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Managing and Exchanging Knowledge Underlying Aerospace Engineering Design Decisions

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Introduction

The engineering design process is a complex, iterative process through which individuals and teams solve ill-defined, multidisciplinary problems by integrating domain-based technical knowledge.[1,2] Aerospace engineering integrates technical components from many different disciplines, such as aerodynamics, combustion, avionics, materials science, structural analysis, flight mechanics, optimization, and manufacturing. Thus, successful aerospace engineering design requires multidisciplinary communication and cooperation among all stakeholders to balance technical developments within disciplines with design integration across disciplines. However, novice engineers are often unable to decompose, document, and exchange these decisions, and the constraints and trade-offs leading to the decisions, to others also involved in the design process.[3-7]

The typical aerospace engineering degree program culminates with the completion of a capstone design course which satisfies the Accreditation Board for Engineering and Technology's (ABET) student outcome for having an ability to design a system to meet desired needs within realistic constraints.[8] Capstone design also typically incorporates a collaborative aspect, addressing the ABET student outcome for having an ability to function on a multidisciplinary team. Often, assignments are designed with the expectation that students are capable of communicating knowledge underlying design decisions to team members and course instructors. However, students may still be developing collaboration[9] and communication[10] skills throughout capstone design.

This paper discusses the role of managing and exchanging knowledge underlying aerospace engineering design decisions. As a simplified example, a designer may include assumptions about the aircraft's operating environment (e.g. typical operations in marine climate) that lead to selecting a particular engine (e.g. an engine that is resistant to corrosion caused by marine conditions). The environmental assumptions incorporated by the designer would be considered knowledge underlying their design decisions. These assumptions may subsequently impact other designers' decision-making processes, such as the structural engineer's selection of a corrosion-resistant material. However, if the original designer does not effectively manage and exchange their environmental assumption, others also interacting in the design environment may not incorporate that information in their decision-making process. While expert designers may be aware of the critical knowledge underlying design decisions and utilize established methods for exchanging information, novice designers may not be aware of their internal knowledge structures or use effective methods for organizing and exchanging that knowledge.

This paper uses a "scholarship of integration" approach to make connections across various strands of work related to coordinating knowledge underlying design decisions in design teams. A scholarship of integration research approach synthesizes information (i.e. literature findings) across disciplines and places major themes into the larger context of the design process.[11] In performing this type of critical analysis of prior research, larger intellectual patterns can be identified and interpreted.

Aerospace Engineering Design Context

To discuss coordinating knowledge within aerospace engineering design teams, we must first define critical features of the engineering design context. Engineering design is a structured approach to developing, validating, and implementing complex systems.[2] Aerospace engineering design, specifically, can be characterized by many different representations of the engineering design process.[1, 12, 13] One methodology commonly used by aerospace engineering design firms is the system engineering design approach. Systems engineering is an interdisciplinary engineering management process that seeks to provide a balanced set of design solutions capable of meeting specified customer requirements over the entire life-span of the artifact.[14] An essential characteristic of the systems engineering process is the iterative performance of three activities: Requirements Analysis, Functional Analysis, and Design Synthesis.[14-16]

Systems engineering manages complexity by decomposing the system into discipline-oriented design teams and by constantly iterating through the design process to incorporate new information. Aerospace engineering design, in particular, commonly uses an iterative approach to support multidisciplinary design integration.[1] The initial, conceptual design phase frequently calls for the designer to make assumptions about specific attributes using historical regressions.[13] As system characteristics are refined throughout the conceptual and preliminary design phases, performance estimates are iteratively updated to incorporate the new information. To manage design complexity, an aircraft's specific technical components, such as the propulsion system or avionics, are segmented into separate design teams. Technical component design teams must iteratively integrate critical information from adjacent technical systems into design reasoning.[12] Thus, communication of knowledge in aerospace engineering design needs to occur through time as the design evolves within and across design teams.

Aerospace Engineering Design Team Cognition

The cognitive process of aerospace engineering design teams can be viewed using three categories: Shared Knowledge, Goal Alignment, and Information Sharing.

