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Shaping the Future of Aeronautical Engineering: Designing a Capstone Course

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***Abstract*– The rapid advancement of aerospace technologies and industry paradigms necessitates a transformative approach to engineering education. This paper presents a structured framework for designing a capstone course that addresses the evolving competencies required of aeronautical engineers. Focusing particularly on the Colombian context, the study analyzes current challenges and emerging trends in the aerospace sector to identify core technical and transversal skills, along with the critical need for interdisciplinary collaboration. The proposed course integrates project-based learning and real-world engineering problems to bridge the gap between academic training and professional practice. Furthermore, the paper benchmarks existing curricula and international best practices to ensure alignment with both accreditation standards and industry demands. The findings underscore the importance of continuous curriculum innovation to equip future engineers with the agility to respond to technological disruptions and lead sustainable development in a highly dynamic field.**

***Keywords*-- engineering curriculum, capstone, curriculum improvements, competencies, Aerospace engineering, education.**

I. Introduction

Engineering higher education is continuously under pressure to enhance the training of graduates who will shape the future [1]. These pressures may come from international organizations, as well as mandated legislation and standards. Recommendations, regulations, and guidelines frequently emphasize topics such as training focused on capability development, including transversal competencies, the use of more active teaching techniques, and the implementation of continuous assessment. The demand for these adjustments is driven not only by the need for graduates to meet societal requirements but also by scientific research on how individuals learn and which strategies are most effective in facilitating learning [2].

Technological advancements and the need for sustainability are driving significant and rapid changes across industry and academy worldwide [3]. The aerospace sector, in particular, has long been at the forefront of innovation, leading developments in autonomous operations, renewable energy, sustainable engineering, artificial intelligence, propulsion systems, vehicle design, and space exploration [4], [5]. These technological shifts necessitate a redefinition of the skill set required for aspiring aerospace engineers.

Given these challenges, it is crucial to explore innovative ways to enhance curricula and foster student motivation and engagement. Universities and faculty members must adapt by integrating academic knowledge with practical applications. Capstone courses play a key role in this effort, providing students with opportunities to apply and integrate their learning into real-world projects relevant to the industry. According to ABET [6], a capstone course is "*A culminating course that allows students who are nearing graduation to put together the knowledge and skills they have acquired in their program and apply it to a major project or assignment*."

The aeronautical engineering program has been developed Integration of CDIO methodology [7], collaborative learning approaches [8], project based learned [9] and Capstone projects during the curriculum courses from many years The CDIO adaptation process self-evaluated our degree program curriculums, identifying a need for growth in the advanced-level Capstone project.

The proposed capstone experience incorporates project-based learning and real-world problem-solving to ensure relevance and impact. This study examines key trends shaping the future of aerospace engineering and their implications for curriculum development. By analyzing industry reports, accreditation guidelines, and best practices from leading academic institutions, we propose a course structure that emphasizes systems thinking, interdisciplinary collaboration, sustainability, and digital proficiency.

The remainder of this paper is organized as follows: Section II presents the methodology for designing a future-oriented capstone course. Section III reviews the evolving skill set required for aerospace engineers and the role of capstone courses in engineering education. Section IV details the proposed course framework, including learning objectives, project themes, and assessment strategies. Finally, Section V provides conclusions and recommendations for implementation.

II. Methodology

This study utilizes a two-pronged methodological approach comprising a comprehensive literature review and a comparative analysis of existing capstone course implementations in aerospace engineering schools across the globe. The literature review draws on industry reports, aerospace sector publications, accreditation standards, emerging technological trends, and scholarly research to identify the fundamental knowledge areas and skill sets required of aerospace engineers. With a particular emphasis on Colombia, the analysis integrates considerations of professional development within the national aerospace market and addresses local workforce needs. Key themes explored include the integration of advanced technologies, sustainability challenges, and evolving educational strategies that influence curriculum development. To understand how institutions are adapting to these demands, the study also examines best practices in engineering education—particularly those relevant to the design and implementation of capstone courses [10]–[13].

