# The Integration of Stakeholder Requirements within Aerospace Engineering Design Education

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## Abstract

The design of an aerospace vehicle system is a complex integration process driven by technological needs, mission needs, cost, schedule, and the state of the industry. The vehicle then operates in an equally complex context, dependent on many aspects of the environment, the performance of stakeholders (including pilots, operators, and maintainers) and the quality of the design itself. Thus, it is critical to incorporate stakeholder requirements early and throughout the design process. However, students' capstone design experiences in aerospace engineering curricula typically do not incorporate stakeholder requirements. In addition, few studies examine the industry preparedness of aerospace engineering graduates after such design experiences. This research fills this gap by reviewing the design processes and pedagogical techniques related to stakeholder requirements currently embedded in aerospace engineering design experiences and other design curricula.

In this paper, we discuss aerospace engineering design curricula relative to the design paradigm held by several aerospace programs. Then we introduce perspectives of stakeholders within the aerospace community and other design-related fields (e.g. mechanical engineering, software development, and architecture). Finally, we describe a research study promoting student understanding of stakeholder requirements in the context in which aerospace engineering is practiced. This effort will help define competencies and specific content areas that can be integrated into senior aerospace design curricula.

## Introduction

The design of an aerospace vehicle system is a complex integration process driven by technological needs, mission needs, cost, schedule, and the state of the industry. The vehicle then operates in an equally complex context, dependent on many aspects of the environment, the performance of stakeholders (including pilots, operators, and maintainers) and the quality of the design itself. Thus, vehicle systems design requires an understanding of not only the technical and performance components, but also the needs and limitations of the stakeholders in the operational context. Satisfying the needs of all stakeholders, however, is a complicated challenge for designers and engineers. Consequently, stakeholder requirements are at times neglected until the latter stages of the design process and/or design decisions are made without considering the operational context of the vehicle system [1-5] . These decisions can have significant impacts on the overall design, the subsequent life-cycle costs, and the safety of stakeholders. Thus, it is critical to examine how to better incorporate stakeholder requirements and context considerations early and throughout the design process.

In the final year of most undergraduate curriculum, aerospace engineering students participate in a senior (also known as capstone) design course, which aims to provide an authentic design experience for the students and to prepare them to overcome design-related challenges during their careers. This authentic experience must introduce students to not only the technical and performance components of design, but also the stakeholder-related components. However, while many studies discuss ways to teach aircraft and space system design[6-14], few studies examine the effects of the design experiences on graduates' preparedness for making challenging design decisions in industry[15, 16]. Due to the economic and human consequences of aerospace vehicle design, literature on aerospace engineering design education has discussed the need to emphasize a broader design perspective[17]. As a result, this paper fills this gap by reviewing the perspectives on stakeholders in design relative to current pedagogical techniques related to stakeholder considerations in aerospace engineering and other design curricula.

In this paper, we discuss aerospace engineering design curricula, highlighting the design paradigm common to several aerospace programs. Then we introduce perspectives of stakeholders within the aerospace community and other design-related fields (e.g. mechanical engineering, software development, and architecture). Finally, we describe a research study promoting student understanding of stakeholder requirements and the context in which engineering is practiced.

## Aerospace Engineering Design Curricula

In the final year of most undergraduate aerospace engineering curriculum, the students participate in a senior capstone design course focused on aircraft, spacecraft, or another technical component (e.g. engine design). For many students, this course is their first opportunity to experience design. While courses vary from program to program, these design experiences generally include a large-scale team project accompanied by instruction on the overall aerospace design process. The most variability among courses and programs lies between the required texts and the requirements of the large-scale project. The subsequent sections describe three common aspects found in a review of publicly-available aerospace engineering senior design course syllabi from several universities, including MIT, Georgia Tech, Virginia Tech, University of Texas-Austin, Iowa State University, and Purdue University, and published works from aerospace and engineering education conferences and relevant journals.

### *Isolated Courses*

Both MIT and Georgia Tech offer elective courses which focus on human performance within an aerospace system. These courses introduce students to factors which affect a human's performance, such as perception, attention, decision-making, and ergonomic considerations[18, 19]. Students also begin to examine effect of interactions between the human and automation on total system performance[18, 19]. These issues can be critical in the design of the cockpit and its displays, feedback systems, alerting systems, and other systems requiring human monitoring or action. These courses, however, are taught in isolation from the required courses in aerospace engineering fundamentals and aerospace design. As isolated courses, they may be insufficient in training students to integrate these topics into the design of aerospace systems in their capstone courses and in the future, as professional engineers[20]. By the time of a student's senior capstone design course, he or she may be unaware of the connections between their human performance-related elective and aerospace design.

