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A SYSTEMS ENGINEERING FRAMEWORK FOR ADOPTING RAPIDLY EMERGING TECHNOLOGY ITEMS DURING THE DEVELOPMENTAL PHASE – AIRCRAFT SYSTEM DESIGN CASE

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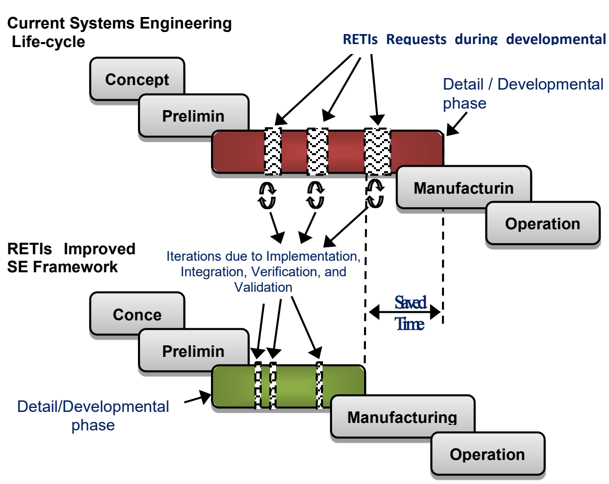
Graphical Abstract



Abstract

The rapid emerging evolution of the aerospace industry, driven by continuous advancements in technologies such as electric propulsion, autonomous systems, and advanced materials, presents both opportunities and challenges. The integration of these Rapidly Emerging Technology Items (RETIs) during the developmental phase of Systems Engineering (SE) introduces significant complexity, often resulting in project delays and cost overruns. This study proposes an improved SE framework designed to address these challenges by facilitating the efficient incorporation of RETIs during the developmental phase of the system engineering processes. Drawing on feedback from 21 industry experts, each with over 15 years of experience, the study identifies effective strategies to streamline RETI adoption. Qualitative analysis revealed that the improved framework—featuring enhanced communication between RETI drivers and design organizations, a rigorous screening process, integrated techniques, and a centralized repository for data management—significantly reduces the time required for technology integration while maintaining competitive advantages. The findings demonstrate that the proposed framework improves technical performance, ensures system safety, and optimizes the integration process during the developmental phase. By addressing the limitations of traditional SE methodologies, this research provides a comprehensive solution to the challenges posed by RETIs, offering a scalable and efficient approach for modern engineering applications..

Keywords: *Systems Engineering, Development phase, Rapidly Emergent Technology Items, Aircraft design, Systems.*

1.0 INTRODUCTION

The aerospace industry is rapidly evolving due to advancements in emerging technologies, such as electric propulsion, autonomous systems, and advanced materials. These innovations not only enhance performance, safety, and efficiency but also meet regulatory demands and help companies maintain a competitive edge. The integration of these technologies is particularly critical during the developmental phase of Systems Engineering (SE), a pivotal stage in the SE life cycle [1, 2]. However, incorporating Rapidly Emerging Technology Items (RETIs) introduces challenges, including increased complexity, iterative design demands, and the risk of project delays and cost overruns [3, 4].

Systems Engineering (SE) is an interdisciplinary methodology focused on ensuring the successful realization of complex systems. By integrating multiple disciplines, SE addresses the needs of customers, users, and stakeholders while balancing technological, financial, and operational considerations [1]. This study enhances the traditional Vee-model of SE by incorporating four key improvements to better manage the integration of RETIs, including promoting stronger communication between RETI drivers and the Design Organization (DO) through Technology Alliances, a Screening mechanism for compatibility, the

Aggregation of RETIs using the Subset Technique, and a centralized repository to improve stakeholder communication and automate processes. These improvements aim to streamline integration and improve system efficiency.

2.0 MOTIVATION

The adoption of the Systems Engineering (SE) approach is essential for both current and future systems design for several reasons. Firstly, SE effectively reduces design and development cost overruns and rework by providing a structured framework for managing complexity and mitigating risks [4]. As systems become increasingly complex, SE plays a critical role in preventing system failures and managing uncertainties throughout the development process [5]. Additionally, SE provides a structured framework that facilitates monitoring technical progress, ensuring timely project delivery, and supporting workflow comprehension. Integrating SE within the Design Organization (DO) enhances returns on investment and reduces overall delivery costs [4]. However, the responsibility lies with systems engineers to develop strategies that enhance product modularity and adaptability, allowing for seamless modifications during both the design phase and the lifecycle of the product.

3.0 HOW SYSTEMS ENGINEERING CONTRIBUTE TO PROJECT EFFICIENCY AND BUDGETARY OUTCOMES

A study by Madni and Purohit [6] on Model-Based Systems Engineering (MBSE) further highlights its positive impact on cost and timeline efficiencies in large-scale aerospace and defense projects. Their research shows that MBSE adoption increased engineering output by over 60%, improved quality, and expanded project scope without additional funding. This was largely achieved through early defect detection, model reuse, and reduced rework in later stages of the system life cycle.

Similarly, a NASA case study by Holladay, Knizhnik [7] highlights significant reductions in cost, schedule, and rework in aerospace projects by utilizing MBSE practices, showcasing the clear, tangible benefits of advanced Systems Engineering methodologies for effectively managing complex systems. These examples demonstrate the real, tangible benefits of using advanced SE methods to manage complex projects more efficiently.

However, it is important to recognize that adopting SE methodologies does not come without challenges. The initial costs of adoption, specialized skills required, and organizational culture play a critical role in determining the success of SE integration. These factors highlight the complexity of realizing the full potential of SE methodologies in practice.

4.0 PROBLEM STATEMENT

The challenges associated with Systems Engineering (SE) in the aviation industry emerge from three distinct angles: components (emerging technologies), methodologies (SE design processes), and the systems themselves (aircraft).
Figure 1 illustrates these challenges, offering a comprehensive view of how these factors interact to complicate system design during the developmental phase.

