Research on the Competency Requirements of Systems Engineers in Aero-Engine Development

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Abstract: In response to the current technological landscape of aero-engines, which are complex and involve multi-disciplinary coupling, the role of systems engineers is introduced in aero-engine development. Research is conducted from various perspectives, including systems engineering methodology and the aero-engine development process. It is proposed that systems engineers should be both specialists and generalists, and an analysis is provided regarding their technical and conceptual requirements. The knowledge, skills, abilities, behaviors, and cognition that systems engineers must possess are identified to establish a common communication platform within multi-disciplinary aero-engine development teams, balance coupled relationships among various disciplines, address unexpected emergent properties, and make sound decisions. Additionally, pathways and safeguards for cultivating the competencies of aero-engine systems engineers are proposed, thereby supporting the development of aero-engines.

Keywords: Aero-Engine; Systems Engineer; Professional Technical Capability; Organizational Management Capability; Systems Thinking Capability

1. Introduction

The development of aero-engines involves a multi-layered architecture encompassing complete aircraft systems, components/systems, subsystems, and parts. Its design technology has evolved into a highly integrated comprehensive system that combines aerodynamics, thermodynamics, computational technologies, structural engineering, materials science, and manufacturing processes. The convergence of cutting-edge technologies, coupled with the nonlinear interactions between components, interdependent elements, and overall objectives, creates complex coupling relationships that render the development process exceptionally intricate [1-3]. Meanwhile, the rapid advancement of aero-engine technology has made it impossible for engineers to master all relevant knowledge, leading to the prevailing trend of specialized knowledge domains and technical disciplines in modern aero-engine R&D. However, when professionals from different disciplines collaborate, their perspectives often become constrained by inherent limitations.

Based on the actual needs of aero-engine research and development, this paper determines the responsibilities of aero-engine system engineers, and then summarizes the ability requirements of three aspects for system engineers, namely professional technology, organizational management and system thinking, and discusses the training approaches of system engineers from three aspects, namely personnel selection, job transfer practice and system construction.

2. The Responsibilities of System Engineer in the Development of Aero-Engine

In past aviation engine development, localized combustion chamber modifications caused altered exhaust temperature fields, leading to high-pressure turbine outer ring ablation failures. Similar incidents frequently occur when individual component or detail improvements are implemented without comprehensive consideration of their impacts on other parts. The root cause lies not in a lack of specialized knowledge, but rather in the absence of goal-oriented holistic planning. To meet design requirements and objectives, each component unit or discipline often adopts measures most favorable to their own field. However, these measures may create conflicting constraints for the entire aircraft system.

Systems engineering methodology is a comprehensive and balanced scientific approach refined through practical experience by leading aerospace enterprises worldwide. System engineers play diverse roles, potentially fulfilling all or some of the following 12 responsibilities: requirements manager, system designer, system analyst, verification/qualification engineer, logistics/operations engineer, subsystem coordinator, user interface specialist, technical manager, information manager, process engineer, collaborator, and systems engineering advocate [4].

It plays a pivotal role in guiding system architecture development, defining and allocating requirements, evaluating and balancing design solutions, balancing technical risks across systems, defining and assessing system interfaces, comprehensively supervising verification and validation activities, and performing numerous other critical tasks [5-6]. This ensures that system development adheres to appropriate systems engineering methodologies, that the system technically meets specified requirements, focuses on optimizing the entire system rather than individual subsystem designs, and excels at balancing the organizational and technical interactions within complex systems.

In aviation engine development, system engineers are responsible for organizing two closed-loop processes. The first is the requirements line: requirements analysis, requirements traceability, and requirements implementation. The "requirements analysis" phase requires engineers to thoroughly understand the needs of stakeholders, including military and aircraft manufacturers. This involves translating stakeholder requirements into specific aviation engine specifications, providing accurate inputs for subsequent design solutions. Additionally, system engineers evaluate the implementation of requirements to ensure the product meets not only aviation engine specifications but also customer demands.