To complement the literature findings, this study compares capstone course models from leading aeronautical engineering programs worldwide [14]–[16]. The analysis focuses on course structures, learning outcomes, instructional strategies, and partnerships with industry. By identifying common frameworks and innovative pedagogical approaches, such as project-based learning, interdisciplinary collaboration, and applied problem-solving, the study highlights elements that contribute to impactful capstone experiences. Insights from recent aerospace industry publications are used to align academic efforts with evolving employer expectations, ensuring that the proposed course framework remains relevant to current and future workforce requirements.

Designing a capstone course that effectively responds to the dynamic nature of the aerospace industry requires a grounded understanding of both global benchmarks and local contexts. The combined findings from literature and course benchmarking offer a robust foundation for developing a course that not only meets accreditation and educational standards but also anticipates the technical and transversal competencies demanded by modern aerospace challenges. This dual strategy informs the design of a course that bridges academic training with real-world performance, preparing students to contribute meaningfully to the future of the sector.

III. THE NECESSARY COMPETENCIES FOR AN AERONAUTICAL ENGINEERING

Professional competence in aeronautical engineering extends far beyond the theoretical knowledge gained during formal education. It now includes the ability to effectively apply knowledge, skills, and judgment in complex technical and social contexts. As modern aerospace challenges grow in complexity, engineers must be equipped not only with domain-specific expertise but also with the behavioral and interpersonal capabilities required to operate in multidisciplinary and often international environments. Competence, therefore, is a multifaceted construct encompassing cognitive, practical, attitudinal, and experiential dimensions [17].

Although the literature presents various definitions of competence, this study adopts the definition proposed by [18], which states that "*competencies are the knowledge, ability, and behavior required to perform an effective work task*." This view emphasizes the integrated nature of professional performance, where knowledge alone is insufficient without the capability to act, adapt, and deliver results in dynamic settings.

Competencies are generally categorized into two main groups: hard skills and soft skills [19]. Hard skills include the technical proficiencies and theoretical knowledge required to perform tasks related to aerospace systems, such as design, simulation, analysis, and testing. These may involve expertise in aerodynamics, structural design, propulsion systems, and systems integration. Soft skills, in contrast, refer to cognitive and interpersonal capabilities such as communication, teamwork, leadership, adaptability, and critical thinking. The interplay between these skill sets is vital in preparing engineers to lead and innovate in a field marked by rapid technological evolution and global collaboration.

As an initial foundation for identifying the core competencies for future aeronautical engineers, this study draws on the research conducted by Henao et al. [20], which employed a foresight-based approach tailored to the Colombian aerospace context. This study highlights the importance of aligning educational outcomes with industry projections, particularly in areas such as systems thinking, innovation management, and interdisciplinary problem-solving. Furthermore, the study is supported by the National Qualifications Framework for the Aeronautical Sector [21], a collaborative document developed by the Inter-American Development Bank (BID), the Civil Aviation Authority, and the Ministry of Education. This framework plays a critical role in aligning the competencies developed through academic programs with the actual needs of the aeronautical labor market, thereby bridging the gap between theory and practice.

To avoid a purely local perspective and foster broader applicability, additional academic and industrial sources were analyzed. These were then compared against the ABET accreditation criteria, which offer a globally recognized benchmark for program outcomes in engineering disciplines. This comparative approach allowed the research to incorporate international perspectives while preserving alignment with Colombian policy and industry needs, enhancing the relevance and transferability of the proposed competency model.

In Colombia, the general profile of an aeronautical engineer includes the capacity to design, construct, evaluate, and maintain aircraft and aerospace systems, in compliance with national and international scientific and technological standards. Additionally, these professionals are expected to manage projects, oversee aeronautical infrastructure development, and ensure adherence to quality assurance systems, safety regulations, and operational protocols within the aviation industry.

