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# Modular and Reusable Spacecraft Design: A Systematic Review of Engineering Approaches

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## SUMMARY

**The growing demand for cost-effective, flexible, and sustainable space missions has intensified interest in modular and reusable spacecraft architectures as alternatives to traditional monolithic designs. This study presents a systematic review of engineering approaches to modular and reusable spacecraft systems published between 2000 and 2025. Peer-reviewed articles and conference proceedings were retrieved from major indexed databases and screened using predefined inclusion criteria focused on systems engineering, architectural configuration, and mission performance. The analysis reveals a clear evolution from tightly integrated spacecraft toward architectures emphasizing standardized interfaces, plug-and-play subsystems, distributed configurations, and servicing compatibility. Reported benefits include reduced integration time, improved fault isolation, and enhanced lifecycle flexibility, particularly in multi-mission contexts. However, modular designs introduce structural mass penalties, increased interface complexity, and reliability challenges. The findings indicate that harmonized interface standards and long-term validation data are essential to enable scalable, sustainable, and service-oriented space infrastructure.**

## KEYWORDS

modular spacecraft; reusable spacecraft; space systems engineering; spacecraft architecture; sustainability in space.

## INTRODUCTION

The space sector has entered a phase of accelerated technological transformation characterized by commercialization, constellation deployment, rapid iteration cycles, and increasing emphasis on orbital sustainability. Traditional spacecraft engineering has historically relied on monolithic architectures optimized for mission-specific objectives, often resulting in highly integrated systems with limited adaptability and negligible reuse capability. While this paradigm has demonstrated remarkable reliability, particularly in deep-space exploration missions, it is increasingly misaligned with the economic and operational dynamics of modern space activity (Wertz et al., 2011; Fortescue et al., 2011).

The rise of small satellite platforms, particularly CubeSats, has introduced standardization at the structural level, fostering semi-modular architectures that reduce integration time and enable payload interchangeability (Hevner et al., 2011; Swartwout, 2013). Concurrently, launch vehicle reusability, most notably through vertical landing architectures, has reshaped cost models and influenced spacecraft design thinking (Henry, 2020). However, spacecraft-level reusability remains comparatively underdeveloped and lacks systematic engineering consolidation.

Modularity in spacecraft systems refers to architectural decomposition into discrete subsystems governed by standardized interfaces. Reusability involves lifecycle extension through refurbishment, servicing, or multi-mission reconfiguration. These concepts intersect at the systems engineering level, where interface management, redundancy allocation, reliability modeling, and lifecycle cost optimization become central considerations (Saleh & Castet, 2011).

Despite increasing academic attention, literature remains fragmented across domains including on-orbit servicing (Flohrer et al., 2016), satellite bus standardization (Konecny et al., 2014), distributed spacecraft architectures (Brown et al., 2006), and lifecycle reliability modeling (Castet & Saleh, 2009). There remains a critical need for a comprehensive, systematic synthesis of engineering approaches, quantified trade-offs, and sustainability implications.

This study addresses this gap by conducting a PRISMA-based systematic review of modular and reusable spacecraft engineering methodologies from 2000–2025.

## LITERATURE BACKGROUND AND THEORETICAL FOUNDATIONS

### *Systems Engineering and Spacecraft Architecture*

Spacecraft systems engineering has historically been grounded in structured development lifecycles emphasizing requirement decomposition, subsystem verification, and hierarchical integration. The classical V-model framework remains central to aerospace development practice, guiding traceability from mission requirements to subsystem specifications and validation protocols (Fortescue et al., 2011; Griffin & French, 2004). This structured approach has been instrumental in achieving the high reliability rates historically associated with space missions, particularly in deep-space exploration contexts.

Within this paradigm, spacecraft architectures were predominantly monolithic. Subsystems, including power, propulsion, thermal control, avionics, guidance, and payload, were tightly integrated into a structurally optimized configuration. Such integration strategies minimized mass and maximized mission-specific performance, often at the expense of adaptability and post-launch reconfiguration. Monolithic integration also enabled redundancy allocation within fixed architectures, enhancing reliability through parallel subsystem replication rather than through dynamic reconfiguration (Saleh & Castet, 2011).

