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Decision-support for Rocket Propulsion Technology evaluation

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Abstract:- The evaluation of rocket propulsion technologies involves complex trade-offs among performance, reliability, technological maturity, cost, environmental impact, and mission adaptability. These criteria are frequently hierarchical, interdependent, and characterized by uncertainty or incomplete information, making traditional additive or fully compensatory decision models inadequate. This paper proposes a hierarchical interval outranking model to support preferential classification of rocket propulsion technologies under imperfect knowledge. The proposed framework allows criteria to be decomposed into coherent sub-criteria across multiple levels (e.g., thrust performance, specific impulse, structural complexity, scalability, lifecycle cost, and Technology Readiness Level). Interaction effects such as synergy, redundancy, and antagonism among criteria are explicitly incorporated through interaction weights. Uncertainty in performance data, weights, veto thresholds, and majority thresholds is modeled using interval numbers. The method generates credibility indices for outranking relations at each hierarchical level and supports ordinal classification into preferentially ordered categories. This enables decision-makers to conduct both global and dimension-specific assessments while preserving essential structural properties such as monotonicity and consistency. The applicability of the model is demonstrated through a comparative assessment of selected rocket propulsion technologies. Results illustrate how the proposed approach captures complex performance trade-offs and supports transparent, structured, and robust technology evaluation in aerospace decision-making contexts.

Keywords: *Rocket propulsion technologies, Technology readiness level, Multi-criteria decision analysis.*

1. Introduction

The assessment and selection of rocket propulsion technologies constitute a strategic decision problem in aerospace engineering. Modern space missions require propulsion systems that simultaneously satisfy demanding performance, reliability, cost, safety, environmental, and technological maturity constraints. These dimensions are inherently multi-criteria, frequently hierarchical in structure, and often characterized by incomplete or uncertain information. Traditional evaluation approaches based solely on single performance indicators (such as specific impulse or thrust-to-weight ratio) are insufficient to capture the complex trade-offs that arise in real mission planning and technology development contexts.

The growing diversity of propulsion technologies (including chemical (liquid and solid), electric (ion and Hall-effect thrusters), and hybrid systems) further increases the need for structured decision-support methodologies. In practice, propulsion technology assessment relies on heterogeneous data sources, including experimental performance reports, mission heritage documentation, thermochemical calculations, and technology readiness evaluations. Importantly, a significant portion of this information is publicly available through institutional aerospace databases and archival systems.

In this study, the empirical data used to construct and evaluate decision alternatives are drawn exclusively from publicly accessible and verifiable aerospace repositories. These include the NASA Open Data Portal [1], [2], which provides structured datasets related to aerospace systems and missions; the NASA Technical Reports Server

(NTRS) [3], which contains peer-reviewed technical reports and experimental performance documentation; the JANNAF Propulsion Database maintained by the Joint Army-Navy-NASA-Air Force Interagency Propulsion Committee [4], which compiles propulsion system specifications and subsystem characteristics; and NASA's Chemical Equilibrium with Applications (CEA) program documentation for thermochemical performance calculations [5]. Additionally, Technology Readiness Level (TRL) assessments are based on standardized NASA definitions and guidelines [6].

These databases provide directly measurable and verifiable quantitative indicators such as thrust levels, specific impulse (Isp), propellant characteristics, chamber pressure, system mass, operational heritage, and maturity levels. Because these data originate from experimental records, engineering documentation, or validated thermochemical models, they constitute an appropriate foundation for building a hierarchical decision model grounded in real and reproducible evidence.

From a methodological perspective, propulsion technology evaluation presents three major challenges. First, performance criteria are naturally organized hierarchically. For example, overall propulsion effectiveness may depend on thrust performance, efficiency metrics, structural and integration characteristics, operational reliability, and technological maturity, each of which can be decomposed into measurable sub-criteria derived from technical documentation. Second, criteria often interact. High specific impulse may imply increased system complexity or power requirements; higher thrust levels may entail structural penalties; and maturity levels may influence reliability assessments. These interactions are not adequately captured by purely additive aggregation models. Third, many parameters are affected by uncertainty, variability across testing conditions, or incomplete reporting.

To address these challenges, this paper proposes a hierarchical interval outranking model with interacting criteria to support the preferential classification of rocket propulsion technologies. The model allows criteria to be structured according to engineering logic derived directly from the publicly available databases mentioned above, while incorporating interaction effects and interval representations of uncertain parameters. By generating credibility indices for outranking relations at different hierarchical levels, the approach enables both global and dimension-specific assessments of propulsion alternatives.

The contribution of this work is twofold. First, it provides a structured, data-grounded framework for propulsion technology evaluation based exclusively on publicly verifiable aerospace databases. Second, it introduces a decision-support mechanism capable of handling hierarchical structures, interacting criteria, and interval-valued information (features that reflect the real complexity of propulsion system assessment).

2. Materials and Methods

2.1 Data Sources and Data Extraction

The empirical basis of this study is restricted to real, publicly available, and verifiable aerospace databases. All quantitative indicators used to define the hierarchy of criteria and evaluate propulsion alternatives are directly obtained from the following institutional repositories:

1. NASA Technical Reports Server (NTRS), which provides peer-reviewed technical reports, engine test data, propulsion system analyses, and performance tables [2].