At the international level, the set of required competencies is even broader and reflects the global nature of the aerospace field. From a technical standpoint, professionals must demonstrate deep expertise in core engineering areas such as aerodynamics and fluid mechanics, aircraft structures and advanced materials, propulsion systems, flight dynamics and control, avionics, as well as aircraft manufacturing and maintenance processes [18], [22]–[26]. These technical domains are complemented by business and regulatory competencies—such as project management, systems engineering, lifecycle analysis, and compliance with international aviation authorities and certification bodies [27].

Furthermore, as the aerospace industry undergoes digital and environmental transformation, future professionals must be capable of integrating sustainability principles, data-driven decision-making, and emerging technologies such as artificial intelligence, digital twins, and additive manufacturing into their work. Thus, the formation of aeronautical engineers must be dynamic, competency-driven, and responsive to future industry disruptions.

IV. Results

In alignment with international best practices, the Aeronautical Engineering program defines product design as the cornerstone of its culminating design experience, following an approach similar to that outlined by [28]. This advanced course offers students the opportunity to develop tangible, practical solutions tailored to the evolving needs of the aerospace industry, while simultaneously cultivating an entrepreneurial and innovation-oriented mindset essential for their future professional careers.

The course structure is grounded in a systematic and iterative design methodology, which guides students through the development of an Aerospace Product Design. This capstone experience synthesizes and applies the technical, analytical, and creative competencies acquired throughout the curriculum. Beginning with the formulation of a real-world problem, students are challenged to interpret a set of technical, operational, and client-defined requirements. Through this process, they cultivate essential engineering skills such as critical thinking, systems-level analysis, trade-off evaluation, risk assessment, and design validation—skills that are crucial for success in professional aeronautical engineering practice.

Design challenges are addressed collaboratively in interdisciplinary teams, simulating the dynamics of real-world aerospace projects. This team-based approach fosters communication, negotiation, and leadership abilities while reinforcing each student's capacity to integrate knowledge from diverse fields such as aerodynamics, propulsion, avionics, materials science, and systems engineering. Moreover, the collaborative format encourages students to expand their skill sets as they respond to evolving project demands and technological constraints. Project stakeholders, typically representing real or simulated aerospace clients, define design goals and functional specifications, providing a professional context and performance benchmarks that reflect industry realities.

A defining feature of this course is its contextual relevance to the Colombian aerospace sector. The program incorporates national challenges into the design process, recognizing that Colombia faces a unique set of structural, infrastructural, and operational barriers that limit its competitiveness and integration with global aerospace markets. Rather than treating these limitations as constraints, the program reframes them as opportunities to foster local innovation, drive technological modernization, and explore sustainable and context-sensitive engineering solutions.

As part of this strategy, the Aerospace Product Design course identifies and integrates several key problem areas and emerging trends that shape both local and international aerospace development [22]. These include:

a) Sustainability: Emphasizing eco-efficient solutions, emissions reduction, and lifecycle-oriented design.
b) Emerging and Digital Technologies: Leveraging tools such as artificial intelligence, digital twins, additive manufacturing, and automation in aerospace design and operations.
c) Infrastructure Capacity: Addressing logistical, regulatory, and physical limitations within national aerospace infrastructure.
d) Fleet Replacement and Modernization: Evaluating aging aircraft, maintenance challenges, and the need for sustainable renewal strategies.
e) Drone and Air Mobility Applications: Exploring UAV systems, urban air mobility, and their integration into regulated airspace.
f) Space Exploration: Engaging students in the foundational concepts of orbital mechanics, satellite systems, and space vehicle design.

These themes reflect not only the current challenges in Colombia but also broader global concerns that are redefining aerospace innovation and professional practice. By engaging directly with these complex and future-oriented issues, students are encouraged to apply design, simulation, modeling, and systems thinking tools to generate robust, scalable, and innovative solutions. In doing so, the course equips graduates to become contributors to technological advancement in both the national and global aerospace arenas.