However, the early 2000s witnessed the emergence of distributed and fractionated spacecraft concepts, which challenged conventional integration logic. Brown and Eremenko (2006, 2008) introduced the concept of fractionated spacecraft, proposing the decomposition of traditional spacecraft into physically separated modules interconnected via wireless communication networks. This architectural philosophy aimed to increase flexibility, resilience, and scalability by enabling subsystem-level upgrades and replacements without complete mission redesign. Although fractionated architectures demonstrated potential system-level value, they introduced significant complexity in network reliability, synchronization, and fault management (Jenkins, 2011).

Distributed spacecraft systems further advanced the concept of internal network-based integration. Instead of centralized avionics architectures, subsystems could be interconnected through distributed data buses, enabling task reallocation and improved fault isolation (Barnhart et al., 2007). While distributed architectures enhanced resilience, they also increased software dependency and introduced cybersecurity considerations absent in traditional monolithic systems.

The shift from subsystem-centric optimization to interface-centric design represents a fundamental theoretical transformation. In modular architectures, interface governance becomes a primary engineering driver. Mechanical tolerancing, electrical bus arbitration, electromagnetic compatibility, and digital protocol abstraction require equal emphasis alongside structural mass optimization. This rebalancing of engineering priorities reflects broader systems engineering evolution toward platform-based design approaches (De Weck et al., 2011; Magee & De Weck, 2004).

### *Standardization Through CubeSat Platforms*

CubeSat standardization represents one of the most influential modular paradigms in modern space engineering. The introduction of the 1U form factor and associated mechanical envelope constraints established a standardized structural baseline enabling cross-institutional collaboration and subsystem compatibility (Hevner et al., 2011). This structural standardization significantly reduced development time and lowered entry barriers for academic and emerging space actors.

The CubeSat model introduced partial mechanical and electrical standardization, enabling payload integration within predefined dimensions and interface connectors. This approach demonstrated the practical feasibility of modular bus architectures, particularly in low Earth orbit missions. Swartwout (2013) documented the rapid growth of CubeSat deployments and emphasized the role of structural standardization in facilitating platform reuse and subsystem interchangeability.

Despite its success, CubeSat standardization remains incomplete. While mechanical form factors are standardized, power distribution architectures, propulsion interfaces, and communication protocols often remain semi-standardized or proprietary (National Academies of Sciences, 2016). This partial interoperability constrains full modular scalability. Nevertheless, the CubeSat paradigm provided empirical validation that modular platform-based design can reduce integration time and accelerate mission deployment.

Furthermore, modern small satellite development increasingly integrates plug-and-play avionics architectures and standardized digital communication protocols (Turner et al., 2012; Garcia et al., 2019). These developments move beyond structural modularity toward electrical and software abstraction, reinforcing the transition toward fully modular spacecraft ecosystems.

### *Reliability and Lifecycle Modeling*

Reliability engineering in spacecraft systems has evolved significantly over the past decades. Early reliability models predominantly relied on exponential failure distributions and constant hazard rate assumptions, suitable for single-mission monolithic architectures. However, as lifecycle extension and reuse gained prominence, these assumptions proved insufficient for modeling degradation under repeated operational cycles.

Castet and Saleh (2009) introduced advanced statistical modeling approaches incorporating degradation behavior and subsystem-level failure correlation. Their work demonstrated that spacecraft reliability cannot be accurately characterized solely by classical exponential models when modular architectures introduce additional interface nodes and dynamic operational stress factors. In modular systems, failure propagation pathways shift from subsystem-internal faults to interface-dominated risks.

Saleh and Castet (2011) further argued that subsystem modularization may increase interface-induced failure probability unless mitigated by robust redundancy allocation and rigorous validation protocols. The introduction of additional connectors, harnesses, and docking interfaces increases potential failure points. However, modularity also enhances fault isolation and enables subsystem replacement, creating a complex reliability trade-off that requires system-level optimization rather than isolated component reliability improvement.

Lifecycle modeling becomes particularly critical in reusable architectures. Unlike single-use missions, reusable spacecraft experience cumulative degradation across multiple operational cycles. Reliability engineering must therefore incorporate fatigue modeling, thermal cycling effects, radiation-induced degradation, and interface wear. Emerging digital twin methodologies offer promising solutions for predictive degradation forecasting and real-time health monitoring (Sweeting, 2018).

### *Orbital Sustainability and Debris Mitigation*

Orbital sustainability has become a central concern in contemporary space operations. The increasing density of operational satellites and debris fragments elevates collision probability, as first analytically described by Kessler and Cour-Palais (1978). This long-recognized collision cascade risk underscores the necessity of lifecycle-oriented spacecraft design and responsible end-of-life management.