2. NASA Open Data Portal, which catalogs structured datasets related to aerospace systems, missions, and engineering performance [1].

3. JANNAF Propulsion Database, maintained by the Joint Army-Navy-NASA-Air Force Interagency Propulsion Committee, containing propulsion system specifications and subsystem-level data [4].

4. NASA Chemical Equilibrium with Applications (CEA) thermochemical model documentation and associated reference data for theoretical propulsion performance estimation [5].

5. NASA Technology Readiness Level (TRL) framework, used for maturity assessment [6].

Only parameters that can be directly retrieved from these databases or computed using officially documented NASA tools are included in the model. No proprietary or estimated data are introduced.

For each propulsion alternative, the following measurable attributes are extracted:

- Vacuum thrust
- Specific impulse in vacuum
- Chamber pressure
- Propellant type
- Engine dry mass when available
- Technology Readiness Level
- Reported operational or test heritage

Performance data are obtained from propulsion system test reports archived in NTRS. When theoretical performance limits are required, they are computed using the NASA CEA methodology described by [5], ensuring consistency with NASA thermochemical standards.

All extracted data are organized into a structured decision matrix. When multiple test conditions are reported, values are represented as intervals bounded by the minimum and maximum documented values.

2.2 Definition of Decision Alternatives

Decision alternatives consist of rocket propulsion technologies for which sufficient, consistent, and directly retrievable quantitative data are available in the selected public databases. Only propulsion systems with documented numerical performance values in the NASA Technical Reports Server, NASA Open Data Portal, or the JANNAF Propulsion Database are included. The selection procedure is strictly evidence-based and reproducible.

2.2.1 Inclusion Criteria

A propulsion system is incorporated as a decision alternative only if it satisfies all of the following conditions:

1. Documented Performance Data: At least vacuum thrust and vacuum specific impulse must be explicitly reported in NASA technical documentation or JANNAF propulsion records [3], [4].

2. Identifiable Propellant and Engine Type: The propulsion category must be clearly specified, for example liquid bipropellant, solid propellant, monopropellant, ion engine, or Hall-effect thruster.

3. Technological Maturity Information: Development status must be identifiable through explicit TRL classification or through documented flight or test heritage consistent with NASA TRL definitions [6].

4. Consistency of Units and Test Conditions: Reported performance metrics must be convertible to consistent engineering units. When different test conditions are reported, they must be explicitly documented.

These criteria ensure that every alternative is supported by verifiable engineering documentation rather than inferred or estimated values.

2.2.2 Classification of Propulsion Alternatives

Based on publicly documented propulsion categories in NASA technical literature, decision alternatives may include (see [7], [8]):

A. Chemical Liquid Propulsion Systems: Examples documented in NTRS include LOX/LH2 engines, LOX/RP-1 engines, and hypergolic bipropellant systems. Performance tables typically report thrust, chamber pressure, expansion ratio, and specific impulse [1].

B. Solid Rocket Motors: Solid propulsion systems with documented thrust curves, burn time, and total impulse are included when numerical values are provided in technical reports archived in NTRS.

C. Electric Propulsion Systems: Ion thrusters and Hall-effect thrusters are considered when specific impulse, thrust level, input power, and efficiency are reported in NASA technical documentation.

Each propulsion alternative is treated as a distinct action in the decision model. If multiple configurations of the same propulsion family exist with independently documented data, they are considered separate alternatives [9], [10].

2.2.3 Data Extraction Protocol

For each propulsion alternative, a structured extraction template is used. The following variables are recorded directly from the databases:

- Vacuum thrust in Newtons
- Vacuum specific impulse in seconds
- Chamber pressure in Pascals
- Engine dry mass in kilograms when available
- Propellant type
- Documented TRL or development phase
- Evidence of flight heritage or ground testing

When data are derived from NASA CEA calculations, the input parameters are strictly those documented in NASA references and standard propellant thermodynamic tables [5], [11]. No speculative thermochemical assumptions are introduced.

If multiple reports provide different values for the same parameter, the documented minimum and maximum values are recorded to construct interval representations. Each interval is traceable to at least one specific technical report.

2.2.4 Treatment of Missing Data

Alternatives with incomplete documentation are excluded if essential performance variables are absent [12], [13]. However, when non-critical variables are missing, two procedures are followed:

1. If the missing variable is reported in another NASA technical report concerning the same engine model, that value is used with proper documentation.

2. If variability across test campaigns exists, the interval approach is adopted rather than selecting a single representative value.

No data imputation, statistical estimation, or interpolation outside documented values is performed.

2.2.5 Reproducibility and Transparency

Each propulsion alternative included in the experimental section is accompanied by:

- Citation of the NASA report or database entry from which data were extracted
- Report identification number when available
- Clear indication of test conditions

This guarantees full reproducibility of the dataset and enables independent verification.

2.3 Hierarchical Structure of Criteria

The hierarchical structure of criteria is constructed exclusively from measurable and verifiable engineering indicators documented in the NASA Technical Reports Server, the NASA Open Data Portal, the JANNAF Propulsion Database, and NASA's Chemical Equilibrium with Applications reference documentation. The structure reflects established propulsion performance theory and NASA engineering evaluation practices rather than subjective aggregation [14], [15].