A. Key Problems and technological trends

Sustainability

Global aviation is undergoing a critical transition toward more sustainable operation and an initiative “aviation net zero" that is a commitment by the aviation industry to reduce carbon emissions to zero by 2050. That includes the development of new propulsion systems, including electric, hybrid, hydrogen fuel cell technologies and the use of sustainable aviation fuels (SAFs). This challenge involves:

- Designing and adapting aircraft that will be able to integrate these emerging technologies while ensuring energy efficiency, operational reliability, and adaptability.
- Developing implementation strategies that address limitations of infrastructure and energy access.
- Proposing viable solutions to incorporate renewable energy sources into the operation and maintenance of these aircraft.

Student engagement in this topic not only enhances technical skills but also fosters an understanding of the environmental and economic impacts of proposed solutions.

Emerging and digital technologies

Artificial intelligence (AI) and machine learning (ML) are being used to improve safety, reduce costs, and optimize operations in the aerospace industry, on the other hand Additive manufacturing, also known as 3D printing, is considered as one of the most well-suited manufacturing technologies for the aerospace industry offering a more efficient and cost-effective way to manufacture components compared to traditional methods. The implementation and use of these technologies require:

- Designing aerospace components or systems that take all the advantage of the new manufacturing technologies.
- Developing implementation strategies that address increasingly demand integration and interoperability of systems driven by AI.
- Proposing viable solutions to incorporate new technologies into the operation and maintenance of aerospace vehicles and systems.

Infrastructure capacity

Colombia's aeronautical infrastructure faces significant challenges especially in terms of capacity, these limitations and the actual status of the infrastructure hinder the integration of modern, technologically advanced flying vehicles in both civil and military sectors. Addressing this issue requires:

- Designing solutions to upgrade and modernize airports, heliport, hangars, workshops, and maintenance centers to accommodate next-generation aircraft.
- Developing methodologies to optimize airport operations through the effective implementation of advanced systems.
- Identifying design solutions that enhance the operational capacity of existing aircraft while meeting international standards for sustainability and efficiency.
- Design and construct new facilities according to the advances in flying vehicles for example the development of vertiports.

Projects in this area provide students with the opportunity to apply advanced concepts in design and structural analysis, contributing to the strategic development of the sector's infrastructure.

Fleet replacement and modernization.

The strategic planning of the fleet is considered as a big challenge during the strategic planning of airlines, with a directed implication on the efficiency of its operation. The modernization of an airline's fleet can reduce its operating costs, improve the perceived quality of service offered to passengers, and mitigate emissions. The delivery of a new aircraft can take many years for this the fleet planning must be accomplished within a reasonable horizon of time, taking into a count uncertainty.

- Analyzing impacts of fleet replacement and modernization, considering all the actors involved on the aircraft industry ecosystem.
- Developing new aircraft and flying vehicles configuration that allows a rapid fleet replacement and modernization, prioritizing aspects such as autonomy, payload capacity, and sustainability.

By addressing this challenge, students engage in the design of aeronautical systems while exploring solutions that go beyond technical considerations to include regulatory and economic factors.

Drones and air mobility applications

Drones are increasingly used in fields such as precision agriculture, security, and logistics. However, their integration into Colombian airspace faces major barriers, including regulatory challenges, operational compatibility, and social perception. Air mobility developments are an emerging transportations system and their cchallenges include safety, privacy, and communication security Overcoming these obstacles requires:

- Designing innovative solutions that enable the safe and efficient coexistence of drones and new air mobility vehicles with conventional aviation, maximizing their operational benefits.
- Analyzing the economic, social, and technological impacts of drone and air mobility adoption, proposing regulatory frameworks that support their growth while mitigating potential risks.
- Developing drone and air mobility vehicles configurations tailored to the specific needs of the Colombian market, prioritizing aspects such as autonomy, payload capacity, and sustainability.

By addressing this challenge, students engage in the design of advanced aeronautical systems while exploring solutions that go beyond technical considerations to include regulatory and societal factors.

Space exploration

The rapid progress made in Space Technology led to extraordinary accomplishments for the whole human race. Space can be considered an important factor in development and grow of world economies. The huge distances between objects in space make space travel hard and risky.