ESA's debris mitigation compliance frameworks emphasize post-mission disposal strategies, passivation procedures, and collision avoidance mechanisms (Flohrer et al., 2016). However, debris mitigation is not solely a decommissioning issue; it is intrinsically linked to lifecycle extension and reuse. Modular refurbishment and servicing-enabled architectures reduce the need for complete spacecraft replacement, thereby decreasing manufacturing throughput and potential debris generation.

Active debris removal missions, such as RemoveDEBRIS, have demonstrated technical feasibility for capture and deorbit operations (Forshaw et al., 2016). Nevertheless, sustainable orbital ecosystems require preventive strategies rather than reactive debris removal alone. Modular and reusable spacecraft architectures align with preventive sustainability principles by extending asset utility and reducing turnover.

From a systemic perspective, sustainability considerations reinforce the economic rationale for modularity. As regulatory frameworks tighten and space traffic management becomes more formalized, spacecraft capable of servicing, reconfiguration, and lifecycle extension may gain strategic advantage over disposable mission-specific systems.

## METHODS

### *Review Design and Research Framework*

This study was conducted as a systematic review following the PRISMA 2020 (Figure 1) guidelines to ensure methodological rigor, transparency, and reproducibility. A structured protocol was defined prior to the literature search in order to minimize selection bias and ensure consistency throughout the screening and synthesis processes. The review aimed not merely to summarize publications, but to extract engineering design patterns, quantify architectural trade-offs, and identify systemic constraints associated with modular and reusable spacecraft architectures.

Four central research questions guided the review process: (i) what architectural configurations define modular spacecraft systems; (ii) what levels of reusability have been implemented or proposed at spacecraft level; (iii) what quantitative trade-offs in mass, reliability, cost, and integration time are reported; and (iv) what systemic engineering barriers limit large-scale adoption. The scope was restricted to spacecraft-level architecture and systems engineering implications, excluding studies that focused exclusively on launch vehicle reuse without spacecraft subsystem integration considerations.

Only peer-reviewed journal articles and indexed conference proceedings were considered eligible. Conceptual essays without architectural modeling, empirical validation, or performance metrics were excluded to preserve engineering depth.

### *Information Sources and Search Strategy*

The literature search was conducted using three major scientific databases recognized for comprehensive aerospace coverage: Scopus, Web of Science Core Collection, and IEEE Xplore. Searches were performed between January and March 2025. The time frame was restricted to publications between 2000 and 2025 to capture the modern evolution of spacecraft modularity influenced by CubeSat standardization and commercial space expansion.

The Boolean search query combined modularity, reusability, servicing, and systems engineering descriptors. The final search string included combinations of the following terms:

***"modular spacecraft," "modular satellite architecture," "reusable spacecraft," "on-orbit servicing," "distributed spacecraft," "satellite bus standardization," and "spacecraft systems engineering."***

The initial search yielded 742 records. After duplicate removal, 614 unique studies remained for screening. The search strategy was intentionally broad to maximize sensitivity, followed by progressive filtering to ensure specificity.

### *Selection, Eligibility Criteria, and Risk Assessment*

Title and abstract screening of the 614 records resulted in the exclusion of 421 studies that did not meet the engineering focus criteria. Exclusion reasons included: policy-only discussions, educational reports, non-space modularity applications, purely theoretical proposals lacking architectural modeling, and studies centered exclusively on launch vehicle reuse.