Courses in Systems Engineering concepts have also been incorporated into some aerospace curricula[21, 22]. These courses focus on introducing students to the processes and tools used in the systems engineering process prior to their capstone courses. Specifically, students are required to consider the needs and wants of the customer and the necessary trade studies for balancing those requirements with cost, risk, and performance requirements[21, 22]. While capturing the view of stakeholders as customers and introducing students to a broader perspective of design, these isolated courses are also not integrated into the capstone design experience, such that the how and when of the application of these concepts may be lost to students. In addition, the view of stakeholders as customers and clients is just one perspective, as will be explained further in subsequent sections. Students are not necessarily asked to consider the importance of the operational context and other critical stakeholders, such as pilots, ground personnel, and non-users.

### *Design Textbooks*

For the different vehicle systems, faculty typically require one of four classic texts: *Aircraft Design* by Roskam (1990), *Fundamentals of Aircraft and Airship Design* by Nicolai and Carichner (2010), *Aircraft Design –A Conceptual Approach* by Raymer (2009), and *Space Mission Analysis and Design* by Wertz and Larson (1999). These texts place a large emphasis on aircraft and spacecraft sizing, in which competing quantitative performance metrics, such as weight, cost and fuel economy, are traded in pursuit of an 'optimal' design concept[23-26]. Where stakeholder-related metrics are included, they represent stakeholders via surrogates. The use of surrogates allows for quantitative approximations of different stakeholder characteristics to be traded with measures such as weight and cost. For example, when examining life-cycle costs of an aircraft, the experiences of maintainers and manufacturers are incorporated using metrics such as "maintenance-man-hours per flying hour" and "tooling hours" respectively[23]. Pilot limitations and needs are captured in trade studies regarding fuselage and cabin size along with metrics such as "training costs" and "training hours"[23]. With sizing a spacecraft, astronauts are represented by their body weight and the weight of their required food rations and equipment[26]. Some stakeholder concerns may also be presented as constraints on the design, such as the physiological effects of space travel and human safety in the spacecraft design text[26] and aircraft handling qualities in the aircraft design texts[23-25].

The text by Nicolai and Carichner (2010) extends the discussion of stakeholder considerations beyond the other texts to include topics such as (1) whether to pursue a manned or unmanned aircraft systems design and (2) how to reduce life-cycle costs by reducing "touch labor" and operations costs (p.648). The authors also introduce requirements to "accommodate human frailties" (p.17), to take into account "man-rating" an aircraft (e.g. change in the required factor-of-safety) (p. 19), and to satisfy military standards[23]. While these discussions are a step toward a representation of the stakeholder as more than a surrogate, the focus of these texts is on technology and the technical aspects of the vehicle. There is no explanation of how to integrate stakeholder-related requirements and considerations throughout the design process. In addition, the texts do not describe how students can or should consider the purpose of the design as viewed by the stakeholders in the operational context, but instead may cause students to implicitly see the stakeholder as the source of constraints and costs, limiting the design's ability to achieve the maximum technical performance highlighted in the text.

***Design Project***

An important aspect of the capstone course is the design project. In contrast to product design or other capstone courses, the life-span of aerospace vehicles is longer than consumer products, which imposes constraints on the extent to which students can experience the entire design cycle within a year long course. Each year NASA and the American Institute of Aeronautics and Astronautics, along with industry and other organizations, publish design competitions for undergraduates to design an assortment of aerospace systems. Some competitions, such as Design-Build-Fly (DBF), provide students with opportunities to understand the effects of their design on manufacturing, maintaining or operating a system[27]. The testing phases of the design process provide students with critical hands-on experiences, which can emphasize the importance of understanding the operational context of the design and the stakeholders who are affected by the design[28].

Other competitions or industry projects are exclusively focused on the conceptual and preliminary phases of design[29, 30]. These design tasks include unmanned aircraft systems, air racers, or deep space habitation modules[29, 30]. Each project provides students with a Request for Proposals that dictates the requirements for the aerospace system they will design. Some past design competitions and projects have included an array of human-related design requirements, from cargo handling system with time constraints for loading and unloading to the environmental effect of the reduction of the number of pilots in the cockpit[30-32].