The second cycle forms a closed loop of architecture design, implementation, and evaluation. The architecture design must meet requirements, implement functions, and approach optimal values within constraints of time, budget, and resources, while considering the technical maturity of available elements and acceptable risks. Since there are multiple solutions to meet requirements, architecture becomes crucial. This is a creative process where intuition and experience play crucial roles. At its core, it involves extensive trade-offs. System engineers must assemble multidisciplinary teams with expertise in aerodynamics, thermodynamics, structural engineering, lubrication, air systems, transmission, materials, dimensional analysis, noise control, strength, heat transfer, and performance matching to complete the aero-engine architecture design. This process requires defining the engine's hierarchical structure and component units while ensuring clear interfaces and well-defined requirements between them. After completing the architecture design, engineers provide technical guidance to ensure accurate implementation of system requirements and solutions, thereby preventing quality issues during product development. Following design completion, engineers conduct comprehensive evaluations of the overall engine solution to maintain alignment with objectives and fully meet customer needs.

3. Ability Requirements of System Engineers in Aero-Engine Product Development

Based on the responsibilities of system engineers, the core competencies for this role are summarized into three key areas: technical expertise, organizational management, and systems thinking. Technical expertise manifests as technical insight, representing acquired knowledge and skills that demonstrate depth and breadth in professional practice. Organizational management skills primarily involve communication and leadership-qualities that should embody the personal charisma and humanistic traits of a system engineer, serving as competency benchmarks. Systems thinking involves comprehensive coordination across disciplines, components, and systems, demonstrating effective application of systems engineering methodologies in practice, which constitutes behavioral standards. These three competencies form the "bucket theory" of an aero-engine R&D system engineer's capabilities, requiring balanced integration where none can be omitted [7].

3.1 Professional Technical Competence

The development of aircraft engines requires the application of numerous innovative technologies to enhance performance and optimize functionality. However, due to limitations in human cognition and technological advancement, the interconnections between these technologies often prove unpredictable, inevitably leading to emergent characteristics. Such phenomena are not confined to the design phase but may also emerge unexpectedly during manufacturing, testing, and other critical stages. This necessitates that systems engineers possess acute technical insight, effectively manage these emergent characteristics, accurately identify key technical aspects, determine problem-solving approaches, and strategically allocate relevant technical resources.

System engineers are responsible for organizing technical activities such as requirement analysis and system architecture design. During these processes, they must ensure the system's robustness is adequate and that interfaces between components/subsystems are clearly defined. This role requires engineers to possess deep technical expertise, the ability to understand prior experiences, and the capacity to learn from both successes and failures.

System engineers must not only possess profound technical expertise in specialized domains but also demonstrate comprehensive knowledge mastery. Their core competencies involve acquiring broad disciplinary knowledge through deep specialization, identifying cross-disciplinary connections, recognizing their overarching significance, and applying multidisciplinary foundations to develop effective problem-solving approaches.

3.2 Organizational Management

Leadership is a critical responsibility for system engineers. The aviation engine R&D team consists of numerous technical specialists. For individual technicians, stronger professional expertise and distinct personal characteristics are highly valued. For the team, a system engineer's leadership should not only identify members who outsmart others but also recognize those who surpass their own capabilities. This involves skillfully building team cohesion, understanding team members' initiative, fostering creativity, and identifying development directions. It also entails ensuring system integrity, maintaining influence, objectively assessing situations, and securing resource availability.

Throughout the entire lifecycle, this approach involves ensuring proper engagement of domain experts, pursuing all favorable opportunities, and identifying and mitigating all significant risks. When conflicts arise, system engineers must be able to find a compromise solution that considers task context, boundary conditions, and coupling relationships. This solution should represent the optimal approach to task completion and gain recognition from technical experts across all domains.

3.3 System Thinking

A systems engineer must possess a holistic systems perspective, considering the background environment, interfaces, and interrelationships. Starting from the engine's overall framework, they should view their tasks, fundamental conditions, and problem-solving approaches as an interconnected and mutually influential whole. This requires identifying core issues, analyzing and synthesizing data, and demonstrating systems thinking to uncover cross-disciplinary relationships between components/subsystems. The engineer must prioritize tasks, maintain focus on critical requirements, and interpret new information or changes affecting the engine's integrity. When such developments impact the system, they should formulate comprehensive revision strategies that address the entire system.

Meanwhile, system engineers 'work is not constrained by professional biases. They prioritize holistic efficiency and outcomes, identify core requirements, and develop superior solutions [8]. The advancement and innovation in aeronautical engine science and technology increasingly demonstrate interdisciplinary integration and the application of multidisciplinary knowledge. System engineers' knowledge frameworks and competency requirements must fully reflect these characteristics. Their professional expertise requires horizontal expansion, demonstrating strong cross-disciplinary understanding, creative problem-solving capabilities, and the ability to maintain open-minded objectives. By effectively leveraging past experiences and managing risks, they can better address complex challenges.