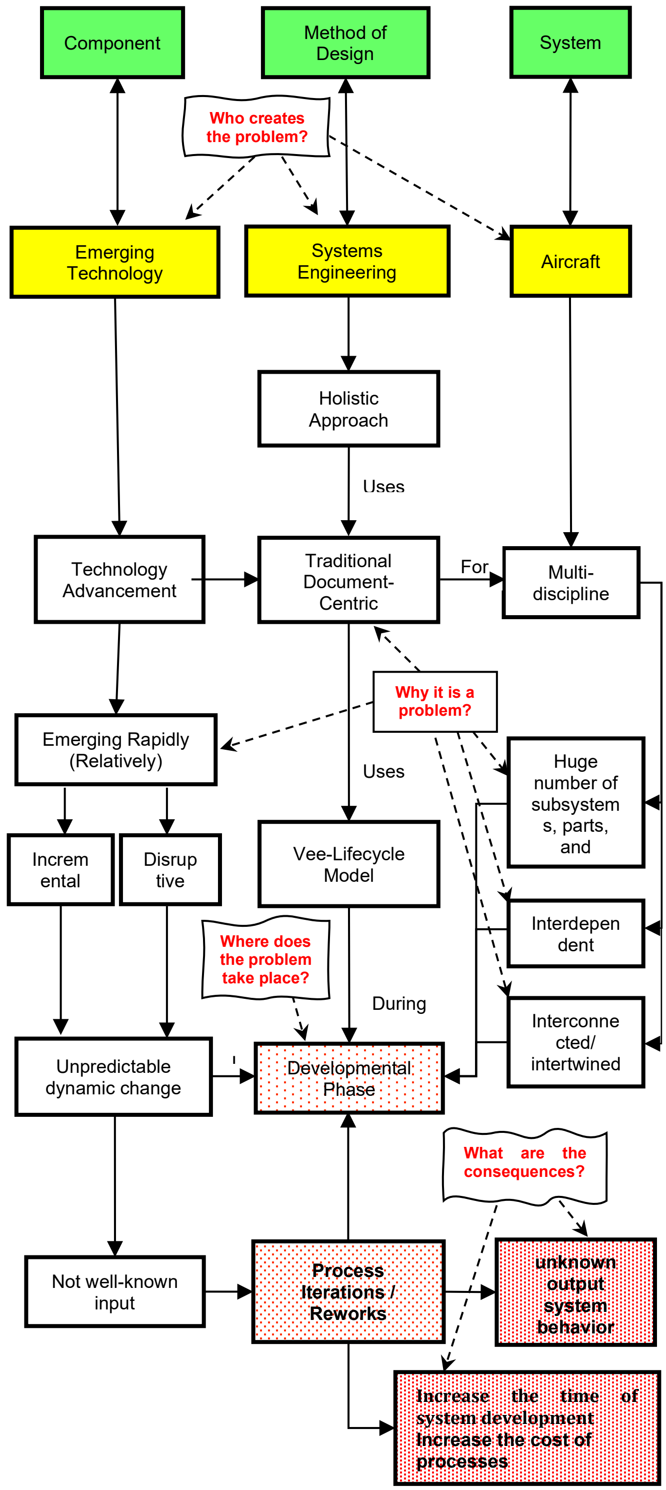


Figure 1 Study problem flowchart

First, emerging technologies, represented as components in Figure 1, evolve rapidly and unpredictably, introducing unfamiliar inputs that disrupt established design processes. These technologies, while offering opportunities for innovation and competitive advantage, also bring increased complexity that existing SE frameworks struggle to accommodate [4]. The integration of Rapidly Emerging Technology Items (RETIs) into system design adds an additional layer of difficulty, requiring systems engineers to navigate the uncertainties associated with new components.

Second, the **system** itself (aircraft) is a highly complex and multidisciplinary entity, consisting of numerous interconnected subsystems and components [8, 9]. As shown in Figure 1, the interconnectedness and interdependence of these subsystems increase the complexity of the design process, leading to iterative cycles that extend development timelines and increase costs [3]. The unpredictability of system behavior becomes especially apparent when new technologies are introduced—technologies that may bring unknown inputs not previously considered. These unknown inputs make it difficult to predict and control system outcomes [5, 10]

Third, **traditional SE models**, such as the Vee-lifecycle, face significant challenges in managing the fast-paced changes introduced by Rapidly Emerging Technology Items (RETIs). As illustrated in Figure 1, both emerging technologies and system complexities converge during the developmental phase—the longest and most critical stage of systems engineering [9]. The rigid, document-centric nature of traditional models struggles to keep up with the rapid innovation cycles, especially in industries like aviation [4].

Emerging technologies introduce unpredictable and incremental changes, often disrupting established SE processes. This leads to rework, delays, and cost overruns as engineers attempt to integrate these changes late in developmental phase. Additionally, the complex and interconnected nature of aircraft systems—comprising numerous interdependent subsystems—further complicates the process. These interdependencies make the development phase increasingly iterative, stretching timelines and inflating budgets.

In short, the developmental phase is where these challenges manifest most severely [11]. To mitigate these issues, a more adaptive SE framework is essential for efficiently integrating RETIs during the development phase and managing the complexity of modern systems.

5.0 EXISTING SYSTEMS ENGINEERING FRAMEWORK

In the field of Systems Engineering (SE), a significant portion of the literature has focused on frameworks aimed at improving internal processes, risk management, and enhancing methodological agility. While these aspects are vital to SE, there is a noticeable gap in addressing the challenges posed by RETIs and their integration into complex systems. The fast pace of technological innovation introduces new complexities that traditional frameworks often struggle to manage effectively.

5.1 Enterprise and Agile Frameworks

McDermott, Henderson [12] enterprise systems engineering framework successfully incorporates Model-Based Systems Engineering (MBSE) and Digital Engineering (DE) to manage interconnected systems within enterprises. While their framework offers a structured approach to emerging technologies, it lacks sufficient flexibility to handle the continuous and unpredictable introduction of new technologies. This challenge is particularly perceptive in sectors where technological advancements happen at an unprecedented pace, leading to a need for frameworks that can dynamically evolve alongside external innovations.

