DESIGN KNOWLEDGE COORDINATION: ENHANCING NOVICE AEROSPACE ENGINEERS' DESIGN SKILLS THROUGH COORDINATED DECISION-MAKING

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DESIGN KNOWLEDGE COORDINATION: ENHANCING NOVICE AEROSPACE ENGINEERS' DESIGN SKILLS THROUGH COORDINATED DECISION-MAKING

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To my large and crazy family

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SUMMARY

Design Knowledge Coordination is the mechanism that enables individuals and teams to align tasks, resources, and knowledge to make decisions about a design. Previous research has investigated the impact of coordination in the context of high-stress, time-sensitive work environments, such as mission control operations, air traffic control, transportation systems, and emergency response systems. These work environments differ from aerospace engineering design in that the individuals are typically supported by strict work protocols and processes intended to enable coordination. Conversely, aerospace engineering design depends upon designers' understanding of technical disciplines relative to the overall design objective and has a loose protocol for coordinating technical developments within the design.

Though effective coordination is required in the successful design of an aerospace vehicle, instruction in design knowledge coordination has yet to be researched in the literature. Thus, this work uses qualitative and quantitative methods to address three research questions: (1) What design knowledge coordination does aerospace engineering require? (2) How do aerospace engineers coordinate and integrate knowledge about a design? (3) What educational interventions can better support novice aerospace engineers' design knowledge coordination?

To answer the first research question, a framework of structuring design knowledge and design knowledge coordination was characterized from an analysis of engineering design literature. This framework was then analyzed for indicators of coordination using a systematic literature review of processes that encompass coordination. The second component of research question one, an evaluation of the coordination and integration inherent to the aerospace engineering design process, was addressed by establishing an authoritative example of the aerospace engineering design process, as captured by texts commonly referenced in traditional aerospace engineering capstone courses. Indicators of coordination were identified at all stages in the design process using a qualitative coding scheme developed through the systematic analysis of related literature.

The second research question applied a multiple case study method: An analysis of observations of student teams in a capstone design course captured indicators of coordination as well as emerging themes and strategies for coordination. Additionally, each students teams' design process was characterized and compared to the design process within the authoritative text, characterized in research question one. These findings were contrasted with students' perspectives of their engineering design, observable through a focus group discussion.

The third research question connected findings from research question one and two to literature on engineering education strategies to identify learning goals and design activities that could better support students' design knowledge coordination. Suggested evaluation criteria connect the findings from all three research questions to the design knowledge coordination framework.

This research contributes to both the aerospace engineering design community and the aerospace engineering education community by defining key indicators of coordination as well as outlining indicators to identify and enhance novice designers' coordinated decision-making within the aerospace engineering conceptual design process. Further, results of this research will address the noted gap between aerospace engineering education and the needs of industry for engineering graduates to use effective approaches to engineering design, integration, and synthesis.

CHAPTER 1 - INTRODUCTION

Merriam-Webster defines coordination as “the process of organizing people or groups so that they work together properly and well.” Gerson (2008) extends this definition to discuss coordination as a mechanism that “(1) connects two things together and makes them part of a larger system of dependencies, (2) it does so in specific ways, and (3) it also holds them apart and keeps them distinct.” Applicable to this research, coordination can be viewed as a process that enables individuals and teams to align multidisciplinary tasks, resources, and knowledge to make decisions about a complex systems design.

This thesis frames aerospace engineering design itself as a coordinated process. *Design Knowledge Coordination* is a structured approach to integrating design considerations across the different disciplines in engineering design through use of goals, tasks, metrics, and decisions. Design knowledge coordination distinguishes coordination in the same manner as Strauss (1985) distinguishes the division of labor: “(1) task to task, (2) person to task, and (3) person to person” (Strauss, 1985, p. 2). Thus, knowledge can be coordinated across designers on the same design task or different design tasks, and in addition may need to be coordinated within the tasks being performed by any single designer. Additionally, the amount and type of coordination may change depending on the needs of the task and/or designer at that moment within the design process, requiring the designers to think not only about what knowledge needs to be coordinated, but when.

Within aerospace engineering, design knowledge coordination is apparent through the recognition that the design process encompasses distinct, yet interdependent design components. In the design of an aerospace vehicle, key tasks and disciplines are inherently kept separate in the design process. For example, the propulsive system is generally designed separately from the structural materials. However, in the design of the propulsive system, the designer would have to know the required thrust capability as well as various velocities achieved by the aircraft. An output of the propulsion design would be outlet temperatures and the weight of the system. Similarly, while the structural design doesn’t directly incorporate every aspect of the propulsive system, it does also rely on knowing the aircraft velocities (and accelerations), and the engine’s outlet temperature can place a constraint on the materials related to the withstanding maximum temperature at specific locations. Through a coordinated process, engineering designers would incorporate shared and consistent information from both the propulsive analysis and the structural analysis in their design process. Additionally, they would maintain a clear approach to integrating the considerations of each into the design process. Depending on how the design team is structured, some of this design knowledge coordination will need to occur within individual designers’ tasks, while other aspects of the design may need to be coordinated across two or more members of the design team.

Effective coordination is required in the successful design of an aerospace vehicle, yet the behaviors associated with coordination design knowledge have not been fully explored. Previous research has investigated the impact of coordination in the context of high-stress, time-sensitive work environments, such as mission control operations, air traffic control, hospitals, and emergency response systems (Garbis & Artman, 1998; Patterson, Watts-Perotti, & Woods, 1999; Hughes, Randall, & Shapiro., 1993; Berndtsson & Normark, 1999; Magid et al., 2009; Chen, Rao, & Upadhyaya, 2008). These work environments differ from an aerospace engineering design context in that the individuals are typically supported by strict work protocols and processes intended to enable coordination (Charness & Tuffiash, 2008). Conversely, aerospace engineering design is enabled through individual designers’ understanding of technical disciplines relative to the overall design objective and an abstract protocol for communicating and coordinating technical developments within and across the disciplinary areas. Designers generally share pertinent knowledge about the design as they deem necessary, rather than by following explicit protocols for coordinating their knowledge.

1.1 Research Context

The work described in this thesis is seated at the intersection of aerospace engineering design, complex decision-making, and engineering design education. While the context of this work is outlined within each chapter, this section gives a brief overview of the essential components of these three areas areas as well as an outline of the scope of this research.

1.1.1 Scope

This research integrates an analysis of conceptual design with research in complex decision-making and practices in organizational management to enhance engineering design education. Thus, this research spans aspects of each of those fields (conceptual design, complex decision-making, organizational management, and engineering education). However, in spanning those fields, the focus of this research is to define, analyze, and evaluate engineering design as a coordinated process. This is compared to evaluating the execution of the design process by any individual designer or team.

As a general field, design symbolizes the "conception and realisation of new things" (Cross 2006, p1). When considering engineering design, Simon (1996) references engineered products as artifacts that are created outside of natural environments: “Synthetic or artificial objects and more specifically prospective artificial objects having desired properties are the central objective of engineering activity and skill. The engineer, and more generally the designer, is concerned with how things ought to be how they ought to be in order to attain goals, and to function.” (Simon, 1996, p. 4).

From the perspective of engineering design research, cognitive constraints within engineering designers make it difficult for designers to consider a large and complex design process without breaking the process into smaller pieces of information about the design and the design environment. Thus, design is commonly achieved through a structured process with divisions in the design tasks that separate design decisions into meaningful pieces of information about the design. Engineering design has incorporated methods to address the different approaches to breaking down the design process, such as Work Breakdown Structures and Concept of Operations Definition (INCOSE, 2003; NASA, 2007).