With the conceptual design projects, stakeholder requirements can be included. However, it is important to note that students may choose not to prioritize these requirements or may not make critical connections between these requirements and the overall performance of the vehicle system. The result is highly dependent on the RFP and how the students' experience is structured. Due in part to the challenging nature of a senior design course, the RFP needs to explicitly state stakeholder considerations as critical requirements to the design, or otherwise frame the projects so that students must take into account stakeholder and context concerns to accomplish the performance and technical feasibility goals of the project[33, 29]. Thus, it becomes necessary to consider how stakeholder- and context-related requirements are currently valued within the RFPs and the capstone courses as a whole.

Within the conceptual design projects, there are some which are organized with an industry partner. Others, however, do not promote conversations with the client or users of the system, which is distinct from design curricula in other engineering departments where client-based projects are common place[34-37]. A recent study in design education emphasized that immersive experiences with clients or customers provides student with an opportunity to experience the importance of considering context and stakeholders in design[38]. In some cases, students who lacked a design experience with customer/user interaction were found to view design as entirely technology-centered[38]. The focus of design was viewed as a technical problem that does not affect "others" or "humans"[38] (pg. 157). This is a narrow perspective of design, especially in the context of vehicle design, which impacts operators, passengers, etc.

***Summary***

Stakeholder and operational context considerations can be incorporated into an aerospace curriculum through a variety of mechanisms. Within an isolated course, students can begin to perceive the critical nature of humans in aerospace design. However, if it is not integrated into the capstone design curriculum, this course may not be sufficient for providing students with a broader perspective of design. The classical design textbooks represent stakeholder needs and limitations via surrogates. While some of the texts discuss passenger safety, stakeholder- and context-related regulations, and handling qualities, the emphasis is on the technology and technical components of the aerospace vehicle. Finally, the large-scale design project may incorporate human- or context-related requirements, but if satisfying these requirements is not required as part of an assessment rubric or graded assignment, students may assume these requirements are not important. In addition, in a conceptual design focused course, students may not be exposed to the operational side of design and a design's effects on manufacturing, maintenance, and operation.

## Stakeholders in Design Curricula from Other Fields

User. Client. Customer. Stakeholder. There are a variety of words used to describe individuals who are impacted by the design of a system and/or whose needs impact the design of a system. In Buede's system's engineering textbook[39], he describes multiple categories of stakeholders, where each stakeholder has a different perspective on the system and its requirements. Yet, it is clear from Visser's work that "some views of design focus strongly on people, others do not"[40] (p. 31). Some of these different perspectives of the stakeholder then may be more important to the designer than others, while some designers may not find any of these perspectives important. This section outlines three different representations of "stakeholder" that appear in the literature and design-related courses and how these representations are currently incorporated into the aerospace design curriculum.

*Stakeholders as Clients/Customers.* In the product development world, an understanding of customer needs can be critical for the successful launch of a new product. As a result, the education of students in this area begins with an examination of customer and market needs. Otto and Woods (2001) and Pugh (1990) emphasize the importance of market and competitor analysis to determine consumer acceptance of the design[41, 42]. "Many new technology-development initiatives are undertaken with no basis for market acceptance other than management belief. If the developer thinks the technology is amazing and valuable, then everyone else should also"[41] (p. 112). To prevent this approach to design, Ulrich and Eppinger (2011), authors of the textbook *Product Design and Development*, describe the first activity within the design process as the identification of customer needs. The outputs of this activity are customer need statements with weightings of importance[43]. Later in the process, the authors incorporate customer response into the prototyping and testing activities to ensure that customer needs have been met by the product[43]. These processes, however, only briefly discuss stakeholders outside of the customer and client, and society as a whole is only considered from the perspective of the environmental impacts of the product[43].

In many product design capstone courses, students have the opportunity to work with companies and clients closely throughout the design process[36, 44]. Students need to consider the marketing aspects of the design and understand the importance of satisfying the customer[22]. The importance of the customer is also implicit in some aerospace capstone courses, where the students are responding to an RFP or similar document[11]. Yet, with an RFP, students must take the initiative to better understand stakeholder needs and limitations. In addition, without certain systems engineering tools it may be challenging for students to determine how these considerations can be prioritized or integrated. Some aerospace programs have gone farther and organized actual customers for their capstone projects[45, 46]; in these cases, as with the product design courses, students interact with the customers throughout the capstone experience.