Similarly, the Agile Systems Engineering (ASE) Framework is noted for its ability to manage complexity through iterative development and the integration of MBSE. The adaptability of ASE makes it an effective approach for subsystem integration in environments with evolving requirements. However, despite its flexibility, ASE encounters difficulties in large-scale projects where multiple disciplines and technologies must be integrated swiftly. The framework does not fully address the complexities involved in managing rapidly evolving external technologies, which can disrupt established systems [13].

5.2 Adaptive Frameworks

The Collective Adaptive Systems (CAS) Framework by Wirsing, Jähnichen [14] attempts to address dynamic requirements by allowing systems to adjust in real time. While this framework excels in managing evolving environments and collective behavior, its adaptability to integrate new technologies at the pace demanded by modern systems remains a challenge. CAS frameworks are primarily designed to respond to internal system changes rather than external, fast-paced technological advancements. This limits their effectiveness in rapidly evolving sectors like aerospace.

5.3 Risk and Organizational Gaps in Frameworks

Another challenge with current SE frameworks is their limited focus on mitigating risks associated with the rapid integration of emerging technologies. While many frameworks, such as Framework Recall Mitigation of Amin [15], focus on addressing system-level risks like product recalls, they often fail to account for the broader risks that arise from integrating new technologies. These frameworks also overlook the organizational challenges that accompany the need to rapidly incorporate technologies that are beyond the direct control of the design teams.

Most existing frameworks focus on improving the early stages of the systems engineering lifecycle, emphasizing requirement definition, architecture, and initial design.

However, the proposed improved SE framework is specifically designed for Rapidly Emerging Technology Items (RETIs) to address the complexities that arise during the developmental phase—the longest and most work-intensive stage, where the integration of new technologies becomes increasingly challenging.

Overall, while SE frameworks like those developed by McDermott, Henderson [12], Shibl, Helal [13], and Amin [15], have made significant steps in addressing internal processes and subsystem integration, a crucial gap remains in addressing the external challenges brought by rapidly evolving technologies. These frameworks often lack the flexibility needed for real-time adaptation and fail to provide comprehensive risk management strategies for integrating new technologies. Moving forward, research should focus on developing SE frameworks that are not only more adaptable but also proactive in incorporating emerging technologies, tackling both technical and organizational challenges to align with the fast-paced demands of modern engineering applications.

6.0 METHODOLOGY

This paper investigates the integration of Rapidly Emerging Technology Items (RETIs) within aircraft Systems Engineering. A questionnaire was developed to explore the enhancements derived from incorporating RETIs during the developmental phase of Systems Engineering design processes, as well as the impact of RETI drivers in the aviation industry. A questionnaire was chosen for its cost-effectiveness, efficiency, and simplicity, allowing for broad outreach across multiple platforms while minimizing the pressure for immediate responses [16].

Sampling Approach. Purposive sampling was employed to select participants with substantial expertise in both the technical and managerial aspects of Systems Engineering projects. This approach focused on gathering insights from information-rich individuals, despite the difficulty of accessing a larger expert pool [17]. Additionally, graduate-level practitioners were included to enhance the credibility of the findings, acknowledging the limited participant and ensuring data validity.

Homogeneous Sampling and Snowball Sampling techniques were applied to target participants with similar backgrounds and affiliations. Given the limited availability of individuals with Systems Engineering experience, a sample size of 21 respondents was considered appropriate. Purposeful sampling was utilized to select highly qualified participants, including individuals with extensive design experience, Systems Engineering implementers, researchers, Subject Matter Experts (SMEs), SE practitioners, technology providers, regulatory bodies, and other relevant stakeholders [18].

This approach is particularly effective for studies with small sample sizes, as it focuses on gathering meaningful insights from information-rich participants [18]. While acknowledging the limitations of the smaller sample size, the method successfully ensured the collection of valuable data.

Demographic analysis revealed that 85.7% of respondents held an MSc or PhD, reflecting a high level of expertise and decision-making capacity. Furthermore, over half of the respondents had more than 15 years of professional experience, further supporting the reliability of the findings.

7.0 RESULTS AND ANALYSIS

7.1 Themes Identification

Themes were identified by analyzing both Systems Engineering theories and principles, as well as the data collected from the questionnaires. As Hennink, Hutter [19] point out, identifying themes is a crucial method for interpreting research findings, helping to organize and make sense of complex data.

The data analysis revealed five overarching themes:

1. Design Professionalism: This theme investigates the working environment, organizational approaches, and experiences of respondents.
2. Drivers of Rapidly Emerging Technology Items (RETIs): This theme explores the sources and rationales behind RETIs.
3. Technology Type: This theme focuses on the influence of technology on the design process, categorizing technologies into incremental or radical RETIs.
4. Interaction between Design Organizations and RETIs Providers: The theme discusses the communication channels, partnerships, and alliances formed between design organizations and technology providers.
5. Evaluation Tools for RETIs: The theme dentifies the tools and methods required for effectively evaluating RETIs.

7.2 Summary of the Qualitative Analysis

7.2.1 Design Professionalism

The results of the analysis confirm the diversity of the sample, highlighting the applicability of the framework across multidisciplinary design settings. Project managers and Systems Engineers play pivotal roles in design projects through the Systems Engineering approach, constituting a significant portion of the respondents. Specifically, Systems Engineering (SE) practitioners and project managers represent 40.9% of the sample, providing valuable insights into the enhanced RETIs framework. This strong representation of two key professional segments reinforces confidence in the relevance of the framework.

Furthermore, the inclusion of respondents from 10 different fields of expertise enriches the study by offering a wide range of perspectives. The analysis reveals that 71% of the participants work within a Certified Design Organization (CDO) or an organization in the process of obtaining certification. These organizations are typically mature entities with well-established human resources and infrastructure. In Europe, for instance, the European Union Aviation Safety Agency (EASA) certifies companies based on their design scope and ensures compliance with regulatory standards, including key personnel qualifications and approved procedures.