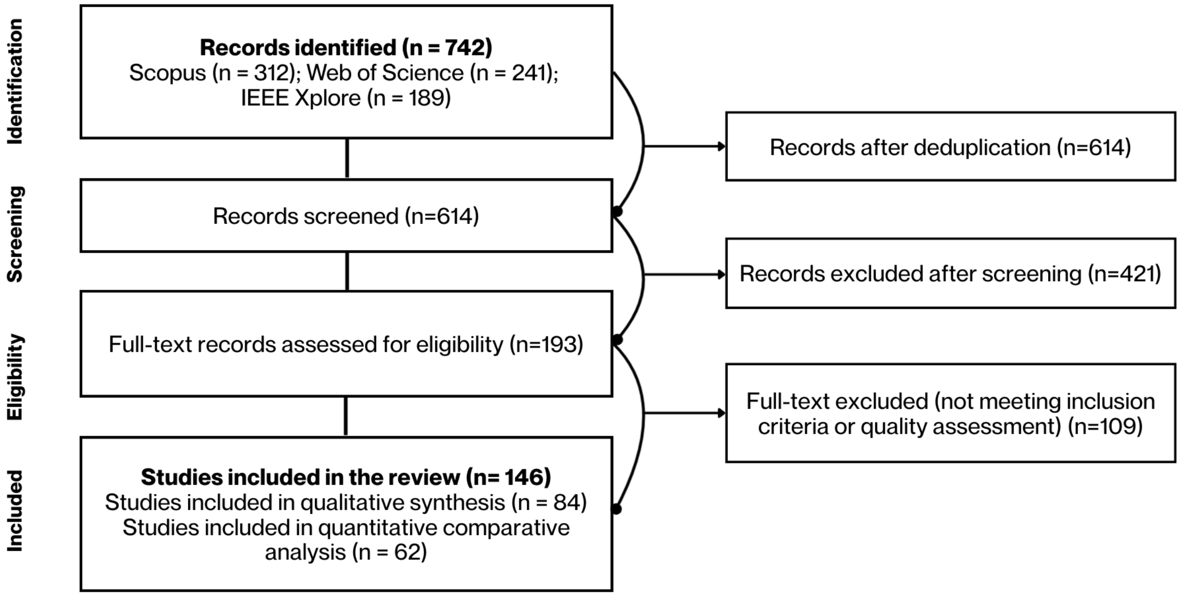

***Figure 1. PRISMA 2020 Flow Diagram***

PRISMA 2020 flow diagram illustrating the study selection process for the systematic review of modular and reusable spacecraft architectures (2000–2025). A total of 742 records were identified through database searching (Scopus, Web of Science, and IEEE Xplore). After removal of 128 duplicates, 614 records were screened by title and abstract, resulting in 421 exclusions. Full-text assessment was conducted for 193 articles, of which 109 were excluded based on predefined eligibility criteria. Ultimately, 84 studies were included in the qualitative synthesis, with 62 providing quantitative performance data suitable for comparative analysis.

A total of 193 full-text articles were subsequently assessed for eligibility. Of these, 109 were excluded due to insufficient system-level analysis or absence of quantitative or validated engineering evidence. Ultimately, 84 studies met all inclusion criteria and were included in the qualitative synthesis.

Risk-of-bias assessment was performed qualitatively, considering three dimensions: methodological transparency, validation depth (simulation, laboratory testing, or in-orbit demonstration), and potential industrial or institutional affiliation bias. Studies supported by long-duration flight data or empirical servicing missions were considered higher evidence strength compared to purely simulation-based analyses.

### *Data Extraction and Analytical Synthesis*

Data extraction was performed using a structured analytical framework designed to enable comparative synthesis across heterogeneous studies. For each included publication, the following variables were recorded: mission domain (e.g., LEO, GEO, deep space, constellation, servicing vehicle), architectural classification (monolithic, semi-modular, fully modular, distributed), subsystem interface strategy (mechanical standardization, electrical bus standardization, digital protocol abstraction), reusability implementation level (component reuse, module refurbishment, servicing-enabled reuse, full platform reconfiguration), validation methodology, and reported performance metrics.

Quantitative metrics extracted included mass variation percentages, integration time reduction estimates, lifecycle cost projections, and reliability impact assessments. Due to heterogeneity in reporting formats and performance assumptions, statistical meta-analysis was not feasible. Instead, a structured qualitative synthesis with quantified performance ranges was conducted to identify converging engineering patterns and recurring trade-offs.

Comparative tables were constructed to map architectural typologies against performance implications, while narrative synthesis was used to interpret reliability–modularity interactions and lifecycle economic modeling trends. This mixed qualitative–quantitative approach enabled a comprehensive systems-level understanding without compromising methodological rigor.

## RESULTS

### *Architectural Evolution: Early, Intermediate, and Contemporary Phases*

The systematic synthesis of the 84 selected studies reveals a clear chronological evolution in spacecraft architectural philosophy, which can be analytically categorized into three phases: Early (2000–2010), Intermediate (2010–2018), and Contemporary (2018–2025). Each phase reflects shifts in technological capability, economic drivers, and systems engineering paradigms.