The hierarchy is designed to mirror the logical decomposition typically found in propulsion system analysis reports archived in NTRS, where overall engine suitability is evaluated through performance metrics, physical characteristics, and technological maturity indicators [4]. The Technology Readiness Level framework provides a standardized maturity dimension [6].

The resulting structure is composed of three levels: a global objective, first-level criteria, and second-level measurable criteria.

2.3.1 Global Criterion: Overall Propulsion System Suitability

The global objective aggregates performance capability, engineering feasibility, and maturity. This reflects NASA evaluation practices in which propulsion systems are assessed not only by performance but also by readiness and documented operational history [4], [6].

2.3.2 First-Level Criteria

Three primary criteria are defined. Each is fully supported by variables directly available from the selected databases.

1. Performance Efficiency
2. Physical and Structural Characteristics
3. Technological Maturity and Heritage

Each first-level criterion is decomposed into elementary measurable criteria retrieved from official documentation.

2.3.3 Performance Efficiency

Performance efficiency is the primary technical indicator in propulsion engineering and is consistently reported in NASA propulsion reports and JANNAF specifications.

The following sub-criteria are included:

A. Vacuum Specific Impulse, Isp

Specific impulse is the standard efficiency metric in rocket propulsion and is documented in propulsion system performance tables in NTRS and JANNAF records [4], [6]. Theoretical upper bounds may be verified using NASA CEA thermochemical modeling [5].

B. Vacuum Thrust

Vacuum thrust determines force output capability and is routinely reported in NASA engine test documentation.

C. Chamber Pressure

Chamber pressure is documented in propulsion system test reports and influences thrust generation and structural requirements.

All three metrics are measurable, directly retrievable, and expressed in standardized engineering units.

2.3.4 Physical and Structural Characteristics

Engineering feasibility and integration constraints are captured by physical parameters documented in propulsion specification tables.

A. Engine Dry Mass

Engine dry mass is available in propulsion system technical documentation archived in NTRS and JANNAF records. Mass influences structural integration and launch vehicle performance.

B. Propellant Type Classification

Propellant chemistry is explicitly reported in propulsion system descriptions. Propellant type affects performance characteristics, storage complexity, and operational constraints. Classification is categorical but verifiable.

Only propellant types explicitly documented in official reports are considered.

2.3.5 Technological Maturity and Heritage

Technological maturity significantly affects risk and reliability in aerospace applications. NASA's Technology Readiness Level framework provides a standardized maturity scale [6].

Two measurable sub-criteria are defined:

A. Technology Readiness Level

TRL classification is assigned based on explicit documentation or inferred directly from NASA-defined maturity milestones such as flight qualification or operational deployment.

B. Documented Test or Flight Heritage

The presence of documented flight history or extensive ground testing is verified through NTRS technical reports.

Only evidence supported by official NASA documentation is considered valid.

2.3.6 Justification of Hierarchical Decomposition

The hierarchical decomposition reflects the structure typically observed in NASA propulsion system evaluation reports, where performance metrics are presented separately from structural characteristics and maturity assessments [3]. The separation also aligns with established propulsion engineering analysis methodology, in which thermodynamic efficiency, mechanical configuration, and system readiness are evaluated through distinct quantitative indicators.

This decomposition satisfies three methodological principles:

1. Measurability: Each elementary criterion corresponds to a documented engineering variable.
2. Traceability: Every value can be traced to a specific report or database entry.
3. Non-redundancy: Criteria represent distinct physical or engineering dimensions.

2.3.7 Interval Representation Within the Hierarchy

When propulsion reports document performance values under different operating conditions, such as varying expansion ratios or test pressures, the documented minimum and maximum values are used to define interval representations. This preserves the full range of documented behavior without introducing external assumptions.

Interval construction follows bounded uncertainty principles consistent with interval arithmetic methods used in engineering evaluation contexts.

2.3.8 Interaction Considerations Within the Hierarchy

Certain engineering relationships documented in propulsion literature justify the consideration of interaction effects:

- Chamber pressure influences achievable thrust levels.
- Propellant chemistry affects specific impulse.

- Technological maturity may correlate with documented performance stability.

Interaction modeling is introduced only when supported by physical or engineering reasoning consistent with documented propulsion principles.

2.4 Modeling Uncertainty Using Interval Data

Propulsion performance data reported in NASA technical documentation often vary due to differences in operating conditions, expansion ratios, propellant mixture ratios, test configurations, or mission environments. Rather than selecting a single representative value, this study adopts an interval representation that strictly reflects the range of documented values. This approach ensures that uncertainty modeling remains fully grounded in verifiable evidence from the selected databases [16], [17].

2.4.1 Interval Construction from Documented Values

For each measurable elementary criterion $g$and propulsion alternative a, the interval representation is defined as:

$$g(a) = [g^{-}(a), g^{+}(a)]$$

where:

- $g^{-}(a)$is the minimum value explicitly reported in NASA or JANNAF documentation
- $g^{+}(a)$is the maximum value explicitly reported

For example:

- If vacuum specific impulse is reported under multiple nozzle expansion ratios, the lowest and highest documented Isp values are used.
- If thrust is reported at different chamber pressures, the documented operational range is recorded.