7.2.2 Drivers of Rapidly Emerging Technology Items

This theme explores the key factors behind the emergence of RETIs and the necessity for a dedicated Systems Engineering framework to manage them.

A strong consensus emerged among respondents, with 90% identifying design change request by "Stakeholders" as the most common source of RETIs. Additionally, 43% selected "Suppliers" as key drivers of RETIs, while 38% mentioned "Regulatory bodies" as significant contributors. These findings highlight the importance of managing external influences through a robust SE framework designed to handle the rapid and unpredictable introduction of new technologies. For validity, in the literature, design changes are typically driven by suppliers, regulatory requirements, or stakeholder demands [1, 2, 20, 21].

Figure 2 illustrates the correlation between RETI drivers and the reasons for their adoption.

Stakeholders: This is the main driver for RETIs, driven by political, economic, and performance-related reasons. These include responding to customer needs, maintaining competitive advantage, reducing costs, and exploring new solutions—all reflecting stakeholder needs and organizational goals. For example, a government defense agency may request the integration of advanced stealth technology, not previously committed to, into a military aircraft during the developmental phase to maintain a competitive advantage and respond to evolving threats. This RETI would require significant design adjustments, such as altering the shape of aircraft and materials, which could extend development timelines but ensure the aircraft meets new strategic and performance objectives.

Suppliers: RETIs from suppliers are tied to performance improvements and new technologies. Research and Development (R&D) of the Suppliers focuses on enhancing technical functions, driving RETIs that boost overall system performance. In the developmental phase, a supplier may introduce a new propulsion system after the initial engine design is set. This RETI improves fuel efficiency, requiring design adjustments but enhancing overall system performance.

Regulatory Bodies: Regulatory drivers focus primarily on safety, introducing RETIs to ensure compliance with safety standards. These technologies are introduced to address specific safety risks, such as improving collision avoidance or ensuring compliance with updated airworthiness standards.

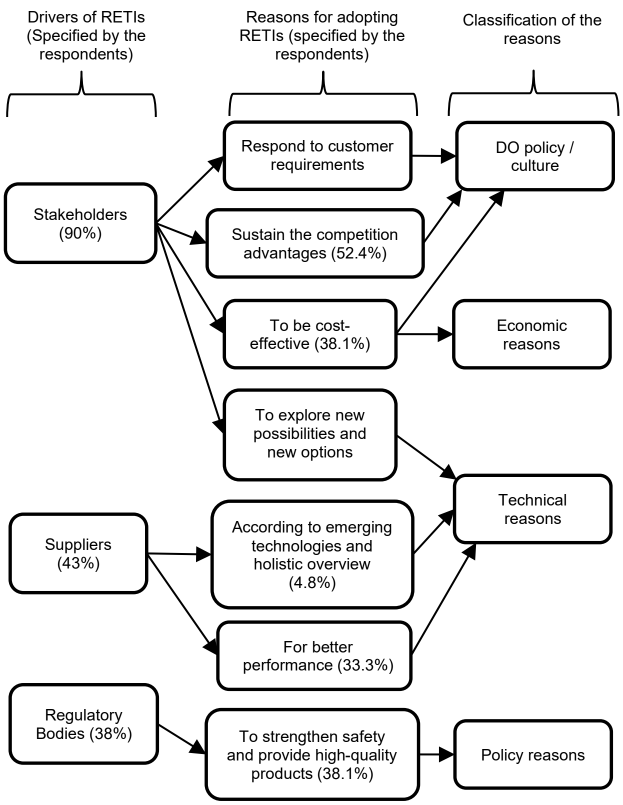


Figure 2 Correlation of the RETIs drivers with the reasons for RETIs adoption

7.2.3 Technology Type

This section explores the influence of technology drivers on aircraft design, highlighting three key categories: Research and Development (R&D) of the Supplier (technology pull), Stakeholders (designers) (technology push), and Regulatory Bodies (technology push). The findings indicate that 62% of respondents attributed integration complexity to Supplier R&D (technology pull), while 24% pointed to Stakeholders, and 14% to Regulatory Bodies (both representing technology push).

In the aviation design sector, R&D of the Supplier (technology pull) plays a pivotal role in the design process by introducing unforeseen technologies after initial agreements. Suppliers, familiar with the core requirements, seek to gain a competitive edge by offering new solutions. On the other hand, technology push—accounting for 38% of RETIs—mainly involves incremental developments. The complexity introduced by technology pull, which often occurs mid-development, generally exceeds that of technology push, necessitating careful consideration for integration during the developmental phase.

7.2.4 Interaction Between the Design Organization (Do) and the Drivers Of (RETIs)

This theme part examines the interaction between Design Organizations (DOs) and the drivers of Rapidly Emerging Technology Items (RETIs), focusing on how internal processes align with external forces. It also explores communication practices between DOs and RETI suppliers, comparing the effectiveness of two-way versus one-way communication.

The results show that 76.2% of experts prefer communication through the Procurement Department, highlighting the importance of technical expertise in managing complex systems like aircraft design. Additionally, 50% of respondents identified business partnerships as the best approach for handling RETIs, citing shared resources, risk mitigation, and increased productivity. Meanwhile, 20% favored technology alliances for their collaborative R&D advantages, despite higher failure rates [22].

7.2.5 Tool for Evaluation of the Rapidly Emerging Technology Items (RETIs)

This theme part focuses on identifying the most appropriate technology assessment tool for RETIs. An open-ended question asked respondents to choose their preferred method for screening and incorporating RETIs into the development phase. The options were: a) Technology Readiness Level (TRL) of NASA, b) internal procedures of the design organization, or c) other, with room for specifications. Results show that 62% preferred the TRL of NASA as a mature tool, while 38% favored an internal evaluation tool developed by their organization. Both tools aid in evaluating RETIs during the screening phase.

8.0 IMPROVED RETIs SYSTEMS ENGINEERING FRAMEWORK

The improvements in the RETIs Systems Engineering (SE) Framework are the result of extensive analysis of previous research and insights from Systems Engineering subject matter experts.