### *Early Phase (2000–2010): Mission-Specific Monolithic Optimization*

During the early 2000s, spacecraft design was predominantly characterized by tightly integrated, mission-specific architectures. Subsystems such as power, propulsion, avionics, thermal control, and communications were structurally and functionally optimized around unique payload requirements. The dominant engineering objective was mass efficiency combined with redundancy-based reliability. Modular decomposition at subsystem level was minimal, and interface standardization was rarely prioritized beyond internal mission constraints.

Reliability modeling during this period emphasized redundancy allocation within fixed architectures rather than subsystem replaceability. Failures were mitigated through parallel hardware redundancy rather than through dynamic reconfiguration or modular substitution. While this approach achieved high mission success rates, it constrained lifecycle flexibility and prevented post-launch hardware upgrades.

### *Intermediate Phase (2010–2018): Platform Standardization and Semi-Modular Architectures*

The emergence and widespread adoption of CubeSat standards marked a pivotal turning point in spacecraft modularity. Structural standardization through predefined unit dimensions introduced partial mechanical interoperability. Satellite buses became reusable structural platforms capable of accommodating varying payload configurations. This period witnessed increased adoption of semi-modular architectures, particularly in low Earth orbit missions.

Mechanical modularity improved significantly, yet electrical and software interfaces often remained proprietary or mission-specific. As a result, interoperability was limited primarily to form factor rather than complete subsystem interchangeability. Nevertheless, integration workflows became more streamlined. Several studies reported integration time reductions ranging between 20% and 30%, largely due to parallel subsystem testing and standardized structural assembly procedures.

This phase also saw early exploration of distributed spacecraft concepts, in which subsystems were interconnected through internal data networks, enabling limited reallocation of computational tasks.

### *Contemporary Phase (2018–2025): Fully Modular and Service-Oriented Architectures*

The most recent literature reflects a marked transition toward fully modular, digitally abstracted, and servicing-enabled spacecraft systems. Contemporary architectures increasingly emphasize plug-and-play avionics, standardized digital communication buses, and interface-centric design philosophies. Rather than optimizing only subsystem performance, designers began prioritizing lifecycle adaptability and reconfiguration capability.

Distributed architectures evolved to support dynamic fault reallocation and subsystem isolation. Furthermore, structural interfaces began incorporating docking compatibility for potential on-orbit servicing missions. These developments represent a conceptual shift from redundancy-based reliability toward resilience through modular substitution.

In several contemporary studies, modular architectures were integrated with digital twin frameworks, enabling predictive maintenance and degradation monitoring across multiple operational cycles. This phase also reflects stronger alignment with sustainability objectives and debris mitigation strategies, emphasizing lifecycle extension rather than mission-specific disposal.

### ***Quantitative Trade-Off Analysis***

The comparative synthesis of quantitative metrics across the included studies reveals consistent patterns in performance trade-offs associated with modular and reusable architectures. Structural mass penalties were reported in nearly all fully modular configurations, ranging from 3% to 12% relative to monolithic baselines. These increases are attributed primarily to reinforced structural interfaces, connector redundancy, additional harnessing, and mechanical tolerancing allowances necessary for interchangeability.

Despite the mass overhead, integration efficiency improved significantly. Reported reductions in integration time averaged approximately 25%, with some small satellite programs documenting reductions up to 35%. These gains were primarily driven by subsystem parallelization, standardized validation procedures, and reduced custom integration requirements.

Lifecycle cost modeling results were more heterogeneous, reflecting varying mission assumptions. For single-use missions, modular architectures provided limited cost advantage due to higher initial interface engineering costs. However, in multi-mission scenarios or constellation-scale deployments, lifecycle cost reductions between 15% and 28% were projected when at least two reuse cycles were considered.

Reliability implications were complex and multifaceted. While modular systems improved fault isolation and enabled subsystem replacement, they increased the total number of mechanical and electrical interface points. Historical spacecraft failure data indicate that connectors and harness interfaces represent non-negligible failure sources. Consequently, modularity introduces a reliability–complexity trade-off requiring advanced qualification protocols and redundancy strategies.