From the perspective of team science and project management, design can be viewed as a structured process with divisions in the design tasks intended to separate work responsibilities between multiple people as well as between multiple teams. The divisions of tasks between people and teams considers the expertise of the designer as well as the project management methods that are employed by the overall design manager. Combining the perspectives from engineering design research and team science, approaches, such as Integrated Product and Project Development (INCOSE, 2003), have been developed to effectively manage the complex and integrated decision-making involved in the engineering design process.

These approaches to structuring and decomposing the engineering design process are most effective for later stages of the design process. These later phases have clearly defined tasks, which can be divided along disciplinary, or component boundaries. Conversely, the intent of this thesis is to examine the inherently non-prescriptive conceptual design process and develop an approach for structuring and coordinating knowledge about a design within this initial design phase.

Thus, the scope of this thesis is focused on conceptual design; it strives to characterize structures that are inherent to conceptual design and can be used to define how knowledge about a design can be coordinated within earlier phases of design. Further, the scope of this thesis includes an analysis and evaluation of how the early-stage conceptual engineering design process explicitly incorporates design knowledge coordination. This is accomplished by framing aerospace engineering design as a process with a structure comprising both a sequence of design steps and points where iteration is required. This framing illuminates the inherent coordination needed to successfully complete design tasks in a manner that can be used within educational environments to scaffold novice designers' learning objectives.

1.1.2 Aerospace Engineering Design

Aerospace engineering design differs from other design areas (e.g. graphic, industrial, and software design) in the enhanced complexity involved with clarifying and defining engineering products. Engineering design relates to the design of objects that attain specific goals and functions according to a set of requirements. Further, while the sciences are primarily concerned with analysis, engineering is primarily concerned with synthesis. In a synthesized solution, there is no one correct approach or output design. Instead, the engineering designer uses their best interpretation of the design goals and functionality to define what the system ought to be (Simon, 1996).

Engineering design can also be defined as a structured approach to developing, validating, and implementing complex systems (Pahl, Beitz, Feldhudsen & Grote, 2007). These complex systems entail multiple points of interaction characterized through overlapping, interdependent, and often conflicting interdisciplinary design parameters, preferences, and constraints (Cross, 2006; Pahl et al., 2007; DAU, 2001). Thus, 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 (Cross, 2006; Nicolai & Carichner, 2010).

Aerospace engineering design can be characterized by many different representations. For this research, the aerospace engineering design process is assumed to follow the general process depicted in Figure 1 and outlined in Raymer (2006), Roskam (1990) and Nicolai & Carichner (2010). This interpretation breaks the design process into three main phases: conceptual design, preliminary design, and detailed design. The design requirements are inputs to the design and are classified through an initial requirements definition process. Conceptual design answers basic questions related to aircraft sizing, performance, and configuration. Advanced technology infusion is also considered within conceptual design to address performance gaps. Preliminary design represents the transition from a dynamically changing design to a more static aircraft configuration. Within preliminary design, technological components are designed and evaluated. Detailed design represents the final stage of design and marks the entrance of full-scale aircraft development. Components are fabricated and physically integrated in the detail design phase. The design process ends with sufficient specifications to drive fabrication.

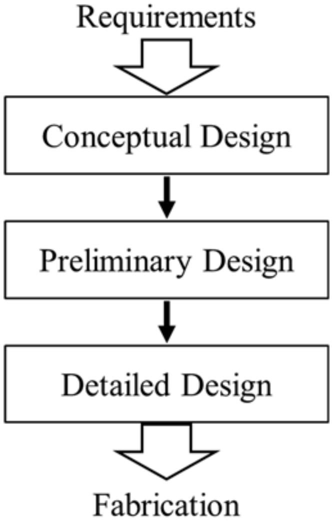


Figure 1. Aerospace engineering design process

Systems engineering is an approach used by aerospace engineering to connect the activities and decisions within the engineering design process with the description of the operational need (DAU, 2001; Moser, 2014; INCOSE, 2004; NASA, 2007). This interdisciplinary approach evolves throughout the lifecycle of the system development and incorporates an integrated perspective of the system solution which balances the technical requirements of the system with the customer needs. Through systems engineering, engineering designers decompose the primary life cycle functions of the design solution and ensures that each stage of the life cycle is accounted for within the design process (DAU, 2001).

There are many other approaches to aerospace engineering design which, in combination with the conceptual, preliminary, and detailed design phases, incorporate an explicit and intentional integrated perspective into the design process. As an example, Integrated Process and Product Development (IPPD) incorporates all disciplines involved with the design, development, manufacture, distribution, support, and management of the designed system (Burt, 1996). Within an IPPD approach, design elements are developed concurrently and integrated early in the design process (Burt, 1996). Further, multidisciplinary collaboration is addressed through team decision-making and careful management of social resources (Burt, 1996).

Inherent to the aerospace engineering design process, designers must recognize the value and importance of disciplines outside their own expertise (Baird et al., 2000). This is particularly important when technical changes to one subsystem must be coordinated with other subsystems. However, engineers are not always aware of, and able to coordinate, the overlapping considerations embedded within their subsystem design. A lack of multidisciplinary awareness and coordination is evident in novice engineers' design practices, particularly compared to expert engineers (Ahmed, Wallace, & Blessing, 2003).

1.1.3 Complex Decision-Making

In complex decision-making, the decision-maker's interpretation of their environment and available information dictates how they approach a specific design problem. Further, the decision-maker's interpretation of their environment may differ from how other decision-makers interpret their environment (Bainbridge, 1997).

A decision-maker's approach to decision-making is guided by both their interpretation of external environmental cues and their internal representation of the environment. However, the information that is available to the decision-maker may be inadequate for complete decision-making (Bainbridge, 1997). Additionally, decision-makers use their understanding of the present state of tasks as well as their prediction of future events and plans to guide design and decision-making strategies (Hollnagle, 1993).

Specifically, in evaluating designers it is critical to consider their expertise as expertise of any decision-maker can cause knowledge needs, awareness, and requests to vary (Ahmed & Wallace, 2004). Novice designers may ask relevant questions when aware of their knowledge needs, supporting design knowledge coordination. 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 design knowledge. Conversely, expert designers tend to employ a well-defined design strategy when problem-solving, without being explicitly aware of the utilized strategic knowledge (Ahmed et al., 2003). For example, in general the expert designer will reason forward through the problem; however, in more difficult problems, experts can alternate reasoning between forward and backward (Badke-Schaub, 2004; Ball, Evans, Dennis, & Ormerod, 1997). Comparatively, novice designers tend to use a deductive approach and only reason backwards from an assumed design solution.

Another difference in expert and novice decision making in engineering design is their awareness of reasons behind a particular design solution (Ahmed et al., 2003). Expert designers generally are aware of a larger problem space and are able to refer to past projects to find similar designs. They are also able to consider the trade-offs between multiple design solutions (Ahmed et al., 2003; Waldron & Waldron 1996). Further, expert designers identify and consider the relevancy of a topic in solving complex design problems.

1.1.4 Aerospace Engineering Design Education

An engineering curriculum is intended to help new engineers develop the skills and knowledge to examine and respond to situations using learned fundamental principles (Grinter, 1994). Prior to graduation, aerospace engineering students typically first complete coursework related to core engineering sciences. This coursework can be divided into six main areas:

1. Mechanics of solids
2. Fluid mechanics
3. Thermodynamics
4. Transfer and rate mechanisms
5. Electrical theory
6. Nature and properties of materials

Within aerospace engineering, these areas generally relate to understanding specific components of an aircraft's design. For example, mechanics of solids informs students' understanding of aircraft dynamics and stability; nature and properties of materials informs students' understanding of structural and material capabilities. Thus, an overarching learning objective of the technical courses is to teach students how to analyze specific components of aircraft design.