*Stakeholders as End-Users.* In human computer interaction, software, and product design education, faculty also focus on the concepts of user research and user testing[47]. At Illinois Institute of Technology, the first phase of the design process introduced to students is comprised of research to know the user and know the context[48]. Within Carnegie Mellon's School of Design, user testing is taught as a form of evaluation within the design process[48]. Buchanan, a faculty member in the program, emphasizes three lines of reasoning which he states are necessary in the design of products: (1) "the ideas of designers and manufacturers about their products," (2) "the internal operation logic" of the products, and (3) "the design and ability of human beings to use the products in everyday life"[49] (p. 20). This model relates product experience with the various elements of the product and focuses on the community of users and the expectation of how the user will interact with the product[49]. These concepts reinforce the emphasis on not only the importance of considering users as stakeholders within the design process, but also incorporating their perspectives into the overall design of the product.

In the design of many aerospace vehicle systems (e.g. commercial aircraft, military jets, or spacecraft), user testing of the entire vehicle system to better understand handling qualities, passenger comfort, or crew feedback systems is extremely expensive and time-consuming, Paradoxically, this cost motivates the better inclusion of stakeholder concerns early in design to prevent expensive testing-redesign cycles later in the design process. However, the cost of high fidelity simulators or full size mock-ups of the aircraft to demonstrate and test that these stakeholder requirements have been met typically also prevents their inclusion in senior design experiences. The consideration of the end users in aerospace vehicle design education, therefore, has come most often with the design of remote-controlled aircraft or human-powered aircraft[13, 28, 50, 51]. In these cases, a student can act as the end user of the aircraft in user testing of the controllability or maneuverability of the aircraft in an operational context the students define.

*Stakeholders at the Center.* In the education community, human-centered design approaches have begun to materialize in different venues from environmental design courses to service learning courses to electrical and computer engineering courses[35, 48, 52, 53]. Additionally, engineering education researchers have begun to examine student experiences, assessment methods, and different interventions related to human-centered design[36, 38, 54, 55]. At the University of Colorado, Boulder, faculty members in the environmental design group describe the role of an environmental designer as solving human environmental problems[48]. Their corresponding design process considers the human as a critical component in developing the problem statement, completing background research, developing hypotheses to the "environmental malfunction," and ultimately evaluating the solution[48] (p. 37). In a product development course at the University of California-Berkeley, the faculty has combined human-centered design and product development approaches[36, 52, 55]. The perspective of the stakeholder at the center of the design process provides students with an opportunity to view all of the critical stakeholders in a project, from the customer to the end user to the non-user. The students revisit the stakeholder requirements and limitations throughout the design process and participate in requirement definition and user testing[52, 53].

An evaluation of students within the product development course specifically has demonstrated that "students developed a strong belief that 'good design dictates that technology can and should serve all members of the potential user population'"[56] (p. 108). Most importantly, the use of a human centered design process in these courses has helped broaden students' perspectives of design, better preparing them to collaborate with other engineers and designers during their careers[55].

In contrast, within aerospace design education, stakeholder considerations are commonly limited to the viewpoint of stakeholders as surrogates. Thus, there is a high reliance on quantitative measures for stakeholder needs and limitations. Many students, then, are not introduced to stakeholder considerations that are challenging to quantify, such as metrics for maintainer's performance or pilot fatigue. The aerospace capstone courses with a broader focus on design provide students opportunities to consider the customer and the end-user more directly. Yet, other stakeholders are not considered due to the constraints on the design project (e.g. conceptual design-focused capstones, inability to perform field testing, etc.). This contrasts with courses in service learning or product design where the courses require students to focus on usability from the start, examining the design problem with a greater focus on the human component.

**Ongoing Research**

Rather than approaches that account for the stakeholders only through the use of surrogates and disregard the considerations related to operational context due to the scope of project, design curricula could, alternatively, examine the design problem from a holistic systems perspective by integrating the human component at the center of the design process. To further this idea, a research study is currently being conducted which aims to integrate approaches to design that focus on stakeholder considerations into the aerospace engineering design curricula. To address the industry perspective, observations and interviews of aerospace engineering design teams and Subject Matter Experts (SMEs) are being analyzed for how the stakeholder perspective is considered at an aerospace vehicle design firm. In addition, these interviews are allowing the researchers to engage in conversations about the major challenges faced by entry-level engineers on design teams.