The refined framework addresses key questions about controlling Rapidly Emerging Technology Items (RETIs) during the SE development phase, such as:

Which phase of the Systems Engineering process is most impacted by the inclusion of RETIs?

How can the improved RETIs SE framework simplify the complexity of SE processes?

In response, the framework introduces four essential components:

1. RETI Drivers (sources)

2. RETI Screening (technology assessment)
3. Systems Engineering Phases (processes)
4. Repository as a Single Source of Truth (pool of information and processes)

These components serve as the foundational pillars of the enhanced RETIs SE framework.

As depicted in Figure 3, the improved framework is modeled after the Vee Systems Engineering Design Model, incorporating RETI drivers, a screening methodology for RETI integration, and a Repository that serves as a single source of truth. The first component, "RETI Drivers," represents an innovative approach. The study categorizes RETI drivers into external and internal sources, providing a comprehensive understanding of the forces driving RETI integration into the SE process.

8.1 RETIs Drivers

This section of the improved RETIs Systems Engineering framework focuses on the integration of RETIs drivers into the ongoing system development process, as illustrated in Figure 4. Systems Engineering emphasizes viewing the system holistically, addressing not only its design but also the external factors that influence it [23, 24]. The proposed framework integrates both internal and external drivers, ensuring their alignment with stakeholders, other systems, and the broader Design Organization (DO) environment. This improved framework acknowledges that system design is impacted by various external factors that may either constrain or enhance the design. It identifies three key RETIs drivers to be incorporated:

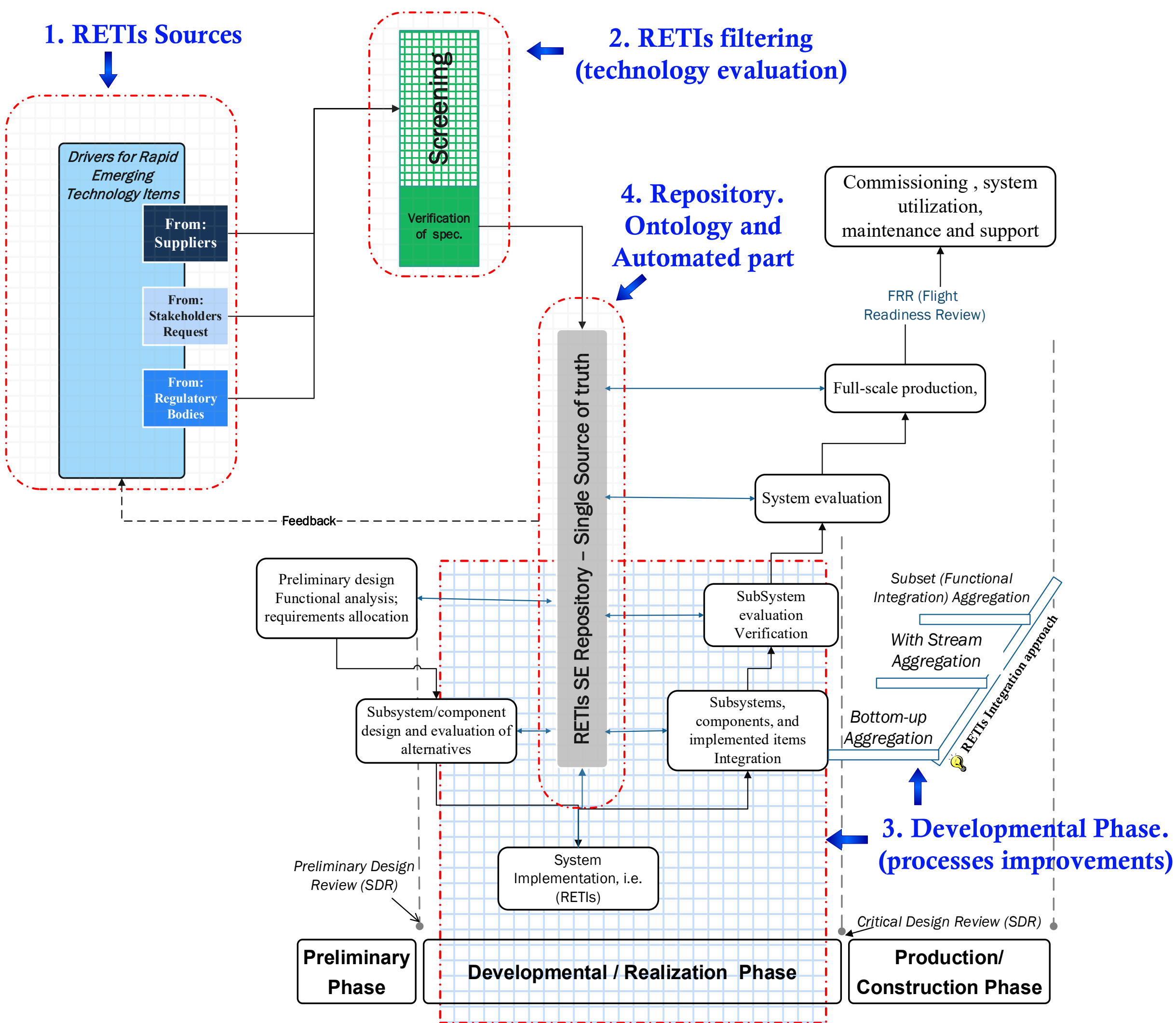


Figure 3 Elements of improved RETIs Systems Engineering framework

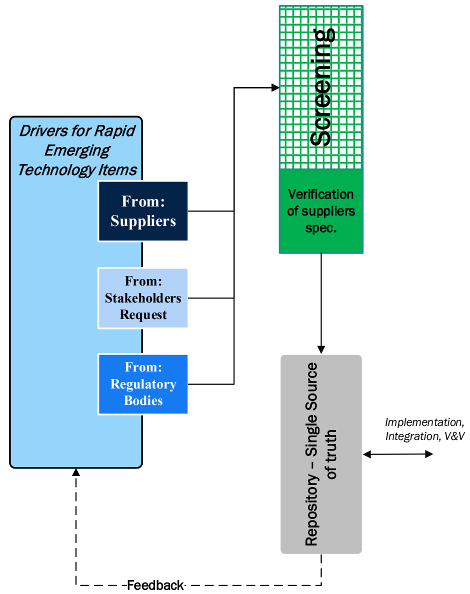


Figure 4 Drivers of the RETIs) in the proposed improved (RETI) framework

Suppliers of RETIs.