The main contributor to engineering students' understanding of design is a capstone course completed toward the end of the program of study. This capstone course is generally designed to satisfy the Accreditation Board for Engineering and Technology's (ABET) student outcomes to have: (c) an ability to design a system to meet desired needs within realistic constraints; (d) an ability to function on multidisciplinary teams; (f) an understanding of professional and ethical responsibility; (g) an ability to communicate effectively; and, (h) an understanding of the impact of engineering solutions in a global, economic, environment, and societal context (ABET, 2016; Dym, Agogino, Eris, Frey, & Leifer, 2005). Thus, the capstone design process is inferred to involve coordination as well as also coordinating other sociotechnical concerns. Assignments are often 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 (Woods, Felder, Rugarcia, & Stice, 2000) and communication

(Paretti, 2008; Paretti & Burgonyne, 2005; Ford & Riley, 2003) skills throughout capstone design. Additionally, the capstone course leverages students' within-discipline approach to systems analysis by integrating disciplinary considerations into the complete design of an aircraft (Dym et al., 2005). Thus, students must not only have a firm grasp of the wide array of disciplinary-based knowledge, but they must also be able to interpret how these disciplines contribute to and integrate within the design of an aerospace system, to the extent that they can coordinate their design knowledge within their individual design activities as well as their design team activities.

In engineering education, Atman et al has conducted research to examine the design processes utilized by student engineers (Adams & Atman, 2000; Atman et al., 2005; Atman et al., 2007; Atman et al., 2008). This research has shown that the design process they apply evolves throughout student engineers' educational experience (Atman et al., 2005; Atman et al., 2007). For example, senior engineering students generally have more breadth in how they approach design problems compared to first year engineering students (Atman et al., 2008). But, when compared to expert designers, even senior engineering students spend less time on problem scoping and also gather less information to solve the design problem (Atman et al., 2007).

The integration of broad sociotechnical factors into the engineering design process was examined by Lewis et al. (2014). This research described the development and implementation of a framework to enhance students' understanding of a product's global, societal, economic, and environmental context and impact. Indeed, while this research found that students are aware of sociotechnical issues, engineering students still struggle with applying design solutions that consider these issues throughout the entire design process.

The capstone course also provides a venue for instructors to evaluate and critique students' integration of knowledge, as well as other skills such as communication, design, and collaboration skills. Essential to this project is the explicit visibility of students' decision-making process overall (Paretti, 2008). Students' decisions are typically evaluated through regular (formal and informal) progress updates with the course instructors. Similar to expectations in a professional environment, students are expected to communicate their design decisions in an organized manner and link their reasoning to the design knowledge and trade-offs that influenced them. Thus, it's important that have a method to assess students' progress through the design process, including critical decisions and the reasoning behind each decision, so that they can evaluate student performance and provide relevant feedback on performance.

However, it's often difficult for instructors to discern students' design knowledge coordination while evaluating team and individual performance in a complex, integrated design project (Dutson et al, 1997). Thus, while students are expected to present progress on design projects to instructors at regular intervals, often it's not evident whether the progress is sufficient for the design task at hand and what feedback to provide. Educational research has previously examined the impact of communication and collaboration skills on student learning outcomes (Paretti, 2008; Norback, Leeds, & Forehand, 2009; Ford & Riley, 2003). However, few studies have examined the impact of exchanging knowledge within the design process as a method of coordinating design decisions. Thus, there is a need for the creation of a framework that helps scaffold novice engineers' approach to coordinating design knowledge.

1.2 Research Approach

The intent of this research is to develop a framework describing design knowledge coordination to support student skill development for coordinating knowledge underlying design decisions within a multidisciplinary, integrated design process. By characterizing 'design knowledge coordination' skills and strategies, they will be more explicit and comprehensible both to the students and to the instructors. Additionally, the design knowledge coordination framework provides a scaffolded approach to developing and evaluating integrated design skills.

This research examines three research questions:

1. What design knowledge coordination does aerospace engineering require?
2. How do aerospace engineers coordinate and integrate knowledge about a design?
3. What educational interventions can better support novice aerospace engineers' design knowledge coordination?

To answer the first research question, a framework of design knowledge coordination was created using analysis of engineering design literature. This framework was then analyzed to identify observable indicators of coordination using a systematic literature review of processes that encompass coordination. The second component of research question one, applying the framework specifically to aerospace engineering design was addressed by reviewing a key set of authoritative texts commonly referenced in traditional aerospace engineering capstone courses. Indicators of coordination were identified at all stages in the aerospace engineering design process.

The second research question was answered using a multiple case study method. An analysis of observations of student teams in a capstone design course captured indicators of coordination identified in the framework created for research question one, as well as emerging themes and strategies for coordination. Additionally, each student team was characterized using the framework and compared to the authoritative text's characterization of design knowledge coordination within the aerospace engineering design process. These findings were contrasted with students' perspectives of their engineering design, observable through a focus group discussion. Research question three connected these findings to literature on engineering education strategies to identify learning goals and design activities that could better support students' design knowledge coordination.

A full breakdown of the research questions and aims is detailed in Table 1.This research contributes to both the aerospace engineering design community and the aerospace engineering education community by defining and characterizing design knowledge coordination in aerospace engineering design. The framework provided with this thesis specifically defines key indicators of design knowledge coordination, suitable for educational interventions to enhance novice designers' coordinated decision-making skills. Further, results of this research will address the noted gap between aerospace engineering education and the needs of industry for engineering graduates to use effective approaches to engineering design, integration, and synthesis.

Table 1. Outline of research questions, aims, tools, and outcomes

Research Questions	Research Objectives	Research Method	Relevant Chapter
Research Question #1: What design knowledge coordination does aerospace engineering require?	*Research Aim #1.1:* Define design knowledge coordination in context of engineering design	Strategic analysis of literature	*Chapter 2:* Reviewing Design Knowledge Coordination in Engineering Design and Engineering Education
	Research Aim #1.2: Characterize design knowledge coordination constructs in the conceptual design process	Application of design knowledge coordination framework to authoritative texts of the AE design process	*Chapter 3:* Design Knowledge Coordination in Authoritative Texts on Conceptual Aerospace Engineering Design
Research Question #2: How do novice aerospace engineers coordinate and integrate knowledge about a design?	*Research Aim #2:* Describe and evaluate novice aerospace engineering approaches to design knowledge coordination	Case studies of student design teams	*Chapter 4:* Design Knowledge Coordination by Novice Aerospace Engineering Designers *Chapter 5:* Student-Centered Approach to Integrating Design Knowledge Coordination in Aerospace Engineering Education
Research Question #3: What educational interventions can better support novice aerospace engineers' design knowledge coordination?	*Research Aim #3:* Characterize educational interventions to scaffold students' approach to design knowledge coordination	Evaluation of student focus groups	*Chapter 6:* Characteristics of Educational Interventions That Support Design Knowledge Coordination

CHAPTER 2 - REVIEWING DESIGN KNOWLEDGE COORDINATION IN ENGINEERING DESIGN AND ENGINEERING EDUCATION

Research within engineering design has identified strategies for managing and integrating knowledge about a design (Department of Defense [DOD], 1998; Shekar, Venkataram, & Satish, 2011; NASA 2007). These approaches incorporate systematic, model-based processes that explicitly connect interdependent functions and components within the design of a complex system. Yet, the literature does not address how these methods could be applied within engineering education to scaffold novice engineering designers' integration of knowledge about a design. Thus, this chapter develops a framework that connects engineering design research to research in other fields related to design knowledge coordination.