Shared Knowledge

A team's mutual knowledge is described as "knowledge that the communicating parties share in common and know they share."[17] Clark and his colleagues have frequently referred to mutual knowledge as the "common ground" among collaborators.[17-19] Notably, mutual knowledge enables team members to frame information sharing with an accurate awareness of the knowledge held by other team members.[18,19] Similar to mutual knowledge, a shared mental model (SMM) is a type of collective knowledge structure held by members of a team and are used to interpret a task and to coordinate team member actions.[20, 21] A team SMM represents the mutual knowledge among the team members by which they can interact with one another.[22] SMM's provide a frame or mechanism within which team coordination and adaptation can be examined and explained.[23] Further, the team's external performance environment shapes and is shaped by team member cognition and action.[23]

As such, engineering designers must recognize the considerations and constraints of disciplines outside their own expertise.[24] This is particularly important when technical changes of one sub-system affect the performance of other sub-systems. However, engineers are not always aware of the overlapping considerations embedded within their sub-system design. A lack of multidisciplinary awareness is evident in novice engineers' design practices. Whereas expert engineers and designers are able to recognize design trade-offs and limitations, novice engineers do not employ similar design strategies.[25] A high level of mutual knowledge increases the ability of team members to exchange useful and relevant information. In the same way, the receiving team member is able to accurately comprehend the exchanged information and incorporate the essential pieces of knowledge into their approach to problem solving and decision-making.

Mutual knowledge can be constructed by examining an event from the perspective of one's team members as well as through their own perspective.[26] Additionally, SMM's are supported through team communication (e.g. leader briefings) and team interaction training.[23] Of note, in situations with novel circumstances team mental models are linked to team communication processes and overall team performance.[23, 27]

Goal Alignment

Aerospace engineering tasks are directed by design goals that are understood by all stakeholders and designers and are used integrate designers' efforts. High-level design goals are derived from a specified market or military need and clearly state the overall purpose of the design.[1] Design teams share at least one high-level goal, and more detailed goals and design requirements should remain consistent with the high-level goals. However, due to the associated disciplinary division between design teams, detailed design preferences and specific discipline-based goals do not necessarily align.[22, 23, 28]

Often, conflicting design issues identified in later stages of design are a result of disparate higher-level design goals. The ramifications of disparate higher-level design goals are apparent in studying the design of the F-111 Aardvark and the F-35 Lightning.[5, 7] While the completion and delivery of the F-35 design is still underway, the F-111 was deployed to the United States Air Force (USAF) in 1967. Originally, the F-111 was commissioned for both the USAF and United States Navy (USN); however, conflicting high-level design goals caused the Navy to terminate the F-111B variant and instead pursue the F-14 Tomcat.[5] The USAF desired a vehicle that could act as a low-altitude penetrator and high-altitude supersonic fighter, while the USN wanted an aircraft that could function for extended periods away from the launching aircraft carrier. The disparate higher-level design goals led to disagreement and conflict with nearly every lower-level vehicle requirement. Whereas both military units could agree on the use of variable geometry wings, they were unable to resolve most other issues.[5] Similarly, the F-35 uses one basic airframe on three aircraft models to meet the opposing needs each military branch.[7] This approach was expected to reduce the vehicle's Life Cycle Cost by pooling acquisition costs[29]. However, the vastly contrasting service-specific needs led to design inefficiencies, budget overruns, and program delays.[29]

Thus, a clear and synchronous understanding of high-level design goals is needed to appropriately elaborate lower-level design characteristics. For example, the high-level design goal of the C-5 Galaxy was to design an aircraft capable of transporting a United States Army division across the continental United States to a distant location[4]. This high-level design goal for the C-5 Galaxy was explicitly defined at the start of the design process and was used to develop all of the lower-level vehicle requirements. Moreover, agreement on lower-level requirements was achieved through open communication and information sharing among a variety of stakeholders:

"The organizations cooperated, exchanged data, and debated alternatives, continuously narrowing the choices and communicating the evolving baseline to all team members... This phase of the systems engineering process culminated in a balanced, achievable, and integrated set of requirements that were fully understood by all parties, and that remained stable throughout the development of the aircraft." (Griffin, 2005, p. 15)

Information Sharing

As part of aerospace engineering design, exchanging knowledge underlying design decisions is a critical mechanism for enabling constructive team processes.[28, 30, 31] Exchanging knowledge, or information sharing, is defined as the collective exchange and utilization of knowledge and expertise previously held by a limited number of group members.[28, 32, 33] Information sharing has three aspects that should be addressed for enhanced team interactions: awareness of the distribution of information, understanding of the approaches for sharing information, and understanding of how information can be integrated into reasoning about design decisions.