Suppliers are responsible for providing predefined technology items and subsystems for integration into the main system of interest (SoI). According to survey results, 62% of respondents identified supplier R&D as a major technology pull factor. Suppliers drive incremental or disruptive improvements that are often not planned during the conceptual phase of the Systems Engineering lifecycle. Due to the lengthy design phase, particularly in sectors like aeronautics [25], new technologies have time to evolve and be integrated into the system.

One scenario involves Safran, an engine supplier for the A320neo family [26]. R&D of Safran in ultra-high bypass ratio (UHBR) engines and lightweight composite materials has led to significant improvements in fuel efficiency (5-10%). However, these innovations introduced challenges such as changes in engine configuration, electrical loads, and aerodynamic parameters. The improved RETIs Systems Engineering framework facilitates better communication between Safran and A320neo designers, enabling more efficient integration of new technologies, reducing implementation time, and streamlining re-validation processes.

Stakeholders.

This study defines stakeholders as users or consumers involved in requesting, receiving, testing, or utilizing system products, encompass developers, designers, testers, and decision-makers within the development team. This group includes team managers, the leadership of the Design Organization, and the heads of associated departments [1].

SE specialists believe stakeholders often advocate for incorporating most RETIs into the system under design.

Regulatory Bodies.

Regulatory authorities, comprising government agencies, safety executives, legal representatives, quality assurance auditors, trade unions, and others, may establish operational standards that influence system creation and operation. According to Huang [27], legislation may drive innovation and technological advancement to meet safety objectives in operations.

The aviation industry sector presents an ideal application for this type of RETIs driver. Additionally, environmental and safety concerns drive the development of significant technologies in response to regulatory agency directives. For example, emerging environmental considerations are compelling regulatory bodies to impose restrictions on noise and engine emission levels [25].

8.2 RETIs Screening Part

The RETIs screening procedure assesses emerging technologies for inclusion in the design, serving as a critical filter between RETI sources and the design repository to manage system complexity. 35. This ensures that RETIs, whether focused on design innovation, such as miniaturization [28, 29] and electrification [30, 31], or regulatory compliance, meet technical specifications and stakeholder expectations.

Screening involves verifying RETI origins, determining technological compatibility, and assessing the impact on design and system performance. This includes evaluating their ability to improve design efficiency while adhering to economic and environmental standards. The process incorporates technology readiness levels (TRL) [32] and other readiness metrics, as discussed by Vik, Melås [33], to assess technological maturity and integration risks.

By facilitating the inclusion of RETIs into the design process, this approach enhances decision-making and strengthens the ability of the organization to adopt innovative technologies efficiently.

8.3 Systems Engineering Lifecycle –Developmental Phase

The developmental phase of Systems Engineering, also referred to as the realization phase, focuses on preparing the system for transition to the next stage by ensuring it has the necessary structure and functionality to meet operational requirements throughout its lifecycle. Both NASA and INCOSE define this phase through four interdependent processes: implementation, integration, verification, and validation [34, 35].

The need to improve Systems Engineering design methodologies arises from several challenges [36]:

- Increased complexity: Modern systems are more intricate and interdependent.
- Technological advancements: Rapid innovation requires faster adaptation.
- Organizational changes: Agile approaches are needed to address evolving structures.
- Regulatory pressures: Stricter standards demand continual design updates

In response, the proposed framework integrates methodologies to address Rapidly Emerging Technology Items (RETIs) during the developmental phase. Every system passes through standard lifecycle phases, including conception, development, manufacturing, usage, support, and retirement [1]. This study uses "developmental phase" and "realization phase" interchangeably.

Figure 5 presents lifecycle models from various entities, with the developmental phase as the focus. These models follow the typical system engineering cycle—conception, preliminary, realization, and manufacturing—though they differ in processes.

The Vee model in Figure 6 outlines SE activities used by design organizations to manage developmental design activities, ensuring proper implementation, integration, verification, and validation [1].