Specifically, this chapter presents a systematic literature review. This review was conducted to identify connections across various related research studies to develop a framework of design knowledge coordination. This approach applies a scholarship of integration by synthesizing information (i.e. literature findings) across disciplines and placing major themes into the larger context of the design process (Boyer 1990). In performing this critical analysis of prior research, larger patterns were identified and interpreted. Additionally, this form of scholarship "is better equipped to build interdisciplinary partnerships, develop frameworks that transcend disciplinary paradigms, and respond to complex, multifocal, contemporary issues at the individual and societal level" (Crismond & Adams, 2012 p. 742).

Such systematic literature reviews have been employed by other researchers, particularly within engineering education research, as a method to draw together various strands of research and connect research findings to practical strategies for enhancing educational environments (Borrego, Foster, & Froyd, 2015). For example, Turns et al (2014) incorporated a systematic literature review, i.e. a scholarship of integration, as a way to introduce a framework for thinking about reflection and to discuss example instances of the framework within educational settings. Crismond & Adams (2012) used this approach to articulate the Informed Design Teaching and Learning Matrix. In using scholarship of integration, the major theme in previous studies is the translation of research findings into use-inspired frameworks (Crismond & Adams, 2012). Similarly, this thesis examines research findings across engineering design and the social sciences, and creates a framework that will be used in subsequent chapters to characterize strategies of coordination within aerospace engineering design education and practice.

The systematic literature review for this thesis was conducted using three steps, depicted in Figure 2 and detailed in the following three sections. First, the context of research was framed using an analysis of engineering design literature and case studies depicting application of complex decision-making within this context as described in the next section. Then, a strategic literature search examined research pertaining to complex systems decision-making and engineering design reasoning for its insights into design knowledge coordination. Finally, strategies for design knowledge coordination were defined, particularly emphasizing those that are observable to others outside the design team, notably to instructors of capstone design. Based on these three steps, a framework is provided and discussed for characterizing the design knowledge coordination being applied in an engineering design process.

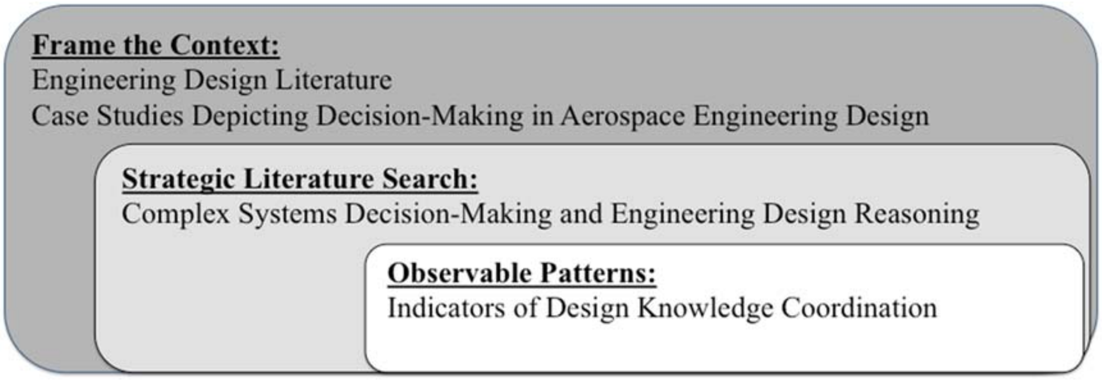


Figure 2. Overview of the systematic literature review process

2.1 Frame the Context: Engineering Design

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 (Nicolai & Carichner, 2010; Pahl et al., 2007). Engineering design can also be defined as a structured approach to developing, validating, and implementing complex systems (Pahl et al., 2007). As a general field, design symbolizes the "conception and realisation of new things" (Cross, 2006, p. 2). However, engineering design differs from other design areas (e.g. graphic, industrial, and software design) in the complexity involved in clarifying and defining new engineering products with multiple points of interaction characterized through overlapping, interdependent, and often conflicting interdisciplinary design parameters, preferences, and constraints (Cross, 2006; Pahl et al., 2007; DAU, 2001).

Through engineering design, a product is created for a specific set of stakeholders. The stakeholders can be direct users/operators of the system or they can be indirect groups that impose requirements and/or constraints on the system. For example, in designing a car, the driver would be considered a direct user of the system. Passengers would also be a type of stakeholder, although they do not directly interact with the vehicle in the same manner and have a different set of requirements. A regulator is also a stakeholder, placing strict requirements and constraints on design, such as emissions and safety requirements.

Design parameters aren’t only dictated by the stakeholders. The design is also influenced by the operating environment of the vehicle. Collectively, the stakeholders’ considerations and the operating environment create a set of information that is used to make design decisions. These initial decisions flow into the next phase of design to make even more detailed decisions about the design. Occasionally, earlier decisions may be reevaluated as the new information about the design becomes known.

As more decisions are made throughout the design, a converging and diverging decision process emerges (Cropley, 2006). On the converging side, a set of multiple pieces of information are used to close the design space and identify specific information. As information becomes known, designers can continue to the next design task and the next set of decisions. This movement to a subsequent design task may then open up more options about the design, or reveal a diverging set of parameters. For example, in the design of an aircraft, engineers first set a general layout of the vehicle (wing placement, type of tail, etc). The designers typically converge on one aircraft configuration. After the configuration is set, the engineers are then able to re-open the design space for other aspects of the design. For example, they can examine the lift characteristics of the wing and decide on the inclusion of high-lift devices. Once that set of decisions is converged, another divergence occurs as the technical decisions must be made even more detailed (e.g. specific geometry of the wing and high-lift devices).

The "knowledge underlying design decisions" references the information that designers use to justify their decisions and decision-reasoning. This knowledge is fed back into the process and used to generate more decisions about the design. As a simplified example of knowledge underlying design decisions, 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 in 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 a designer does not effectively characterize the relevant environmental assumptions, he or she may not incorporate that information in their decision-making process. Further, once the design team includes more than one designer, this design knowledge also needs to be shared within the team. 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.

In engineering, the designed systems can be very complex and involve multiple types of component design that may be split into separate designers or design teams. While the overall design goal (e.g. build a car) has not changed, the primary focus of the engineers on each separate component design may adapt to their specific tasks, as will the type information they use to make design. However, every component still needs to be integrated onto the same overall product.

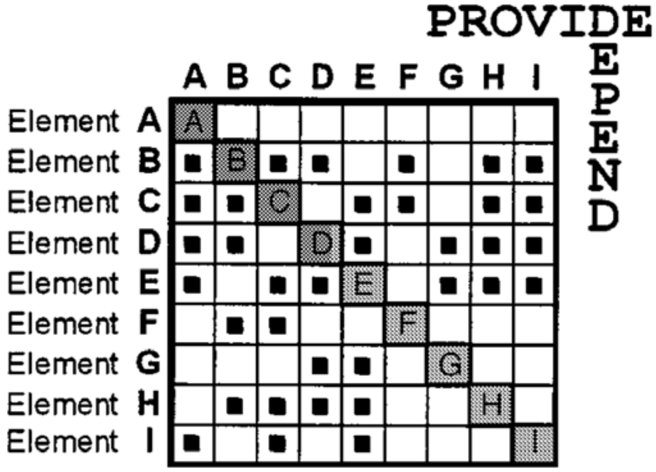
Aerospace engineering design, specifically, can be characterized by many different representations of the engineering design process (Nicolai & Carichner, 2010; Raymer, 2009; Roskam, 1990). One methodology commonly used by aerospace engineering design firms is the system engineering design approach. 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 (DAU, 2001; Moser, 2014; INCOSE, 2004; NASA, 2007). An essential characteristic of the systems engineering process is the iterative performance of three activities: Requirements Analysis, Functional Analysis, and Design Synthesis (DAU, 2001; van Lamsweerde & Letier, 2000; NASA, 2007).