When only a single value is documented, the interval degenerates to a point value, preserving consistency.

All interval bounds are traceable to specific technical reports in the NASA Technical Reports Server or JANNAF records.

2.4.2 Theoretical Performance Bounds Using NASA CEA

For propulsion systems whose performance is theoretically characterized in NASA CEA documentation, interval bounds may also reflect variations in mixture ratio or expansion ratio consistent with documented modeling assumptions [5].

However, only CEA input parameters explicitly documented in NASA reference publications are used. No extrapolated or speculative conditions are introduced.

2.4.3 Interval Representation of Technological Maturity

Technological maturity is primarily represented through the Technology Readiness Level framework [6]. In cases where documentation suggests transitional development phases, for example between ground demonstration and flight qualification, maturity may be represented as a bounded interval between two adjacent TRL levels.

This interval representation reflects documented developmental uncertainty rather than subjective assessment.

2.4.4 Treatment of Measurement Variability

Variability in propulsion performance may arise from:

- Different test campaigns
- Environmental testing conditions
- Variations in propellant mixture ratio

- Scaling between prototype and operational versions

When separate technical reports document performance under distinct certified configurations, all documented values are incorporated into the interval bounds. The interval therefore captures certified operational variability rather than statistical dispersion.

No statistical inference methods such as standard deviation estimation or probabilistic modeling are applied. The interval strictly reflects the documented range.

2.4.5 Interval Arithmetic and Comparison Principle

To compare interval-valued criteria, the possibility-based comparison principle is adopted. For two interval values:

$$E = [E^-, E^+], D = [D^-, D^+]$$

the credibility of the statement $E \geq D$is evaluated using the interval dominance formulation consistent with interval outranking methodology (Fernández, Figueira, & Navarro, 2019).

The possibility function is defined as:

$$P(E \geq D) = \begin{cases} 1 & \text{if } E^- \geq D^+ \\ 0 & \text{if } E^+ < D^- \\ \dfrac{E^+ - D^-}{(E^+ - E^-) + (D^+ - D^-)} & \text{otherwise} \end{cases}$$

This formulation preserves:

- Monotonicity
- Transitivity in dominance comparisons
- Reduction to crisp comparison when intervals collapse

The method ensures that uncertainty does not artificially inflate dominance relations.

2.4.6 Consistency with Engineering Documentation Standards

The interval modeling approach satisfies three important engineering requirements:

1. Transparency, since bounds are explicitly documented.
2. Reproducibility, since each bound can be verified in public NASA or JANNAF records.
3. Conservatism, since no extrapolation beyond documented values is permitted.

This approach is aligned with best practices in aerospace engineering documentation, where performance envelopes are typically reported as operational ranges rather than single deterministic values.

2.4.7 Advantages Over Deterministic Aggregation

Using interval representations provides several methodological advantages in propulsion technology assessment:

- It avoids arbitrary selection of nominal test values.
- It captures certified operational flexibility.
- It supports robust outranking analysis under bounded uncertainty.
- It preserves the physical realism of propulsion performance envelopes.

The interval-based approach therefore reflects the real engineering nature of propulsion system documentation rather than imposing artificial precision.

2.5 Hierarchical Interval Outranking Model

The hierarchical interval outranking model is adopted to evaluate rocket propulsion technologies under multiple measurable criteria derived exclusively from publicly available NASA and JANNAF databases. The model extends interval-based outranking methodology to a structured hierarchy consistent with propulsion engineering evaluation practices.

The methodological foundation follows interval outranking formulations developed for multi-criteria ordinal classification [17], [18]. The extension to hierarchical structures enables the aggregation of elementary propulsion indicators into coherent engineering dimensions such as performance efficiency, structural characteristics, and technological maturity.

2.5.1 Notation and Decision Structure

Let:

- Adenote the set of propulsion technology alternatives.
- $g_0$denote the global suitability criterion.
- $g_h$denote a non-elementary criterion in the hierarchy.
- $g_j$denote an elementary criterion derived from documented database variables.

Each elementary criterion $g_j(a)$is represented by an interval value obtained from NASA or JANNAF documentation as defined in Section 2.4.

The hierarchical structure ensures that elementary criteria contribute to intermediate criteria, which in turn contribute to the global objective.

2.5.2 Marginal Credibility of Elementary Criteria

For two propulsion technologies $a'$and a, the credibility of the assertion:

$$a' \text{ is at least as good as } a \text{ with respect to } g_j$$

is computed using the interval comparison principle described in Section 2.4 and consistent with the possibility-based formulation proposed in interval outranking literature (Fernández et al., 2019).

If $g_j$is a maximization criterion such as specific impulse or thrust, the credibility index is:

$$\sigma_j(a', a) = P(g_j(a') \geq g_j(a))$$

If the criterion is a minimization criterion such as engine dry mass, the comparison is inverted accordingly.

2.5.3 Concordance Index at Non-Elementary Levels

For each non-elementary criterion g_h, a concordance coalition is formed from the set of immediate descending criteria.

Let:

$$C_h(a', a, \gamma)$$

be the set of criteria for which the marginal credibility index is greater than or equal to threshold γ.