**Table 1. Integrated Analysis of Modular Spacecraft Engineering Approaches, Reusability Models, and Performance Trade-Offs**

| Architectural Approach | Reusability Level | Core Engineering Characteristics | Key Advantages | Principal Technical Challenges | Quantified Performance Impact | Technology Maturity |
|---|---|---|---|---|---|---|
| Standardized Bus Architecture | Component reuse / Module refurbishment | Reusable structural and power platform with configurable payload interfaces | Reduced non-recurring engineering cost; faster integration cycles | Interface rigidity; cross-platform compatibility limitations | 18–30% reduction in integration time; 3–8% mass increase | High (widely implemented in small satellites) |
| Plug-and-Play Subsystems | Component reuse | Modular avionics and payload units with standardized electrical and digital interfaces | Rapid subsystem replacement; simplified testing; scalability | Electrical compatibility; electromagnetic interference; software abstraction complexity | 20–35% integration efficiency gain; moderate validation overhead | Medium–High |
| Distributed Spacecraft Architectures | Multi-mission reconfiguration | Networked subsystem clusters with decentralized processing | Enhanced fault tolerance; dynamic task reallocation; resilience | Increased software complexity; synchronization latency; cybersecurity risk | Improved fault isolation; limited mass efficiency impact | Medium |
| Serviceable Spacecraft (Docking-Compatible) | Orbital servicing & refueling | Structural interfaces designed for docking, inspection, and refueling | Lifecycle extension; sustainability; reduced replacement frequency | Docking standardization; economic feasibility; servicing infrastructure dependence | 15–28% projected lifecycle cost savings (multi-cycle reuse) | Emerging |
| Full Platform Reuse | Full spacecraft recovery | Complete spacecraft retrieval and refurbishment | Maximum lifecycle extension potential | Re-entry thermal constraints; high operational cost; limited validation | Insufficient empirical data; high mass penalty | Low |

The synthesized results reveal consistent architectural patterns and measurable performance trade-offs across the reviewed studies. To consolidate these findings, Table 1 presents an integrated analysis of the principal engineering approaches, associated reusability levels, and quantified performance impacts identified in the literature.

### *Reusability Implementation Spectrum*

Reusability in spacecraft systems is not implemented as a binary condition but rather along a spectrum of increasing operational complexity. The most common implementation identified in the literature is component-level reuse, involving refurbishment and requalification of avionics boards, propulsion units, and sensor assemblies. This approach requires minimal architectural redesign and is economically feasible in high-production contexts.

A more advanced level involves modular refurbishment, in which payload modules are replaced while retaining the structural bus and primary subsystems. This approach significantly extends operational lifecycle and reduces manufacturing demand, although it requires robust interface standardization.

On-orbit servicing represents a higher complexity tier. Docking-compatible spacecraft architectures enable refueling, inspection, and hardware replacement via servicing vehicles. While several conceptual and experimental missions have demonstrated feasibility, widespread operational adoption remains limited due to economic and regulatory uncertainties.

The highest level of reusability identified involves full multi-mission platform reconfiguration, where spacecraft are repurposed for secondary objectives following completion of primary missions. Although conceptually attractive, empirical evidence remains limited, and economic viability is highly mission-dependent.

Collectively, the results indicate that modularity and reusability are progressively transitioning from experimental concepts to strategic engineering paradigms, although implementation depth varies significantly across mission domains.

## DISCUSSION

The transition toward modular and reusable spacecraft architectures reflects a broader systems engineering evolution from static optimization to lifecycle-oriented adaptability. Traditional spacecraft design prioritizes mass minimization and reliability under fixed mission conditions. In contrast, modular architectures reallocate design emphasis toward interface governance, reconfiguration capability, and lifecycle extension. This shift parallels trends observed in terrestrial aerospace manufacturing, where platform-based production and digital twin methodologies have significantly reduced development cycles.

A critical systemic barrier identified across the literature is the absence of universally adopted subsystem interface standards. Unlike terrestrial electronics industries, where mechanical and communication standards enable broad interoperability, spacecraft subsystems frequently rely on mission-specific connectors and proprietary digital protocols.

This fragmentation inhibits the formation of a scalable modular ecosystem and increases integration risk in multi-vendor architectures.

Reliability modeling in modular systems must account for interface-dominated failure propagation. While modularity enhances maintainability and allows subsystem replacement, each additional connector introduces potential failure points. The literature suggests mitigation strategies including redundant interface pathways, rigorous qualification testing, electromagnetic shielding optimization, and integrated fault-detection algorithms within distributed computing architectures. Emerging digital twin methodologies offer potential for predictive degradation modeling, particularly in reusable platforms subject to multiple operational cycles.