Systems engineering manages complexity by decomposing the system into discipline-oriented design teams and by constantly iterating through the design process (within and across teams) to incorporate new information. Aerospace engineering design, in particular, commonly uses an iterative approach to support multidisciplinary design integration (Nicolai & Carichner, 2010). The initial, conceptual design phase frequently calls for the designer to make assumptions about specific attributes using historical regressions (Roskam, 1990). 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 (Raymer, 2009). Thus, communication of knowledge in aerospace engineering design needs to occur through time as the design evolves within and across design teams.

As the engineering designers move through the aerospace engineering design process, they continuously iterate and update knowledge about the design. However, the interdependence of components creates a challenge to maintain consistent metrics throughout the design process. For example, an initial calculation of aircraft weight leads to a calculation of fuel volume, maximum takeoff weight, and range capabilities. But, the initial weight calculation incorporates an estimate of material weight, which is updated later in the design process as more specific decisions are made about the material composition. As the design converges on specific material breakdowns for each of the aircraft components, typically decided in the preliminary design phase, the designers must iteratively update their empty weight calculation. Updating the empty weight calculation impacts the maximum takeoff weight, fuel volume, and range capability. These values flow into the performance capabilities of the aircraft. This simple example is representative of larger issues that engineers may encounter as they update information about the aircraft within the preliminary and detailed design phases. Thus, engineers use models of iteration to manage the interdependencies of design components and decisions (Steward, 1981; Wynn, Eckert, & Clarkson, 2007; Eppinger et al, 1994; Shekar et al., 2011; Goel & Pirolli, 1992; Guenov & Barker, 2005).

The design structure matrix is a model of decision-making in design that allows engineers to "model, visualize, and analyze dependencies among the functional group of any system and derive suggestions for the improvement or synthesis of a system." (Shekar et al., 2011, p283). The design structure matrix reaches across disciplines and explicates the interdependencies within the task environment (Goel & Pirolli, 1992). This tool also aids in developing an engineering plan to manage information flow within the design work (Steward, 1981).

Figure 3 is an example design structure matrix, as depicted in Browning (2001). This example image shows how information from one element provides information to other elements. Element I is dependent on information from elements B, C, D, and E, and element I provides information to elements A, C, and E. This figure also shows how iteration is embedded within the design process. Element I is dependent on elements C and E, yet it also provides information to those elements. Thus, as information is updated within one element of the design, the other elements must also be updated.



	A	B	C	D	E	F	G	H	I
Element A	A								
Element B	■	B	■	■		■		■	■
Element C	■	■	C		■	■		■	■
Element D	■	■		D	■		■	■	■
Element E	■		■	■	E		■	■	■
Element F		■	■			F			
Element G				■	■		G		
Element H		■	■	■	■			H	
Element I	■		■		■				I

Figure 3. Example design structure matrix (Browning, 2001, p. 292)

The design structure matrix is generally discussed in the context of Concurrent Engineering strategies. Concurrent Engineering leverages knowledge of task interdependencies and coupling to streamline information exchange and task completion (Prasad, Morenc & Rangan, 1993). Within Concurrent Engineering, inconsistencies in knowledge about the design are resolved using strategies for conflict resolution and negotiation. Through these different strategies, concurrent design teams work collaboratively to have a rapid and flexible response to design changes (Chattopadhyay, Hihn & Warfield, 2011; Hihn et al. 2011). A flexible response to design changes is particularly important in highly independent design environments, such as within aerospace engineering design. Multidisciplinary optimization, the design structure matrix, and the Task-Based Model are all approaches to engineering design that leverage the multidisciplinary nature by coordinating the knowledge flowing through the design process (Browning, 2001; Chattopadhyay et al., 2011; Chen, 2005; Clarkson & Hamilton, 2000).

2.1.1 Decision-Making in Engineering Design

Important aspects of decision-making by aerospace engineering designers can be represented using three concepts: Goal Alignment, Shared Knowledge, and Information Sharing. These concepts are highlighted by research in both engineering design and the social sciences. Additionally, these elements can be examined within the context of engineering design.

2.1.1.1 Goal Alignment

Aerospace engineering tasks are directed by design goals that should be understood by all stakeholders and designers and 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 (Nicolai & Carichner, 2010). Within design teams, more detailed goals and design requirements should remain consistent with the high-level goals. However, with disciplinary divisions between design teams, detailed design preferences and specific discipline-based goals may not necessarily align with each other, and their specific relationships with the overall design goal may not be straight-forward and un-confounded by the output of other design teams (Marks, Mathieu & Zaccaro, 2001; Mathieu, Marks & Zaccaro, 2001; Mesmer-Magnus & DeChurch, 2009).

Indeed, conflicting design issues identified in later stages of design have resulted from disparate views of higher-level design goals between design teams. The ramifications of disparate higher-level design goals are apparent in studying the design of the F-111 Aardvark and the F-35 Lightning (Richey, 2005; Gertler, 2014). 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 (Richey, 2005). 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 (Richey, 2005). Similarly, the F-35 uses one basic airframe on three aircraft models to meet the disparate needs each military branch (Gertler, 2014). This approach was expected to reduce the vehicle's Life Cycle Cost by pooling acquisition costs (Lorell et al., 2013). However, the vastly contrasting service-specific needs led to design inefficiencies, budget overruns, and program delays (Lorell et al., 2013).

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 (Griffin, Kinnu & Colombi, 2005). 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 et al., 2005, p. 15)*

2.1.1.2 Shared Knowledge

A team's mutual knowledge is described as "knowledge that the communicating parties share in common and know they share" (Cramton, 2001, p. 346). Clark and his colleagues have frequently referred to mutual knowledge as the "common ground" among collaborators (Clark & Schaefer, 1989; Cramton, 2001; Keysar, Barr, Balin & Paek, 1998). Notably, mutual knowledge enables team members to frame information sharing with an accurate awareness of the knowledge held by other team members (Clark & Schaefer, 1981; Keysar et al., 1998). In a design, the mutual knowledge also represents the knowledge about a design that has been made explicit throughout the design process, including through documentation. This information must also be kept consistent between the design tasks.

Similar to mutual knowledge, a shared mental model (SMM) is a type of collective knowledge structure used to interpret a task and to coordinate designer actions (DeChurch & Mesmer-Magnus, 2010; Cannon-Bowers & Salas, 2001). A team SMM represents the mutual knowledge among the team members of how they should interact with one another (Mathieu, Heffner, Goodwin, Salas & Cannon-Bowers, 2000). As discussed in Marks et al. (2001), teams use the team goal to survey and respond to their environment. SMM's provide a frame or mechanism within which team coordination and adaptation can be examined and explained (Mathieu et al., 2000). Further, the team's external performance environment shapes and is shaped by team member cognition and action (Marks et al., 2001).