4. Ways to Cultivate the Ability of System Engineers

Through the aforementioned capability analysis, system engineers employ the evolving and practical science of systems engineering to meet specific requirements within defined parameters. This process integrates standard engineering disciplines with interdisciplinary approaches in aviation engine development, forming a cohesive, comprehensive, synthetic, and balanced discipline. Consequently, aviation engines evolve into a unified system that transcends the constraints of any single academic field.

System engineers require not only professional expertise and systematic engineering education, but more crucially, their inherent human qualities. They must cultivate habits of proactive learning, hands-on practice, summarization, inquiry, and innovation throughout the aviation engine development process. Therefore, the cultivation of system engineers' capabilities should be expanded and ensured through three key approaches: personnel selection, practical job rotation, and institutional development.

4.1 Personnel Selection

The selection of system engineers can be determined by two comprehensive qualities. On one hand, personality is crucial: candidates should possess curiosity, a desire to explore, and a constant pursuit of information and solutions. They must recognize their limitations, adapt to changes and uncertainties, maintain emotional stability, and demonstrate high emotional intelligence. This quality is particularly evident during prolonged R&D processes, where they need to choose the right approach when conflicts arise, effectively resolving issues through questioning and negotiation. On the other hand, professional skills are essential. The aviation engine R&D cycle is characterized by long development periods, multidisciplinary integration, and strong professional coupling, which necessitates a lengthy training process for system engineers.

To meet the competency requirements for system engineers, two recruitment channels are available. The first channel targets newly hired employees with aviation engine-related majors and a master's degree or higher. These candidates must demonstrate solid mastery of theoretical knowledge in aviation engine structure, aerodynamics, strength, compressors, and control systems. They should excel at integrating theory with engineering practice, possess strong self-learning capabilities, and be proactive in research. Additionally, they need to comprehensively evaluate complex technical factors and select optimal solutions through careful analysis.

Another pathway involves selecting employees with years of experience who possess solid professional expertise. These individuals have demonstrated significant design contributions across multiple models/projects, demonstrating exceptional ability to coordinate with cross-disciplinary teams during design processes. They exhibit strong risk anticipation capabilities and can promptly identify root causes when troubleshooting. Through these technical responsibilities, they showcase high emotional intelligence and learning agility, making them outstanding candidates for system engineer roles.

4.2 Job Transfer Practice

To develop qualified engineers for various systems, we implement rotational assignments across key positions: component structure, air/oil systems, and overall system design. This hands-on approach helps candidates master practical implementation of performance and functional requirements, while building comprehensive expertise in balancing engine components. Through multi-position rotations, professionals expand their technical scope and develop holistic thinking. By embracing continuous learning, observation, and hands-on practice, they sharpen their sensitivity to emergent system behaviors and cultivate problem-solving capabilities that drive innovation.

As a high-temperature, high-speed rotating mechanical product, the structural strength design of aviation engines critically determines their performance and reliability. Structural design represents a creative intellectual endeavor that transforms design concepts (software) into tangible products (hardware). The outcome of structural design is a coordinated integration of performance, strength, materials, and manufacturing across multiple disciplines. Unlike aerodynamic formulas-which yield a single result regardless of the number of calculations-a structural designer may develop multiple conceptual approaches. Structural design is a comprehensive process requiring judgment, balanced compromises, and accumulated experience to achieve the optimal overall solution.

Based on the above understanding, component structure design is taken as the first position of system engineer ability training, and the application of basic knowledge and the improvement of professional knowledge of system engineer reserve are strengthened. In the design of large components, the overall, comprehensive and systematic design ability is cultivated, and the management ability of internal coupling relationships and emergent characteristics is mastered.

Professional roles in aviation engine systems, including air systems and lubrication systems, span the entire engine lifecycle. Engineers must understand the characteristics of individual units or major components to complete system design tasks. For instance, air system design plays a crucial role in cooling hot-end components, chamber sealing, pressure regulation, tip clearance control, and anti-icing. The quality of this design directly determines whether the aviation engine can operate safely and reliably. During the design process, engineers must balance multiple requirements such as axial forces and thermal loads, involving comprehensive optimization from low-temperature components to high-temperature components.