As a design increases in complexity, knowledge about the design reasoning is distributed to more individuals. While effectively distributed knowledge increases creativity and productivity, it is also can hinder overall team effectiveness.[34] Team members may fail to exchange relevant information [32, 34] or to integrate pertinent information into reasoning for design decisions.[34] Team members' approaches to sharing information thus become an important feature of effective team coordination.[28, 30, 31] Research in information sharing has demonstrated a need to examine the effects of the relevancy and newness of the information exchanged among teams and team members to support group decision-making and overall performance of the team.[32]

Beyond formal meetings and tag-ups, continuous, informal communications across immediate working groups increase design team effectiveness and synchronous reflection on goal accomplishment.[3,24] Unprompted design discussions stimulate peer review opportunities and contemporaneous sharing of design tasks.[24] Moreover, these informal gatherings promote continuous awareness of and reflection on design issues, increasing response time to addressing and solving these challenges.[24]

Previous research has investigated the exchange of information along two dimensions, openness and uniqueness.[28] The openness of information sharing broadly describes team communication related to goals, progress, and coordination.[28, 31, 35] The uniqueness of information sharing is related to the number of members with access to a piece of information.[28, 36] Related to the engineering design practices, designers attempt to uncover hidden profiles held by the customer through the Requirements Analysis process. Yet, in discussing alternatives, unique information is often not exchanged in favor of rephrasing and repeating common information.[37]

For example, open communication and cooperation within the C-5 Galaxy's requirements definition process led to the establishment of very stable system requirements and equitable understanding of the overall design goals. In design of the C-5, a concerted effort was made to openly communicate design decisions and requirements definitions to all stakeholders. The systems engineering requirements process involved the expertise of multiple stakeholders to balance the users' needs with current design capabilities and the resulting design decisions integrated information from all domains.[4]

While research has investigated the openness and uniqueness of information sharing, limited work has been done to jointly consider these two dimensions.[38] Fleming and Coso (2014) suggests future research should include expanded definitions of openness and uniqueness to also incorporate aspects of relevancy. To operationalize the relevancy of information sharing, a consideration must be made for how information is integrated or abstracted into final design decisions.[38] Aurisicchio, Bracewell, and Wallace similarly found that more research is needed on the information needs of engineering designers.[39, 40]

Additionally, it is critical to consider the expertise of the designer, which can cause knowledge needs, awareness, and requests to vary.[41] Novice designers may ask relevant questions when aware of their knowledge needs, leading to pertinent information sharing. However, when novice designers are unaware of their knowledge needs, they are subsequently unable to ask questions or to employ a clear design strategy that incorporates the pertinent knowledge about the design. Conversely, expert designers tend to employ a well-defined design strategy when problem-solving, without being explicitly aware of the utilized strategic knowledge.[25]

Discussion

This paper used a scholarship of integration research approach to integrate and synthesize findings from the social science domain (e.g. psychology, organizational behavior, and sociology) with observations from the engineering domain. Implications of this research include the design of educational interventions for creating meaningful design experiences that cultivate effective strategies for managing and sharing knowledge underlying design decisions. Particularly, instructors should consider the three aspects of aerospace engineering design team cognition discussed here (i.e. shared knowledge, goal alignment, and information sharing). Educational interventions should be created to support each component of design team cognition.

In supporting shared knowledge, instructors could incorporate activities to increase student awareness of the roles of the other design team members. Additionally, instructors should create opportunities to demonstrate to students the different difficulties that may arise in integrating multidisciplinary design considerations. As an example, the authors of this paper designed and implemented a workshop intended to cultivate aerospace engineering students' awareness of multidisciplinary considerations within one university's aerospace engineering capstone design course. In this workshop, the students worked individually as well as on small teams to decompose the aircraft systems into disparate technical disciplines and assign design requirements to each of the disciplines. The students also noted the "design drivers" for each discipline (i.e. the design parameters/assumptions/justifications that guide critical design reasoning).

Furthermore, this workshop supported students' goal alignment by asking the students to collaboratively define a full set of design requirements for a given aircraft proposal. In this activity, the students role-played as an expert within each technical discipline that would be included in the design of an aircraft: each group had an "expert" in propulsion, structures, aerodynamics, controls, and management/marketing. The experts were responsible for ensuring their components' requirements were sufficient and had no conflicting considerations. In this activity, the student groups had to reflect on the overall goal of the design, particularly in negotiating conflicting design requirements.

Finally, as discussed throughout this paper, much work has been done to describe theoretical characteristics of sharing knowledge underlying design decisions. However, there is limited research available that applied this theoretical literature within the engineering design domain. Future research should integrate theoretical frameworks with observed aerospace engineering design practices and work to design interventions that support the discussed dimensions of design team cognition.

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