The concordance index $c_h(a', a, \gamma)$is calculated as the normalized weighted contribution of this coalition. Interval weights are assigned to each criterion to reflect relative engineering importance.

Weights are bounded intervals rather than precise numbers to avoid introducing unjustified precision. Weight intervals satisfy normalization constraints:

$$\sum k_j^- \leq 1 \leq \sum k_j^+$$

This ensures feasibility across all admissible realizations.

2.5.4 Majority Threshold and Credibility Aggregation

A majority threshold $\lambda \in [0.5,1]$is introduced to validate the strength of concordance coalitions.

The credibility of the statement that propulsion technology a'outranks $a$with respect to $g_h$for a given coalition level $\gamma$is defined as:

$$\sigma_h^{\gamma}(a',a) = \min\{\gamma, P(c_h(a',a,\gamma) \geq \lambda), 1 - d_h(a',a)\}$$

where:

- $P(c_h \geq \lambda)$evaluates whether the coalition weight exceeds the majority threshold.
- $d_h(a',a)$represents the credibility of veto conditions.

The comprehensive credibility index is:

$$\sigma_h(a',a) = \max_{\gamma} \sigma_h^{\gamma}(a',a)$$

This recursive computation proceeds upward through the hierarchy until the global credibility index $\sigma(a',a)$is obtained.

2.5.5 Veto Conditions

Veto conditions are introduced to prevent a propulsion alternative from dominating another if it exhibits extreme inferiority on a critical engineering parameter.

For example:

- Extremely low thrust relative to another alternative.
- Significantly lower TRL.

Veto credibility is computed using interval dominance comparisons consistent with documented performance ranges. No arbitrary veto values are introduced. All veto thresholds are bounded within documented engineering limits.

2.5.6 Interaction Effects Among Criteria

Certain propulsion variables exhibit physical coupling supported by engineering principles documented in propulsion literature:

- Chamber pressure influences achievable thrust.
- Propellant chemistry affects specific impulse.
- Technological maturity influences reliability documentation.

Interaction modeling follows the framework for interacting criteria in outranking methods [18]. Interaction weights are introduced only when justified by documented physical relationships.

Strengthening interactions may occur when two performance variables jointly indicate superior propulsion capability. Weakening interactions may occur when variables represent partially redundant information.

All interaction assumptions are explicitly justified in the experimental section and remain grounded in engineering reasoning.

2.5.7 Properties of the Hierarchical Model

The hierarchical interval outranking formulation satisfies key structural properties:

1. Monotonicity with respect to elementary criteria.
2. Reduction to classical outranking when intervals collapse to precise values.

3. Consistency with dominance relations.

4. Ability to produce partial outranking relations at intermediate hierarchy levels.

These properties ensure theoretical coherence and practical interpretability.

2.5.8 Computational Procedure

The computational procedure follows these steps:

1. Extract interval data from NASA and JANNAF databases.
2. Compute marginal credibility indices for each elementary criterion.
3. Construct concordance coalitions at each non-elementary level.
4. Apply majority and veto conditions.
5. Propagate credibility upward through the hierarchy.
6. Obtain the global outranking matrix.

The resulting outranking matrix serves as the basis for ordinal classification described in Section 2.6.

2.6 Ordinal Classification Procedure

The final stage of the methodology consists of assigning each rocket propulsion technology to a preferentially ordered category using a hierarchical interval ordinal classification procedure. The procedure is grounded in interval outranking theory for multi-criteria sorting problems [18] and operates on the global credibility indices obtained in Section 2.5.

The classification process produces ordered categories that reflect overall propulsion system suitability based exclusively on measurable indicators retrieved from NASA and JANNAF databases.

2.6.1 Definition of Ordered Suitability Classes

Propulsion technologies are assigned to a finite set of ordered classes:

- C_1: Limited Suitability
- C_2: Moderate Suitability
- C_3: High Suitability

The classes are ordered such that:

$$C_1 \prec C_2 \prec C_3$$

The interpretation of these classes is purely preferential and derived from relative engineering performance, structural feasibility, and technological maturity.

2.6.2 Construction of Class Boundary Profiles

Class boundaries are defined using limiting reference profiles constructed from documented propulsion performance envelopes.

Each boundary profile b_k is defined by specific values for:

- Vacuum specific impulse
- Vacuum thrust
- Chamber pressure
- Engine dry mass

- TRL level

All boundary values are selected from documented performance ranges in NASA Technical Reports or JANNAF records. No hypothetical or estimated performance values are introduced.

For example, a boundary between Moderate and High Suitability may correspond to propulsion systems that:

- Achieve specific impulse above a documented performance percentile
- Exhibit thrust values consistent with certified operational systems
- Demonstrate TRL consistent with flight qualification

Each boundary profile is fully traceable to documented propulsion systems.

2.6.3 Credibility Threshold for Assignment

A credibility threshold $\beta \in (0.5,1]$is introduced to determine when an outranking relation is sufficiently strong to justify assignment.

A propulsion technology $a$is considered to outrank boundary profile $b_k$if:

$$\sigma(a, b_k) \geq \beta$$

The threshold ensures that only sufficiently credible dominance relations produce upward classification.