As such, engineering designers must recognize the considerations and constraints of disciplines outside their own expertise (Baird, Circus, Moore & Jagodzinski, 2000). This is particularly important when technical changes in 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 particularly 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 (Ahmed et al., 2003). 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 (Fussel & Krauss, 1992). Additionally, SMM's are supported through team communication (e.g. leader briefings) and team interaction training (Marks et al., 2001). Of note, in situations with novel circumstances team mental models are linked to team communication processes and overall team performance (Marks et al., 2001; Mathieu, Maynard, Rapp & Gilson, 2008).

2.1.1.3 Information Sharing

As part of engineering design, information sharing is a critical mechanism for enabling constructive team processes (Bunderson & Sutcliff, 2002; Jehn & Shah, 1997; Mesmer-Magnus & DeChurch, 2009). 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 (Stasser & Titus, 1985; Miranda & Saunders, 2003; Mesmer-Magnus & DeChurch, 2009). 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 needs to be distributed to more individuals. While effectively distributed knowledge increases creativity and productivity, it is also can hinder overall team effectiveness (van Ginkel & van Knippenberg, 2009). Team members may fail to exchange relevant information (Stasser & Titus, 1985; van Ginkel & van Knippenberg, 2009) or to integrate pertinent information into reasoning for design decisions (van Ginkel & van Knippenberg, 2009). Team members' approaches to sharing information thus become an important feature of effective team coordination (Bunderson & Sutcliff, 2002; Jehn & Shah, 1997; Mesmer-Magnus & DeChurch, 2009). 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 (Stasser & Titus, 1985).

Beyond formal meetings and tag-ups, continuous, informal communications across immediate working groups increase design team effectiveness and synchronous reflection on goal accomplishment (Daly, Augustine, Davis, Covert & Gray, 2001; Baird et al., 2000). Unprompted design discussions can stimulate peer review opportunities and contemporaneous sharing of design tasks (Baird et al., 2000). Moreover, these informal gatherings can promote continuous awareness of and reflection on design issues, increasing response time to addressing and solving these challenges (Baird et al., 2000).

Previous research has investigated the exchange of information along two dimensions, openness and uniqueness (Mesmer-Magnus & DeChurch, 2009). The openness of information sharing broadly describes team communication related to goals, progress, and coordination (Mesmer-Magnus & DeChurch, 2009; Jehn & Shah, 1997; Henry, 1985). The uniqueness of information sharing is related to the number of members with access to a piece of information (Mesmer-Magnus & DuChurch, 2009; Hinz, Tindale & Vollrath, 1997). Related to the engineering design practices, designers attempt to uncover preferences and information 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 (Lightle, Kagle & Arkes, 2008).

For example, open communication and coordination 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 (Griffin et al., 2005).

While research has investigated the openness and uniqueness of information sharing, limited work has been done to jointly consider these two. Fleming and Coso (2014) suggests future research should include expanded definitions of openness and uniqueness to also incorporate relevancy. To operationalize the information relevancy, consideration must be made for how the information is integrated or abstracted into final design decisions (Fleming & Coso, 2014). Aurisicchio, Bracewell and Wallace (2010) similarly found that more research is needed on the information needs of engineering designers (Aurisicchio et al., 2010; Aurisicchio, Bracewell & Wallace 2012).

2.1.2 Constructs in Engineering Design

This analysis of the engineering design context identified the following four key constructs underlying design knowledge (Table 2).

Table 2. Constructs of engineering design decision-making

Construct of Decision-Making in Design	Description	Literature Area
Goals	Engineering tasks should directed by design goals that are understood by all stakeholders and designers and are used integrate designers' efforts.	Goal Alignment
Tasks	Tasks dictate the direction and future content of overall work within the complex engineering design process	Engineering Design Context
Metrics	A representation of information about the design that is available to or needed by the designer.	Shared Knowledge, Information Sharing
Decisions	Outcomes of a task where a design has to specify new or update previously decided knowledge about a design	Outcome of Process

To expand on these constructs further, a functional interrelationship can be used as an example of organizing and analyzing decisions within the engineering design process (Pahl et al., 2007). This model of the engineering design process breaks a system's overall functions into subfunctions. Decomposing helps engineers analyze the relationship of functions and subfunctions. Additionally, the embedded model incorporates aspects of the system's functions requiring a logical sequence and/or required arrangement. Thus, this model structure was an appropriate method to show logical sequencing and order in completing tasks that contribute to the overall design. Figure 4 shows the example breakdown as depicted in Pahl et al. (2007).

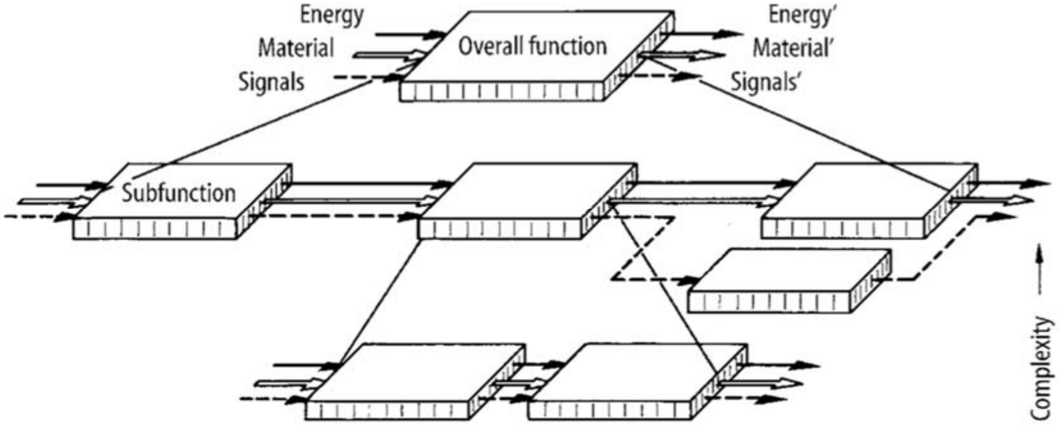


Figure 4. Functional interrelationship decomposition of a system (Pahl et al., 2007, p. 32)

The engineering design process can be similarly decomposed into high-level tasks and subtasks. Within each task and subtask, decisions are made about the design that influence the boundaries and constraints of the design process. Additionally, information is shared between the tasks, as to keep the information about the design consistent throughout the design process. Figure 5 has an abbreviated example of knowledge and tasks throughout the engineering design process. The high-level tasks are the directed assignments required to make decisions about the design. They provide a high-level overview and closely align with the main goals driving the design. Subtasks are embedded within the high-level tasks and direct the work and outcomes of the high-level tasks. Within each subtask, the assignments are completed using metrics of analysis. These metrics contain information about the design and are fed between different tasks. For example, one task might require information about the system's size to calculate the system's weight. In the next task, both size and weight might be used to find another metric, or parameter, of the design. Outcomes of each task and subtask are generally decisions about the design.