- Designing innovative solutions that enable the safe and efficient aerospace vehicles and systems.
- Analyzing the economic, social, and technological impacts of aerospace technologies, proposing regulatory frameworks that support their growth while mitigating potential risks.

By addressing this challenge, students engage in the design of advanced aerospace systems while exploring solutions that go beyond technical considerations to include regulatory and societal factors.

B. Learning experiences

Each semester, the faculty selects a specific problem from among the predefined challenges within the major design experience and communicates it to the students. The general methodology for engaging in this major design experience includes the following key aspects:

- Understanding the context: Students begin by thoroughly understanding the problem and identifying the constraints within the context.
- Identifying constraints: Students prepare an analysis in the form of a baseline, outlining the key restrictions and limitations.
- Proposing design alternatives: At this stage, students propose two potential design options for solving the problem.
- Technical evaluation: A technical evaluation of the proposed design alternatives is conducted in simulated or experimental environments to help select the most feasible option.
- Economic and financial evaluation: Students carry out a financial and economic analysis to assess the viability of the design alternatives.
- Evaluating potential impacts in the PESTELE context: Students analyze the potential political, economic, social, technological, ecological (environmental), legal, and ethical impacts of the design. This includes identifying design and certification standards for the aeronautical product.
- Application of engineering standards: Students must apply the relevant engineering standards and norms applicable to the aeronautical sector within the scope of their design.
- Lifelong Learning: students must develop the ability to continuously update their skills throughout their professional careers. This adaptability is essential to stay current with technological advancements, industry trends, and evolving standards in the aerospace sector.

C. Group Formation Strategy

The Aerospace Product Design course adopts a collaborative work structure that simulates real-world dynamics in the aeronautical industry, allowing students to apply their skills in a practical, results-oriented environment. The group formation strategy is outlined below and follows the guidelines presented in the working document developed by the curriculum committee of the faculty of aeronautical engineering in relation to the development of capstone course strategies [29]:

Criteria for the Formation of Groups

Joint Project: All students enrolled in the course work on a single aeronautical product design project, assigned based on requirements set by the curriculum committee of the aeronautical engineering program.

Division into Sub-Groups: The main group is divided into smaller sub-groups, each tackling specific aspects of the problem posed by the project.

Assignment Based on Skills: Each student selects the sub-group they will join based on their skills and experience from prior courses. Sub-groups may be further subdivided to address specific tasks such as CAD design, sub-systems (e.g., control, hydraulic, electrical, pneumatic), or simulations.

Group Sizes

Overall Size: The total number of students in the main group depends on the number of students enrolled in the course each semester.

Sub-Group Sizes: It is recommended that each sub-group consist of no more than three students to ensure effective communication and manageable task delegation.

Roles Within Groups

Overall Leadership: A project leader is assigned to oversee planning, organization, and the overall development of the design. This leader may also be part of a sub-group.

Sub-Group Leadership: Each sub-group is led by a leader responsible for reporting progress, addressing difficulties, and ensuring smooth communication between the sub-group and the general project leader.

Technical Roles: Roles such as CAD designer, simulation specialist, and subsystem designer are assigned based on the project’s needs and the skills of each member.

Teamwork Evaluation Criteria

Periodic Evaluation: Regular meetings are scheduled where each sub-group presents progress reports, including updates on technical work and internal collaboration.

Individual Feedback: Each member’s individual performance is evaluated during these meetings, with personalized feedback provided to improve contributions.

Uniform Rubrics: All members are evaluated using the same rubric to ensure fair and equitable grading, regardless of their role or responsibility.

Conflict Resolution

Internal Mediation: Conflicts should be initially addressed within the sub-group or main group, with all members participating in the resolution process.

Teacher Intervention: If conflicts persist, the instructor steps in as a mediator to ensure a fair and practical solution is reached.

Distribution of Work

Conceptual Design: All students participate actively in the conceptual design phase to establish a common foundation and understand the project's general objectives.

Preliminary Design: During this phase, the workload is distributed among sub-groups, each developing their specific portion of the design until the final delivery.