Aerospace engineering students' understanding of design, stakeholders, and the operational context of an aerospace vehicle are being assessed throughout their senior year through the use of conceptions of design ranking test and problem formulation tasks based on a submarine design scenario[57]. Since students have different levels of prior understanding about traditional aerospace vehicle design, the researchers chose not to use an aircraft design scenario to gain an unbiased understanding of students' general perceptions of important disciplines in a design project and design requirements. The purpose of this assessment is two-fold: (1) to provide a baseline for students' understanding about design and the role of stakeholders and context in the design process based only on their previous academic experiences, and (2) to assess the effects of a future educational intervention on the engineering students in the senior capstone design course.

The results of the case study and the initial assessment will inform the development of learning outcomes and content areas for an educational intervention for a senior capstone course in aircraft design at a large, research-intensive university. The intention of this intervention is to provide students with the opportunity to consider specifically how stakeholder requirements and concerns can be integrated into the design of a fixed wing vehicle. Lab sessions will focus on important characteristics of engineering design, specifically collaboration, negotiation, and communication. The students will also engage in reflective activities to prime them for the lab activities and content. These reflective activities include the opportunity for students to consider what design activities they have been utilizing in their individual design projects. In addition, the students will be introduced to tools and methods for integrating stakeholder requirements and concerns that they can choose into incorporate into their understanding of the design process for designing a fixed wing vehicle. The overall goal is to have students define how stakeholder requirements will be incorporated into their design process.

The labs are designed with a social constructivist perspective, which contends that knowledge is constructed through social interaction[58-61]. In a learning environment, this theoretical perspective has four main implications. The first is the necessity for social interaction and thus collaborative activities to help students build knowledge about a particular concept[59-61]. The second implication is that collaborative learning should be mediated by a "more knowledgeable other"[61]. The focus in this case is less on direct instruction and more on facilitation. The third implication is the importance of scaffolding, which comes from the Vygotsky's theory known as the Zone of Proximal Development, which is "the distance between the actual development level as determined by independent problem solving and the level of potential development as determined through problem solving with a more knowledgeable other"[60, 61]. The final implication is that learning activities are grounded in authentic, real-world contexts. Thus, these labs will be designed to provide students with the opportunity to work collaboratively on real-world cases, with the instructor serving as a facilitator who is scaffolding the lesson appropriately.

Following the implementation of the intervention, it will be critical to evaluate its impact on the students' abilities to take into account stakeholder considerations during the design process. The evaluation is comprised to two parts: (a) small reflections and a post-intervention version of the original assessment and (b) a critical review of students' capstone projects. The critical review of the capstone design final reports will be completed using a rubric developed based on the findings from this paper and the industry case study.

**Expected Outcomes**

Despite proposals for substantive changes in the field of aerospace systems design, there is a need to better prepare aerospace engineering students to overcome future challenges within the field[6, 17]. The results of this research will also clarify challenges faced by students upon entering into the engineering industry. These challenges should be considered in the development of courses and programs that help bridge the gap between engineering education and industry. In addition, within the aerospace design community, this work will provide empirical results regarding engineers' and engineering students' perceptions of how stakeholder and context considerations are integrated into the vehicle design process.

The work outlined in this paper serves as a starting point for future research in pedagogical techniques for integrating stakeholder considerations into technology-focused capstone design courses. Specifically, the results will help define learning objectives and pedagogical techniques which can support the development of aerospace engineering students' understanding of the role of stakeholders in design and the context in which engineering is practiced. In addition, the evaluation instrument and project assessment rubric will be designed to permit future implementations within any engineering design capstone course, regardless of structure.

While the research is aimed at improving design education in an aerospace engineering curriculum, the hope is that the findings can be generalizable to other engineering disciplines. The results of this study will inform design education in other disciplines, as stakeholder considerations can be integrated into the design process for any complex system. Over the next few decades, technology will continue to advance at a rapid pace. Today's engineering students will need to consider critical design issues, such as the implications of fully automated machines and vehicles or renewable energy that powers cities or aircraft. They will need to make design decisions and compromises between technical considerations and the economic and human considerations[17]. By incorporating stakeholder considerations into the engineering design curricula, this work will assist faculty in preparing their students to respond to these and other future engineering challenges.

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