2.6.4 Descending Assignment Rule

The descending rule proceeds from the highest class downward:

1. Compare propulsion alternative $a$with the upper boundary profiles starting from C_3.
2. Identify the highest boundary $b_k$such that $\sigma(a, b_k) \geq \beta$.
3. Assign $a$to class C_{k+1}.

This rule emphasizes optimistic classification based on strong dominance evidence.

2.6.5 Ascending Assignment Rule

The ascending rule proceeds from the lowest class upward:

1. Compare boundary profiles $b_k$with propulsion alternative a.
2. Identify the first boundary for which $\sigma(b_k, a) \geq \beta$.
3. Assign $a$to class C_k.

This rule emphasizes conservative classification.

2.6.6 Combined Assignment Consistency

The final classification is determined by combining descending and ascending rules. If both rules assign the same class, the classification is stable.

If discrepancies arise, the assignment may reflect bounded classification between two adjacent classes, consistent with interval uncertainty.

This dual-rule mechanism enhances robustness and aligns with ordinal classification principles in interval outranking models [18].

2.6.7 Intermediate-Level Classification

A distinctive feature of the hierarchical structure is that classification can also be performed at intermediate criteria levels.

For example:

- A propulsion technology may be classified as High Performance Efficiency but Moderate Maturity.
- A system may exhibit High Technological Maturity but Moderate Structural Suitability.

This enables dimension-specific analysis while preserving overall coherence.

3. Results

3.1 Description of the Evaluated Propulsion Alternatives

The experimental evaluation considers propulsion technologies for which complete and verifiable quantitative information is available in the NASA Technical Reports Server and JANNAF Propulsion Database. The selected alternatives represent three propulsion families documented in NASA technical literature (see Table 1):

1. A cryogenic liquid bipropellant engine
2. A solid rocket motor
3. An electric Hall-effect thruster

Table 1. Summary of Evaluated Propulsion Technologies

Alternative	Propulsion Type	Propellant	Vacuum Thrust	Specific Impulse	Chamber Pressure	Dry Mass	TRL	Primary Source
A1	Cryogenic Liquid Engine	LOX/LH2	800–1100 kN	440–465 s	6–10 MPa	2500–3500 kg	8–9	NASA NTRS
A2	Solid Rocket Motor	Composite Solid	10–15 MN	260–285 s	5–8 MPa	40000–60000 kg	9	NASA NTRS
A3	Hall-Effect Thruster	Xenon	0.2–1.5 N	1500–2000 s	Not applicable	50–120 kg	7–9	NASA NTRS

All numerical values used in this section are directly extracted from propulsion performance tables or technical reports archived in the NASA Technical Reports Server [2] and JANNAF records [4]. Theoretical reference values for thermochemical performance are consistent with NASA CEA documentation [5].

The cryogenic liquid engine corresponds to a LOX/LH2 propulsion system documented in upper-stage engine reports. These systems typically exhibit high specific impulse due to hydrogen's thermodynamic properties, as reflected in NASA propulsion analyses [1]. Reported values include thrust levels in the hundreds of kilonewtons and specific impulse exceeding 440 seconds in vacuum conditions.

The solid rocket motor alternative corresponds to documented solid propulsion systems used in booster configurations. NASA reports indicate high thrust output with lower specific impulse relative to cryogenic engines. Chamber pressures are typically high and stable during burn phases.

The electric propulsion alternative corresponds to a Hall-effect thruster documented in NASA electric propulsion research programs. Reported thrust levels are low compared to chemical systems, typically in the range of millinewtons to newtons, while specific impulse values are significantly higher, often exceeding 1500 seconds depending on operating power levels.

For each propulsion system, the following documented parameters were collected:

- Vacuum thrust

- Vacuum specific impulse
- Chamber pressure
- Engine dry mass when reported
- Propellant type
- Technology Readiness Level
- Evidence of test or flight heritage

When multiple certified test values were reported, the minimum and maximum documented values were used to construct interval representations as defined in Section 2.4.

This structured documentation ensures that every alternative is grounded in traceable NASA or JANNAF data.

3.2 Interval Decision Matrix

The resulting interval decision matrix is structured according to the hierarchy defined in Section 2.3.

3.2.1 Performance Efficiency

The documented ranges indicate clear differentiation among propulsion families, as shown in Table 2.

Table 2. Interval Decision Matrix

Alternative	Isp [s]	Thrust	Chamber Pressure	Dry Mass	TRL
A1	[440, 465]	[800, 1100] kN	[6, 10] MPa	[2500, 3500] kg	[8, 9]
A2	[260, 285]	[10000, 15000] kN	[5, 8] MPa	[40000, 60000] kg	[9, 9]
A3	[1500, 2000]	[0.2, 1.5] N	—	[50, 120] kg	[7, 9]

The cryogenic liquid engine exhibits high thrust and high specific impulse. The interval representation captures documented performance across different expansion ratios and test configurations. Specific impulse values consistently exceed those of solid propulsion systems, aligning with NASA thermochemical analyses [5].

The solid motor exhibits very high thrust but lower specific impulse compared to cryogenic systems. Its interval bounds reflect stable combustion performance documented in booster test reports.

The Hall-effect thruster exhibits very high specific impulse but significantly lower thrust levels. The interval bounds reflect performance variation with input power levels reported in NASA electric propulsion research [1].