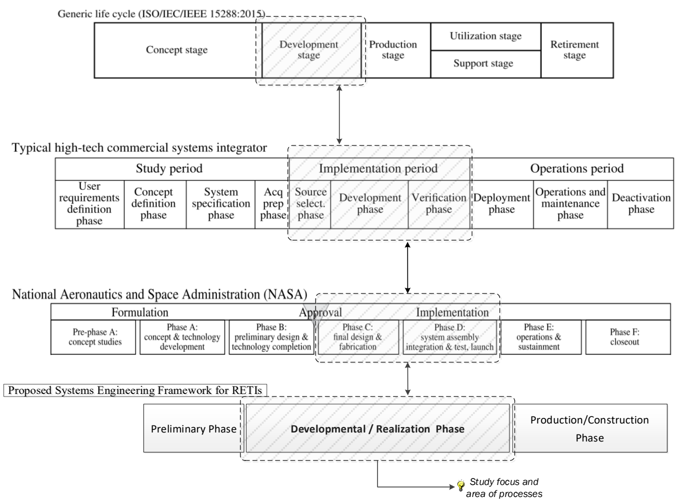


Figure 5 Various representations of the Systems Engineering lifecycles

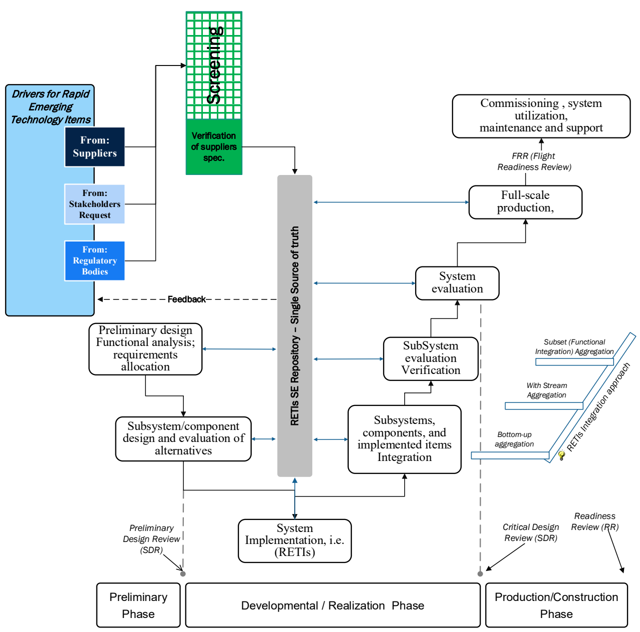


Figure 6 improved RETIs SE framework

8.3.1 Implementation of Rapidly Emergent Technology Items (RETIs)

The proposed framework outlines a structured approach to implementing RETIs, emphasizing preparation, execution, and management. The first step is identifying the source of the RETI—whether it is procured, developed internally, or sourced through external consultation. Engineers then adapt these elements to the System of Interest (SoI), which may require modifications to existing systems to accommodate the new technology. These adjustments are necessary to meet evolving demands introduced by RETIs.

Implementing conventional systems engineering approaches that focus on documents can be difficult because of the need for frequent corrective actions. The proposed improved systems engineering (SE) framework utilizes the model-based systems engineering (MBSE) repository for more effective management. Engineers follow the system element requirements, and the MBSE repository tracks and manages all modifications needed to integrate the RETIs. This system facilitates geometric and data processing, as well as verification and validation. By using this framework, designers can efficiently analyze and make informed decisions about the integration of new technologies. The implementation phase concludes when the RETIs have been successfully executed and integrated into the developmental stage.

8.3.2 Integration of Rapidly Emergent Technology Items (RETIs)

The integration of RETIs is developed based on the principle of Systems Engineering (SE) synthesis [23, 37], ensuring the proper functioning of input elements (i.e., RETIs) and meeting the design requirements of the system. In Systems Engineering, integration is a critical part of the developmental phase, focusing on the smooth incorporation of RETIs into the overall system, much like assembling the final product on a production line.

Traditionally, integration strategies are formulated early in the design process, as seen in the use of a bottom-up integration approach by NASA for technology design. This study introduces a novel approach that combines two additional techniques:

"Integration with the Stream": Assembles implemented elements as they become available.

"Subsets Integration": Also known as "Functional Chains Integration," this method integrates subsets of implemented elements before combining them into the system.

The proposed RETIs aggregation technique merges the strengths of each method, minimizing their individual shortcomings (Figure 7). This integration block in the Vee-model framework ensures the proper functionality of system elements by using a combination of bottom-up, with-stream, and subsets integration methods. Integration activities include updating the integration plan, implementing a strategy to minimize time, costs, and risks, and integrating RETIs with subsystems and the System of Interest (SoI). Additionally, the Verification and Validation (V&V) process is engaged to ensure seamless integration. Early collaboration between the integration plan and the system definition stages is crucial to prevent challenges during system realization. However, given the dynamic nature of system design, it is expected that RETI requests will arise during the developmental phase.

8.3.3 The Verification and Validation

The Verification and Validation (V&V) processes are essential for ensuring that Rapidly Emerging Technology Items (RETIs) are properly implemented and integrated into the System of Interest (SoI).

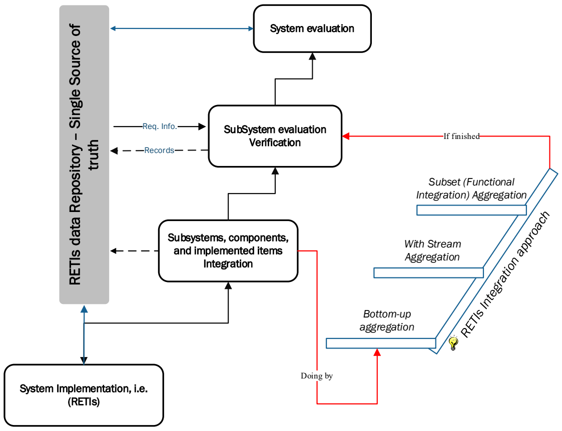


Figure 7 RETIs integration strategy

1) Verification Process

Verification ensures that the architectural and design characteristics of RETIs align with specific requirements, standards, and regulations. In this framework, verification is integrated with the implementation and integration processes, following the SE synthesis principle [35]. There are three verification methods:

Analysis: uses when physical RETIs are unavailable, allowing for non-physical testing to speed up integration (e.g., “with-stream” integration).

Demonstration: Demonstrates that RETIs function correctly based on their observable properties without physical measurements, ensuring they respond appropriately to inputs and tasks.

Inspection: It is a visual examination of components, such as comparing size and aerodynamic configurations of aircraft parts.

Prepare for verification: Define the expected results, informed by expert surveys and correlated with RETIs drivers.

Conduct verification: Choose a verification technique (analysis, demonstration, or inspection) to assess the RETIs.

Compare results: Match obtained results with the expected outcomes. If the verification succeeds, the process moves to validate customer requirements. If it fails, feedback is provided to the repository of the framework to inform stakeholders.

2) Validation Process

While verification ensures compliance with system specifications, validation confirms that the system meets its intended operational capabilities. Validation focuses on proving that operational scenarios and stakeholder expectations can be satisfied [35]. This process is conducted to benefit customers and end-users, ensuring the system performs as expected in its intended environment.

Feedback from validation is also incorporated into the repository to support concurrent engineering and holistic design principles.