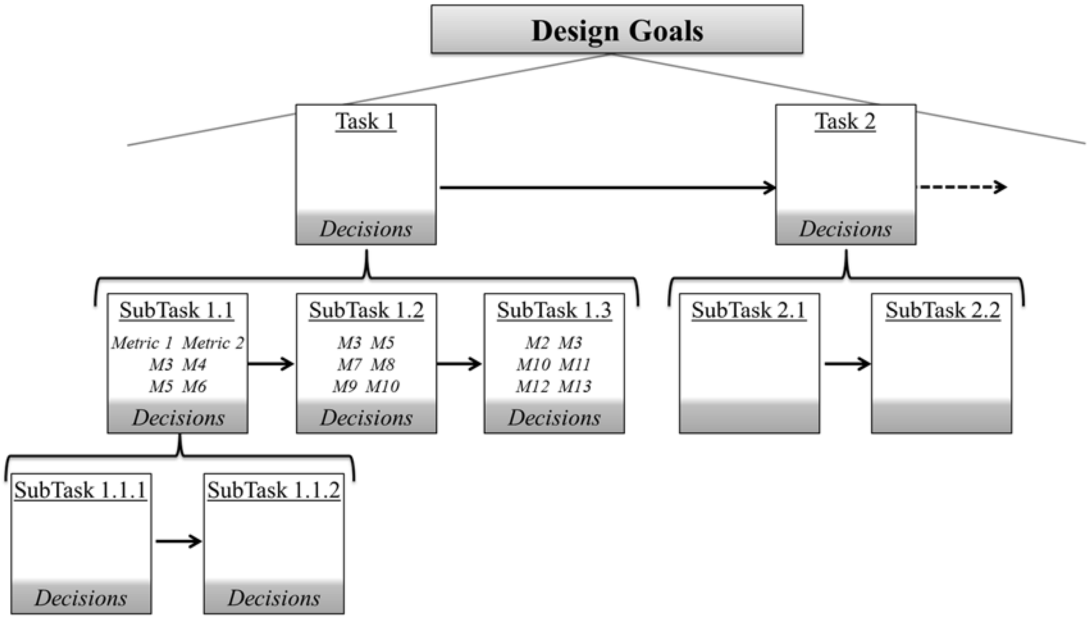


Figure 5. Example of structuring knowledge about a design

Overall, the structured model of the knowledge and tasks in the engineering design process describes the flow of information about a design between tasks and subtasks where the design knowledge is captured by metrics and decisions. This method provides a basis for evaluating the effectiveness of engineers' reasoning for making a specific decision. For example, this model identifies if an engineering team incorporates a range of metrics to justify a decision. It also exposes the task decomposition used by a team and whether that decomposition is sufficient to appropriately complete the design process.

2.2 Strategic Literature Search: Coordination Practices and Theories

The discussion of the engineering design process brought forward many issues with design knowledge that relate to how it might be coordinated. Particularly, the areas of goal alignment, shared knowledge, and information sharing highlight the need to incorporate processes within the engineering design process that keep information and tasks consistent through the process, even as iterations update information about the design. One method for aligning interdependent design activities is to coordinate knowledge about a design.

Gerson (2008) defines coordination as a mechanism that "(1) connects two things together and makes them part of a larger system of dependencies, (2) it does so in specific ways, and (3) it also holds them apart and keeps them distinct." A review of research by Coates et al (2000) found that coordination is a concept that can be used to improve the engineering design process. However, research has not yet established a cohesive and general perspective of coordination for engineering design. To expand on this definition of coordination, this section reviews literature on approaches to design and decision-making that decomposes systems into distinct components while also enabling interdependencies between these components.

2.2.1 Literature on Coordinated Processes

An examination of practices pertaining to design knowledge coordination found four areas of interest: Articulation Work, Coordination Theory, Distributed Cognition, and Knowledge Management Processes. Each of these areas brings both unique and shared perspectives to the discussion of coordination in engineering design. Additionally, these areas describe a process or mechanism that explains how a collective system organizes, makes, and shares decisions.

Articulation Work is an analytic framework that connects the study of task completion to interaction processes. This framework highlights "The specifics of putting together tasks, task sequences, task clusters—even aligning larger units such as lines of work and subprojects—in the service of work flow" (Strauss, 1988, p.164). Similarly, interactional alignment is the process by which tasks and actions are aligned. A key aspect of Articulation Work is the decomposition of work into tasks and subtasks to help create the direction and future content of the overall work (Strauss, 1988; Corbin & Strauss, 1993; Gerson & Star, 1986).

Coordination Theory is the management of dependencies between mechanisms and provides another perspective on task alignment (Malone & Crowston, 1990; Malone &

Crowston, 1994; Gerson, 2008). Within coordination theory, a body of principles outline how activities can be coordinated to work harmoniously together (Malone & Crowston, 1990). These activities can be coordinated by people or by non-human processes (e.g. computer science).

Coordination theory is similar to articulation work in that coordination processes are subdivided by the activities and their interdependencies (Strauss, 1985). However, coordination theory refers specifically to the management of interdependencies through task/subtask relationships and simultaneity constraints (Malone & Crowston, 1994). Tasks/subtask dependencies are managed by identifying and decomposing a common goal for all the subtasks. As a task is decomposed, each subtask must achieve a piece of the larger goal (i.e. subgoal).

Distributed Cognition seeks to understand the organization of cognitive systems by studying the interactions of entities (e.g. people, processes, resources) across different structures (Hollan, Hutchins & Kirsh, 2000; Perry, 1998). This evaluation of interactions across structures considers the differences between internal and external representations of information (Hollan et al., 2000; Hutchins, 2001; Hutchins, 1995). In aerospace engineering design, this form of distributed cognition arises when a designer uses two different artifacts to approach a design task, such as solving for the aircraft weight using an automated computer program and using a Microsoft Excel model.

This type of distribution can be both a help and a hindrance to coordinated decision-making. As a helpful contributor to the engineering design process, distributed cognition often involves the creation and use of artifacts to scaffold and visualize cognition (Liu, Nersessian & Stasko, 2007). However, if the multiple representations of the cognitive space are not consistent, then information may be lost in the distributed process. To maintain a consistent distributed cognitive state, aspects of the approach to information process should be consistently maintained and aligned (Perry, 1998). Specifically, designers should note the goals and resources behind decisions and the inputs and outputs to their multiple representations.

Knowledge Management encompasses organizational, management, and technologically oriented approaches that take advantage of an organization's intellectual assets (McMahon, Low & Culley, 2004). Within complex systems design, designers rely on knowledge embedded in the environment to help coordinate internal cognitive resources with external tools and resources (Kirsh, 2006). A codified strategy of knowledge management allows for the storage of knowledge into databases so that it can be reused when needed (Hansen, Nohria & Tierney, 1999). Technology can be used to codify knowledge as well as to identify relationships among data. Additionally, relationships between the parcels of knowledge are easier to identify when they relate to system level metrics – i.e. high-level interpretations of system design parameters (Kirsh, 2006). Coordination and alignment of knowledge about a design at more detailed-levels requires designers to understand the elements that are driving the interdependencies.

2.2.2 Coordination and the Constructs in Engineering Design

This analysis of coordination practices and theories highlighted four research areas of interest:

1. Coordination Theory
2. Articulation Work
3. Knowledge Management
4. Distributed Cognition

Building on the preceding review of each, Table 3 now relates each to the four constructs summarized in Table 2.

Table 3. Insights from strategic literature search of coordination relative to constructs of engineering design

Literature	Construct of Engineering Design	Coordination Mechanism
Coordination Theory	Goals	Identify trade-offs between discipline-oriented design goals
Articulation Work, Coordination Theory	Tasks	Recognize the links between tasks and subtasks
Knowledge Management	Tasks	Use cross-disciplinary metrics to support iteration across the design and consistently update information about the design
Distributed cognition	Metrics	Maintain consistent values for metrics across the different disciplines
Distributed cognition	Decisions	Incorporate a variety of metrics from other disciplines to justify decisions
Articulation Work	Decisions	Describes the overall impact of a particular decision

Within coordination theory, one of the methods for aligning tasks is to subdivide the overall goal of the project into subgoals that align with each task and subtask (Malone & Crowston, 1990; Malone & Crowston, 1994)). This goal division is integrated into engineering design by dividing the overall project into discipline-oriented goals. Each subgoal aligns with the principles of each discipline. However, the goal must also align with the overall purpose of the design (Mathieu, Marks & Zaccaro, 2001). Thus, conflicts and trade-offs between the goals must be identified at the start of the project.

