative to Plans A and B on the most heavily weighted sub-criteria identified in Table 5, particularly S_7 (Thrust at 23 km/3.2 Ma, weight 0.3997), S_4 (SFC at 11 km/0.8 Ma, weight 0.2653), and S_1 (Thrust at 0 km/0 Ma, weight 0.1414). Plan C's design appears to offer the best trade-off across these critical performance indicators, aligning well with the demanding operational priorities of the dual variable cycle engine (0 to 30 km, Mach 0 to 5). Plan B ranked second (Normalized Value 79.8), showing a better balance than Plan A (Normalized Value 36.4, Rank 3) but ultimately being outperformed by Plan C on key high-priority metrics.

From an aerothermodynamic perspective, this ranking sequence (Plan C > Plan B > Plan A) is fundamentally driven by the variations in the component's aerodynamic throttling capacity across off-design boundaries. Plan A adopts a standard rigid-geometry compressor map; at the critical high-altitude supersonic state (C_4 : 23 km, Mach 3.2), its structural stiffness prevents adaptive modulation of the intake mass flow and pressure ratio, yielding severe static pressure mismatches at the mixing planes and an inflated specific

fuel consumption (S_8). Conversely, Plan C embodies the advanced specialized three-spool layout, integrating variable guide vane mechanisms with 10 groups of dedicated geometry profiles. Under the critical supersonic condition (C_4), Plan C dynamically schedules its guide vane angles to expand the pressure ratio adjustment margin (1.9–2.6) while maintaining an optimal corrected rotational speed (0.2–1.08). This design flexibility provides a massive “technological relief” to downstream components, significantly dampening thermodynamic cycle penalties. Consequently, Plan C excels in the highest-weighted AHP criteria, namely S_7 (Thrust at 23 km/3.2 Ma, weight: 39.97%) and S_4 (SFC at 11 km/0.8 Ma, weight: 26.53%), thereby securing the optimal multi-dimensional compatibility closeness score ($D_C = 0.82704$).

To further visually elucidate these quantitative findings, Figure 5 presents a radar chart mapping the normalized relative performance scores (0–100) of the three candidate schemes against the eight evaluation sub-criteria.



Note: 100 represents the optimal performance (Maximum Thrust or Minimum SFC).

Figure 5. Radar chart illustrating the relative performance of three candidate front fan schemes across normalized sub-criteria S_1 to S_8 . The percentages in parentheses indicate the comprehensive AHP weights for each criterion. Note: A score of 100 represents the optimal performance boundary (i.e., maximum thrust or minimum specific fuel consumption) for that specific indicator.

As visually corroborated by Figure 5, the geometrical profiles of the three schemes distinctively explain the final TOPSIS rankings. While Plan A and Plan B demonstrate isolated superiority in minor criteria (for instance, Plan B excels in S_5 , which only carries a 1.58% weight), Plan C exhibits a highly strategic “multi-dimensional” advantage. Plan C maximizes its performance exactly along the axes corresponding to the highest-priority criteria, specifically S_7 (Thrust at 23 km/3.2 Ma, weight 39.97%) and S_4 (SFC at 11 km/0.8 Ma, weight 26.53%). This graphical representation reinforces the validity of the AHP-TOPSIS framework, vividly illustrating how Plan C optimally allocates its design strengths to align with the dual variable cycle engine’s most critical compatibility and operational demands, thereby securing the highest closeness coefficient.

From a practical engineering perspective, the quantitative improvements offered by Plan C carry profound mission implications. Compared to the baseline Plan A, Plan C yields an 8.85% increase in net thrust (F_n), improving from 58,089.49 N to 63,232.20 N as detailed in Table 7, at the highly critical high-altitude supersonic state (23 km, 3.2 Ma). This directly translates to superior aircraft acceleration capabilities and expanded maneuverability margins during supersonic interception profiles. Furthermore, at the economic sub-cruise state (11 km, 0.8 Ma), Plan C achieves a 3.16% reduction in Specific Fuel Consumption (SFC), dropping from 0.0893 to 0.0865 kg · h⁻¹ · N⁻¹ compared to Plan B. For a long-endurance variable cycle engine, this thermodynamic efficiency improvement drastically reduces fuel burn rate, yielding a substantial extension in the aircraft's combat radius and overall operational range. By quantifying these metrics, the AHP-TOPSIS framework explicitly validates how structural and aerodynamic refinements at the component level map directly onto top-level strategic engineering value.

5. Conclusions

This study proposes a comprehensive multi-criteria decision-making (MCDM) framework to evaluate the systemic compatibility of aircraft engine components. A hierarchical evaluation indicator system was established to bridge component-level aerothermodynamic metrics with top-level overall performance constraints. By coupling the Analytic Hierarchy Process (AHP) with the TOPSIS method, the framework successfully translates subjective engineering expertise and objective operational data into a rigorous quantitative ranking. Validated through a dual variable cycle engine front fan case study across a broad flight envelope (0–30 km, Mach 0–5), the model reliably differentiated candidate architectures and identified the optimal configuration, demonstrating significant evaluation robustness. This methodology offers a scalable and objective paradigm for complex aerospace system design. In future work, we will expand the evaluation of off-design thermodynamic cycles and, to rigorously address inherent design uncertainties, integrate Fuzzy-AHP (FAHP) for expert cognitive variations alongside a stochastic Uncertainty Quantification (UQ) layer utilizing Monte Carlo simulations to map performance deviations, thereby further fortifying system robustness.

Author Contributions: Conceptualization, X.Y., G.Q. and T.Q.; Methodology, X.Y., G.Q. and T.Q.; Validation, X.Y.; Investigation, G.Q. and T.Q.; Resources, G.Q. and T.Q.; Data curation, X.Y.; Writing—original draft, X.Y.; Writing—review & editing, X.Y. and G.Q.; Visualization, X.Y.; Supervision, G.Q. and T.Q.; Project administration, T.Q.; Funding acquisition, G.Q. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by National Natural Science Foundation of China No. 52302510 and No. 62571014, the Beijing Natural Science Foundation under Grant No. 3252015 and No. 4252005, Beijing Nova Program No. 20250484936, Young Elite Scientists Sponsorship Program of the Beijing High Innovation Plan No. 20250699, Tianmushan Laboratory Cross-Innovation Research Team Project No. TK-2024-D-001, and Beijing-Tianjin-Hebei Basic Research Cooperation Project No. F2024201070.

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

Conflicts of Interest: The authors declare no conflicts of interest.

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