8.4 The Repository For The Retis Framework

The RETIs Systems Engineering framework incorporates a repository as a centralized and authoritative source of information to overcome the limitations of current Systems Engineering design approaches. A design repository is a sophisticated system that uses knowledge-based design to model design artifacts. Its purpose is to accurately represent, capture, share, and reuse corporate design information. Additionally, Model-based Systems Engineering (MBSE) is suggested as the facilitator for the repository mechanism in this enhanced framework, given its growing relevance in applications related to Systems Engineering and aeronautical design [4, 38, 39]. Further, the RETIs Framework utilizes the INCOSE Object-Oriented Systems Engineering Methodology (OOSEM) [40], which is a model-based methodology that facilitates the specification, analysis, design, and verification of systems. OOSEM is easily accessible and offers comprehensive technical assistance, making it an excellent option for capturing and analyzing RETIs, as shown in Figure 8. In order to mechanise the repository operations according to OOSEM, the systems engineer must code all aggregation strategies (Bottom-up, With stream integration, and Subset integration) as specified during the developmental process. The repository automation operates according to the principles of the Complex Adaptive System (CAS) theory [41-43]. This theory emphasizes the ability of the system to modify and adjust itself in response to changes in its surroundings or situations through self-organization, learning, and reasoning.

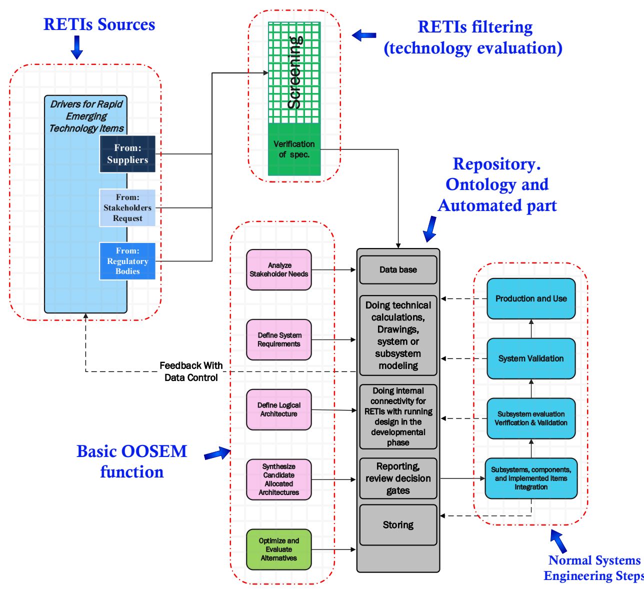


Figure 8 RETIs repository with OOSEM

9.0 SUBJECT MATTER EXPERTS

Subject Matter Experts (SMEs) in Systems Engineering and Aircraft Design were consulted to validate the proposed RETIs framework. Selected for their expertise, the SMEs, including Ph.D.-level professionals, reviewed the framework through a structured survey focusing on six key areas:

1. Adequacy of RETIs Framework: SMEs agreed that the proposed framework effectively reduces the time needed to adopt RETIs during the developmental phase, linking RETI drivers with the design process to streamline integration.
2. Screening Process: Experts highlighted the importance of the screening process in selecting the optimal RETIs based on predefined criteria. This rigorous screening improves the technical and procedural aspects of the design and enhances the competitive advantage of the organization.
3. Aggregation Strategy: SMEs endorsed the combined aggregation approach for RETIs integration, noting that it shortens the time required for adoption. One SME suggested adding a flowchart to further clarify the process.
4. Verification Process: Most SMEs confirmed the rationality of the verification process within the Vee-model framework, appreciating its alignment with traditional systems engineering methodologies.
5. Repository: SMEs supported the concept of a centralized repository as a single source of truth, which accelerates development and simplifies RETI integration. One expert likened the repository to a data lake or warehouse, emphasizing its potential in managing RETI data efficiently.
6. Overall Applicability: SMEs agreed that the proposed RETIs framework is valuable for integrating emerging technologies into the system, filling gaps in existing SE frameworks that struggle with rapid technological advancements during the costly development phase.

SMEs validated the effectiveness of framework in addressing the complexities of adopting RETIs during the developmental phase, while providing suggestions for further refinement.

As shown in the graphical presentation in Figure 9, RETIs Systems Engineering framework improved the current Systems Engineering approach by concentrating on the development phase, significantly reducing processing time and improving overall efficiency.

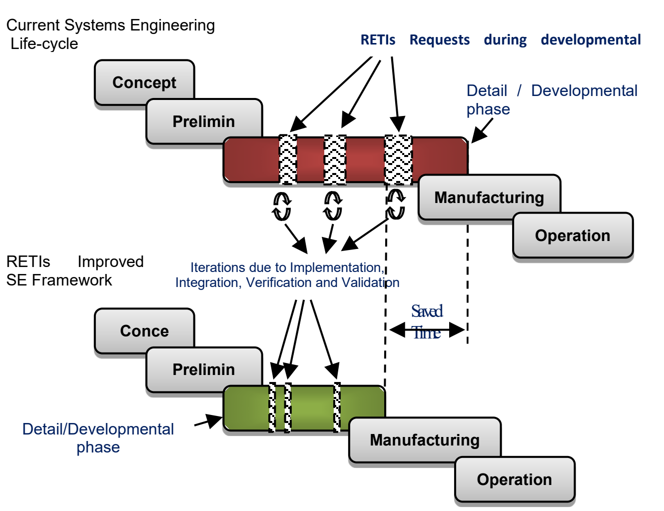


Figure 9 The impact of RETI framework improvements on the time required for iterated processes

10.0 CONCLUSION

This study aimed to improve the Systems Engineering design approach by facilitating the adoption of Rapidly Emerging Technology Items (RETIs) during the developmental or realization phases. The analysis of survey data revealed that while incorporating RETIs increases design complexity, impacts schedules, and adds costs, it also provides significant advantages, such as enhanced technical performance, improved safety, and a competitive edge for design organizations.

The proposed framework introduces several improvements to the traditional Vee model of Systems Engineering. These include better communication between RETI drivers and the design organization, a robust screening process for ensuring compatibility, integration strategies of the "Subset" technique and "with the stream," and a centralized repository to streamline communication and automate processes. These improvements are designed to increase the efficiency of the Systems Engineering approach in implementing RETIs during the critical developmental phase.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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