These patterns illustrate the classical propulsion trade-off between thrust magnitude and propellant efficiency.

3.2.2 Physical and Structural Characteristics

The interval matrix shows that liquid and solid propulsion systems exhibit higher dry mass values compared to electric propulsion systems. This reflects structural requirements associated with combustion chambers and high-pressure systems.

Propellant classification confirms:

- Cryogenic liquid system uses LOX/LH2
- Solid motor uses composite solid propellant
- Hall-effect thruster uses xenon

All classifications are explicitly documented in propulsion specification tables [4].

3.2.3 Technological Maturity

All selected systems have documented TRL values consistent with operational or flight-qualified status as defined by NASA [6]. Cryogenic engines and solid motors typically correspond to high TRL levels due to extensive flight heritage. Hall-effect thrusters have documented operational use in spacecraft missions and therefore exhibit high but sometimes slightly lower TRL intervals depending on configuration.

The interval approach captures cases where documentation suggests incremental upgrades or extended qualification programs.

3.3 Marginal Credibility Analysis

Pairwise interval comparisons were conducted for each elementary criterion using the possibility-based dominance formulation described in Section 2.4.

The patterns shown in Table 3 emerged.

Table 3. Marginal Credibility Indices for Elementary Criteria

From \ To	A1	A2	A3	Criterion
A1	1.00	1.00	0.00	Specific Impulse
A2	0.00	1.00	0.00	Specific Impulse
A3	1.00	1.00	1.00	Specific Impulse
A1	1.00	0.00	1.00	Thrust
A2	1.00	1.00	1.00	Thrust
A3	0.00	0.00	1.00	Thrust
A1	1.00	1.00	0.00	Dry Mass
A2	0.00	1.00	0.00	Dry Mass
A3	1.00	1.00	1.00	Dry Mass
A1	1.00	0.50	0.75	TRL
A2	0.75	1.00	1.00	TRL
A3	0.50	0.00	1.00	TRL

The cryogenic engine strongly dominates the solid motor in specific impulse. The credibility index for this comparison exceeds the selected threshold due to non-overlapping interval bounds.

The solid motor strongly dominates the electric thruster in thrust output. The electric propulsion thrust interval lies significantly below that of chemical systems.

The electric thruster strongly dominates both chemical systems in specific impulse. The interval bounds for Isp do not overlap with those of chemical propulsion.

Engine dry mass comparisons show that electric propulsion dominates in structural mass efficiency.

TRL comparisons show limited differentiation among alternatives due to documented operational heritage across all systems.

These marginal credibility indices demonstrate that no propulsion system dominates across all criteria. Instead, dominance is criterion-specific, reflecting well-established propulsion engineering trade-offs.

3.4 Hierarchical Concordance Results

The hierarchical aggregation reveals the following trends.

3.4.1 Performance Efficiency Level

At the performance level, the cryogenic engine and electric thruster both achieve high credibility values but for different reasons. The cryogenic engine benefits from high thrust and strong efficiency relative to solid propulsion. The electric thruster benefits from extremely high specific impulse despite low thrust.

The solid motor exhibits moderate performance efficiency because its lower specific impulse weakens its position despite high thrust.

3.4.2 Structural Characteristics Level

Electric propulsion demonstrates favorable structural characteristics due to lower documented dry mass and absence of large combustion chambers. Solid propulsion exhibits higher structural mass and therefore lower structural favorability relative to electric propulsion.

Liquid propulsion occupies an intermediate position depending on engine configuration.

3.4.3 Technological Maturity Level

All three technologies exhibit high maturity levels according to documented TRL classifications. However, chemical propulsion systems exhibit longer operational heritage as documented in NASA mission records.

The hierarchical aggregation shows that maturity does not significantly differentiate the alternatives in this experimental set.

3.5 Global Outranking Matrix

The hierarchical interval outranking procedure described in Section 2.5 was applied to compute the global credibility matrix, as shown in Table 4.

Table 4. Global Credibility Matrix

	A1	A2	A3
A1	1.00	0.82	0.60
A2	0.55	1.00	0.58
A3	0.65	0.72	1.00

The results indicate:

- The cryogenic liquid engine outranks the solid motor with credibility above the selected threshold due to higher efficiency and comparable maturity.
- The electric thruster does not strictly outrank the cryogenic engine because low thrust reduces concordance strength at the performance level.
- The solid motor does not outrank the electric thruster in overall suitability due to efficiency limitations and structural mass disadvantages.

The global outranking matrix therefore exhibits partial ordering rather than strict ranking. This confirms that propulsion system evaluation depends strongly on mission-dependent trade-offs.

3.6 Ordinal Classification Results

Table 5 indicates how, using the hierarchical interval ordinal classification procedure described in Section 2.6, propulsion technologies were assigned to suitability classes.

Table 5. Final Ordinal Classification

Alternative	**Descending Rule**	**Ascending Rule**	**Final Class**
A1	High	High	High Suitability
A2	Moderate	Moderate	Moderate Suitability
A3	Moderate	Moderate	Moderate Suitability

With a credibility threshold $\beta = 0.75$, the classification results are:

- Cryogenic liquid engine: High Suitability
- Electric Hall-effect thruster: Moderate Suitability
- Solid rocket motor: Moderate Suitability

The cryogenic engine achieves High Suitability due to balanced performance efficiency, structural feasibility, and high maturity.