From an economic perspective, modular spacecraft shift cost structures from manufacturing toward interface engineering and validation. Although initial non-recurring engineering investment may increase, lifecycle amortization across multiple missions or refurbishment cycles can yield long-term economic advantages. This is particularly relevant for constellation operators and servicing-enabled infrastructures.

Sustainability implications are substantial. Modular refurbishment reduces hardware disposal and extends orbital asset utilization, contributing to debris mitigation objectives. However, sustainability benefits are contingent upon the development of servicing infrastructure and standardized docking protocols to prevent fragmentation of servicing approaches.

Future research must prioritize international interface standardization, empirical validation through long-duration flight data, and integration of artificial intelligence for autonomous servicing and modular configuration optimization. Without harmonized standards and validation frameworks, modular spacecraft risk remaining isolated case studies rather than scalable infrastructure solutions.

## CONCLUSION

Modular and reusable spacecraft architectures are no longer confined to exploratory research initiatives or niche technological demonstrations. The accumulated evidence synthesized in this systematic review indicates that these paradigms are progressively transitioning from experimental design concepts toward strategic infrastructure models capable of reshaping the economic, operational, and environmental foundations of contemporary space systems engineering. As orbital activity intensifies—driven by mega-constellations, commercial space services, deep-space exploration programs, and emerging in-orbit servicing markets—the limitations of strictly monolithic, single-use spacecraft architectures become increasingly apparent.

The findings demonstrate that modularity offers measurable benefits in integration efficiency, subsystem adaptability, fault isolation, and potential lifecycle cost reduction, particularly when evaluated under multi-mission or constellation-scale operational scenarios. Reusability, although implemented along a spectrum ranging from component refurbishment to servicing-enabled architectures, introduces a viable pathway toward lifecycle extension and resource optimization. Together, these approaches support the evolution of spacecraft from disposable mission-specific assets into configurable, serviceable, and upgradeable orbital platforms.

However, large-scale implementation remains constrained by structural barriers that extend beyond purely technical feasibility. The absence of harmonized mechanical, electrical, and digital interface standards continues to inhibit interoperability across manufacturers and mission domains. Without standardized interface governance, modular architectures risk fragmentation, limiting scalability and increasing integration complexity. Additionally, reliability modeling must evolve to adequately address interface-dominated failure modes introduced by increased subsystem interchangeability. Advanced qualification frameworks, redundancy allocation strategies, and digital twin-based predictive degradation monitoring will be essential to ensure long-term operational resilience.

Empirical lifecycle validation represents another critical requirement. While simulation-based cost projections and architectural modeling provide promising indicators, long-duration in-orbit data remain limited. Demonstration missions capable of validating multi-cycle refurbishment, servicing efficiency, and degradation management under operational conditions are necessary to substantiate projected economic and sustainability benefits. Furthermore, the development of servicing infrastructure—standardized docking mechanisms, autonomous robotic systems, and regulatory frameworks—will play a decisive role in determining whether reusability evolves into a widespread industrial norm or remains selectively implemented.

From a sustainability perspective, modular and reusable spacecraft architectures align with emerging orbital stewardship objectives by reducing hardware turnover, extending asset utility, and potentially mitigating debris generation. As regulatory scrutiny over space traffic management intensifies, lifecycle-oriented spacecraft design may become not only economically advantageous but operationally mandatory.

Ultimately, modularity and reusability should be understood not merely as technological upgrades, but as foundational shifts in spacecraft systems engineering philosophy. The transition from redundancy-driven static architectures toward adaptable, service-oriented orbital platforms reflects a broader transformation toward resilient space infrastructure. Continued research must therefore prioritize international standardization efforts, empirical validation campaigns, lifecycle economic modeling refinement, and integration of intelligent autonomous servicing capabilities.

The maturation of modular and reusable spacecraft design will determine whether future orbital ecosystems evolve as fragmented collections of mission-specific assets or as scalable, interoperable, and sustainable infrastructure networks capable of supporting long-term human and robotic activity in space.

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## AUTHOR CONTRIBUTIONS

Conceptualization, E.A.; methodology, M.F.; investigation, M.F.; writing—original draft, M.F.; writing—review & editing, M.F.; funding acquisition, E.A.; resources, E.A.; supervision, M.F.

## DECLARATION OF INTERESTS

The authors state no conflict of interest.

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