After gaining experience in roles such as component structure and system design, system engineers in the reserve pool must undergo training in the overall design department. During component development, these engineers master the interconnections and emergent characteristics across disciplines like pneumatics, structural engineering, strength analysis, and materials science. In the overall design department, their responsibilities expand from specialized expertise to understanding component-system interactions. They must learn to analyze engine subsystem characteristics to ensure technical outcomes align with expectations, while developing the ability to apply scientific methods and practical experience to address the emergent characteristics of complete systems. This represents a qualitative leap in the capabilities of system engineers.

For aviation engine development, the extended R&D cycle makes cultivating system engineers a protracted and demanding process that typically spans two decades. During this phase, trainees navigate increasingly complex engineering systems-from component/functional units to integrated systems and complete aircraft structures. They must master R&D workflows, identify critical design parameters, and understand interdisciplinary connections and their interplay. This journey transforms specialists from single-discipline experts into multidisciplinary generalists, from single-component specialists into holistic aircraft systems engineers, and from technology-focused specialists into comprehensive professionals skilled in both technical expertise and technical management. The career progression path for system engineers is illustrated in Figure 1.

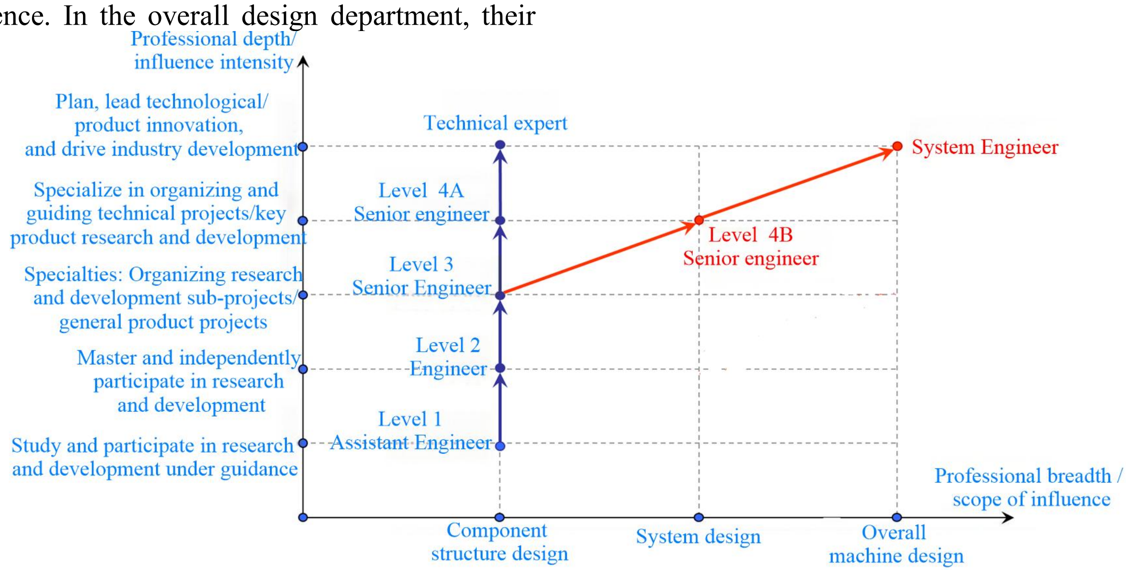

Figure 1. Systems Engineer Competency Framework

4.3 Establishment of the System

Formulate the "System Engineer Grade System" to clarify the ability requirements, knowledge level, professional design experience and project experience of system engineers, and determine the promotion and elimination channels based on project practice.

By progressively increasing the complexity of competency development projects-from designing complex components/subsystems to developing enhanced engines and next-generation engines-the program serves dual purposes. It not only enhances the capabilities of system engineer candidates but also evaluates their leadership, communication, systems thinking, technical insight, and handling of emergent characteristics during the R&D process, ultimately determining their competency level.

5. Conclusion

In the development of aero-engine technology, both specialists and generalists are indispensable. Specialists drive breakthroughs in specialized technologies, creating brilliant industrial innovations. System engineers, as generalists, oversee the entire process-planning, implementation, and evaluation-while balancing multidisciplinary impacts and managing unpredictable emergent phenomena. They mediate conflicts between technical and managerial activities, seamlessly integrating these pearls into a magnificent necklace: the aero-engine.

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