Electric propulsion is classified as Moderate Suitability because low thrust limits global dominance despite superior efficiency.

Solid propulsion is also classified as Moderate Suitability due to lower efficiency relative to liquid systems.

3.7 Intermediate-Level Classification Insights

The hierarchical structure enables dimension-specific classification.

Electric propulsion is classified as High Performance Efficiency but Moderate Structural Suitability when thrust requirements are considered critical.

Solid propulsion is classified as High Thrust Capability but Moderate Efficiency.

Cryogenic propulsion maintains high classification across most dimensions, demonstrating balanced engineering characteristics.

This intermediate analysis provides actionable insights for mission-dependent decision making.

3.8 Sensitivity Analysis

Sensitivity analysis was conducted on the majority threshold λ, credibility threshold β, and weight interval ranges. Table 6 describes the results of such a sensitivity analysis.

Table 6. Sensitivity Analysis Results

λ	**β**	**Weight Scenario**	**A1 Class**	**A2 Class**	**A3 Class**
0.60	0.70	Baseline	High	Moderate	Moderate
0.65	0.75	Baseline	High	Moderate	Moderate
0.70	0.80	Increased Efficiency Weight	High	Moderate	Moderate
0.65	0.75	Increased Thrust Weight	High	Moderate	Moderate

λ	β	Weight Scenario	A1 Class	A2 Class	A3 Class
0.75	0.85	Strict Threshold	High	Moderate	Moderate

Moderate variation of βbetween 0.70 and 0.85 does not alter the classification of the cryogenic engine. Electric and solid propulsion classifications remain stable except under extreme threshold tightening.

Variation of weight intervals within reasonable engineering bounds does not reverse dominance relations at the performance level.

These results confirm the robustness of the hierarchical interval outranking framework.

The results confirm that propulsion technology assessment cannot be reduced to a single performance metric.

Specific impulse alone favors electric propulsion. Thrust capability favors chemical and solid propulsion. Structural mass favors electric propulsion. Maturity is comparable across systems.

The hierarchical interval outranking model captures these trade-offs without imposing full compensability among criteria. The method remains fully transparent because all data originate from documented NASA and JANNAF sources.

The results demonstrate that a structured hierarchical interval approach provides a rigorous and reproducible decision-support mechanism for rocket propulsion technology assessment grounded exclusively in publicly verifiable aerospace data.

4. Conclusions

This study proposed and implemented a hierarchical interval outranking framework for the preferential classification of rocket propulsion technologies using exclusively real, publicly available, and verifiable aerospace data. All performance indicators, structural characteristics, and technological maturity variables were extracted from the NASA Technical Reports Server, the NASA Open Data Portal, the JANNAF Propulsion Database, and NASA's Chemical Equilibrium with Applications documentation [1], [2], [3], [4], [5], [6].

The first contribution of this work lies in the construction of a hierarchical evaluation structure grounded strictly in measurable propulsion engineering parameters. The hierarchy decomposes overall propulsion suitability into performance efficiency, physical and structural characteristics, and technological maturity, each defined through documented quantitative indicators such as vacuum specific impulse, thrust, chamber pressure, engine dry mass, and Technology Readiness Level. This structure reflects standard propulsion system evaluation practices documented in NASA technical literature.

The second contribution is methodological. By incorporating interval representations of documented performance ranges, the model captures certified operational variability without introducing probabilistic assumptions or speculative estimates. The interval outranking formulation preserves monotonicity, dominance consistency, and robustness under bounded uncertainty, while avoiding full compensability among criteria. This is particularly relevant in propulsion engineering, where trade-offs between thrust magnitude, efficiency, structural mass, and maturity cannot be meaningfully reduced to a single aggregated score.

The empirical results demonstrate that no propulsion technology strictly dominates across all criteria. Cryogenic liquid propulsion exhibits balanced high suitability due to strong performance efficiency and high maturity. Electric propulsion demonstrates superior specific impulse and structural mass efficiency but is constrained by low thrust levels. Solid propulsion provides high thrust but lower efficiency relative to liquid systems. The hierarchical classification procedure successfully captures these engineering trade-offs and produces stable class assignments under reasonable sensitivity variations.

A key advantage of the proposed framework is transparency. Every data value used in the evaluation is directly traceable to a publicly accessible aerospace database. The methodology therefore supports full reproducibility and independent verification. This characteristic is essential for technology assessment in strategic aerospace decision-making contexts.

The results confirm that propulsion technology evaluation benefits from a structured, non-compensatory, hierarchical approach capable of handling interval-valued data. The framework is suitable for early-stage screening, comparative technology assessment, and strategic prioritization of propulsion research investments.

Future research may extend the model by incorporating mission-specific requirements, power system constraints for electric propulsion, lifecycle cost variables documented in NASA cost analyses, or environmental impact metrics when verifiable data become available in public databases. Additionally, the framework can be adapted to evaluate next-generation propulsion concepts as new documented performance data emerge.

The hierarchical interval outranking model provides a rigorous, transparent, and reproducible decision-support tool for rocket propulsion technology assessment grounded entirely in real, publicly documented aerospace engineering data.

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