Benefits of the Strategy

This group formation strategy not only fosters technical and collaboration skills but also prepares students to navigate real-world work dynamics in the aeronautical industry. For instance, designing and manufacturing an aeronautical product requires effective interaction between multidisciplinary teams, mirroring industry practices.

D. Evidence Required for the Maximal Design Experience

The following set of evidence will be used to evaluate the quality of the results achieved by students during the Maximal Design Experience in the Aeronautical Engineering program. The evidence is categorized based on the selected design approach:

TABLE I
EVIDENCE FOR THE MAXIMAL DESIGN EXPERIENCE

Design Type	Evidence	Description and Requirements
Conceptual Design/Preliminary Design	Partial Deliveries (sub-group progress)	Designs reports that present the advance and difficulties during the process
Preliminary Design	Detailed CAD Model	Complete 2D and 3D model of the product
Preliminary Design	Computational Simulations	Results of analysis conducted in adequate software according to the process or product analyzed.
Preliminary Design	Prototype Model	Scale physical model reflecting the main configuration and features of the aeronautical product.
Preliminary Design	Cost and Feasibility Analysis	Cost estimates and analysis of technical and economic feasibility.
Preliminary Design	Final Technical Report	Technical report document

D. Evaluation process

To assess a capstone project, is required to examine its relevance to the discipline, thoroughness of research, project scope and relevance, research and literature review, chosen methodology, results and data analysis, clarity in presentation, quality of outcomes, implications of findings, and the overall execution of the project against set criteria; for these a specific rubric need to be developed. The rubric need to evaluate all the aspects considering difference performance levels and be aligned with the learning outcomes related by the course objectives and goals, finally the rubric need to be employed to offer constructive feedback to the students involved on the project related to their métiers and areas for improvement.

V. CONCLUSIONS

The constant evolution of aerospace engineering requires continuous curriculum innovation to ensure that graduates possess the skills needed to meet future challenges. This study has identified key competencies that aerospace engineers must develop, including systems thinking, digital manufacturing, adaptability to technological advancements, and sustainability-focused design. In response to these demands, the proposed course framework incorporates emerging trends such as automation, artificial intelligence, and space exploration, preparing students for a dynamic and ever-evolving industry landscape.

Benchmarking best practices from leading aerospace engineering programs worldwide ensures that the course remains aligned with accreditation standards and industry expectations. The findings underscore that a flexible and forward-looking curriculum is essential to foster innovation, promote development, and maintain leadership in aerospace engineering education.

This study reinforces the importance of a well-structured capstone experience as a fundamental component of engineering education, equipping students with the practical and analytical skills needed to drive progress in the aerospace sector.

However, the effective implementation of the proposed model faces several limitations that must be addressed:

Institutional Resources: Deploying an aerospace product design course requires significant investment in infrastructure, specialized laboratories, and advanced simulation tools. Institutions with limited resources may struggle to provide these essential components.

Faculty Training: The success of the course heavily relies on the preparedness of the teaching staff. Professional development programs are necessary to train instructors in project-based learning methodologies and the latest technological trends in the aerospace sector.

Institutional Challenges: Integrating a course of this nature may require modifications to the existing curriculum structure, which could encounter resistance within academic institutions. Additionally, fostering interdisciplinary collaboration and sustained engagement with industry partners—both critical for course success—can be difficult to establish and maintain.

To address these limitations, the following strategies are recommended:

Strategic Partnerships: Establish collaborations with the aerospace industry and other academic institutions to share resources, expertise, and best practices.

Continuous Professional Development: Implement ongoing training programs for faculty, focusing on the competencies required to guide complex design projects.

Ongoing Evaluation and Improvement: Develop feedback mechanisms and assessment tools that allow the course to be adjusted in response to evolving industry needs and institutional capabilities.

Although the proposed model presents challenges for implementation, its potential to transform aerospace engineering education and prepare students for a demanding and rapidly changing professional environment is significant. With careful planning and strong institutional commitment, these limitations can be overcome, resulting in a high-quality educational experience that meets the demands of the new engineering professionals.

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