As described by both articulation work and coordination theory, the division of work is managed by subdividing activities into tasks and subtasks (Malone & Crowston, 1994; Strauss, 1988). This division also acknowledges the connections between tasks and subtasks toward completing the overall project goals. In managing the connections between the different tasks, the overlapping knowledge can be codified, in this instance by discipline, and reused later in the design process (Hansen et al., 1999). However, the metrics that are used within each subtask must be consistently maintained between tasks (Perry, 1998).

Finally, when analyzing decisions, the distributed metrics across each task can be used to justify overall design decisions (Liu et al. 2007). This distribution of metrics across tasks (and disciplines) supports the incorporation of multiple subgoals into decision-making approaches. Further, the decisions should be clearly stated with an understanding of that decision's impact on the overall design. The articulation of tasks, drivers, and decisions is one method to aligning the design process (Strauss, 1988).

2.3 Identifying Observable Indicators of Design Knowledge Coordination

Using the constructs of decision-making in engineering design presented earlier in Table 2, and the dimensions of design knowledge coordination presented in Table 3, this section extends beyond the conceptual discussion thus far to identify specific observable indicators of design knowledge coordination in engineering design for each of the four constructs.

2.3.1 Goal Definition

As discussed in the earlier section, engineering tasks are directed by design goals that are understood by all stakeholders and designers and are used to 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. Once the need has been identified, the goals and requirements become more specific to the technical and performance-based aspects of the system design. Within the design of a system, goals must remain consistent throughout the complex decision-making process. Inconsistent goals can lead to design flaws that may not be captured until later phases of design.

If goal definition is done well in any design, then a general design goal will be observable from the initial requirements definition. Further, observed from a disciplinary-oriented approach, if goal definition is done well, then the observed design goals will be decomposed into more specific goals for each discipline. Finally, if design knowledge coordination is effective, then the designer(s) will identify trade-offs between discipline-oriented design goals within their discussions.

2.3.2 Task Definition

Task definitions are made to plan the direction and future content of overall work within the complex engineering design process (Strauss 1988; Gerson & Star 1986; Corbin & Strauss 1993). Each task is associated with a specific goal or intended outcome that directs the work being performed. A task's goal is dependent on the information that is available or desired at a particular point in the design process. For example, at the start of the design process, there is little information available about the product. Thus, the engineers' first task is to define the product requirements based on information provided by stakeholders and/or environmental constraints. The system's form will likely change as the design is refined, but an initial decision on system configuration guides the overall components and layout, thus directing the next several tasks in developing individual technical systems. As the engineering designers move forward in the design process, more knowledge about the design is contributed to each task through the design activities. This knowledge is then used to make even more decisions about the design.

Tasks are completed in parallel as well as in series, making the simultaneous trade of information important to enhancing cross-team member decision-making. Higher-level tasks guide the goals of different stages in the design process. Within group decision-making, the group collectively decides how to segment the tasks based on individual resources, which may include time and skills.

The fundamental complexities involved in engineering design are managed by decomposing the larger design project into more manageable tasks and subtasks. These tasks can be centered on evaluating a specific parameter of performance in the design or focused on developing a specific technical system. Within each over-arching task, subtasks guide detailed work toward the larger goal. For example, in defining the initial system requirements and configuration, one subtask is to decompose the customer's request for project proposals (e.g. a Request for Proposal). Another subtask is to identify the requirements placed on the system by different stakeholders. Yet, another subtask is to combine the formal project requirements with the requirements generated by the stakeholders to outline a list of Figures of Merit that evaluate the preferred form of the design. The first two subtasks (decomposing the formal requirements and identifying the stakeholder requirements) may be done in parallel, but the third subtask (classify the Figures of Merit) can only be completed using information generated from the first two subtasks.

If task definition and decomposition is done well in any design, the tasks and subtasks will be identifiable and they will have an order and a hierarchy. Further, observed from a disciplinary-oriented perspective, if task definition is done well then the order and hierarchy of the decomposed tasks will align with the engineering disciplines. Finally, if design knowledge coordination is effective, then the links between the tasks and subtasks will be observable. Additionally, iterations across the design will take place through the tasks and subtasks and will update information about the design.

2.3.3 Metric Determination and Use

Metrics are defined in this thesis as "a representation of information about the design that is available to or needed by the designer." This definition of metrics is broader than that applied in some engineering texts, which consider metrics as a direct representation of a specific aspect about the design (e.g. the wing area) or the design process (Kreimeyer & Lindemann, 2011; Kasser & Schermerhorn, 1994; Shepperd, 1990). Instead, with this broader definition metrics represent any knowledge that is needed to conceive, analyze, or evaluate the design, including intermediary values that do not directly define a specific aspect about the design (e.g. the coefficient of lift). An increasing number of metrics are identified as more information is revealed about the design. To move between tasks, metrics have to be aligned, that is they should be updated to be the same value in subsequent tasks. Designers should use the same metrics and values for those metrics in each phase of the process. Metrics feed in and out of tasks. Metrics can be decisions or they can be used to justify a decision. Some metrics are set at a single value, while others are varied to find an optimal solution in an uncertain environment.

For example, in designing an aircraft, one phase of design would require knowing an approximate weight of the aircraft, where the weight is a metric. Other metrics would include the number of passengers, the required power of the engine, and the size of the wheels. Mathematical equations would determine several of these metrics, such as the required power of the engine. These equations may also require metrics detailing information about the design that is not yet available. The usefulness of metrics is typically guided by a technical interpretation of the engineering design process. That is, physical and mathematical interpretations of the design give a more concrete understanding of the design process. The values of these metrics are typically generated either from previous calculations and decisions or from an external resource, such as a table detailing material strength for a given list of materials. Occasionally, expert engineers are able to use their intuition and expertise to incorporate estimates of the metric values. This information can be updated in later iterations of the design process.

Metrics are typically quantitative indicators of information about the environment or design itself. Further, metrics can also be qualitative information about the design. For example, in selecting a configuration at the start of the aircraft design process, engineers would first need a qualitative understanding the stakeholders and how their concerns impact the design. This qualitative understanding can be transformed to a quantitative interpretation through the assignment of metric representations. For example, the importance of a stakeholder may be initially categorized as high, but this importance can later be quantified on a scale of one to five in relation to other stakeholders.

If metric determination and use is done well in any design, metrics will be apparent in task and subtask completion. Further, observed from a disciplinary-oriented approach, if metric determination and use is done well then the metrics will be defined within the disciplines to guide decisions and tasks/subtasks. Finally, if design knowledge coordination is effective, then the metrics will be consistent across the different disciplines.

2.3.4 Design Decisions

The outcome of a task is generally a decision about the design. Decisions are often a part of setting values for metrics when engineers have to decide on a specific metric value. But, they can also be more qualitative in nature (i.e. what type of landing gear will the aircraft use?). In making the decision, the designer should have concrete justification for why a particular value was selected. Ultimately, decisions are based on the designer’s interpretation of the outcome of each task in relation to the goals of the project. The justification or reasoning behind decisions drives the direction of the overall engineering design. If a value for a metric is aligned with the expectation of the designer, then the designer has validated their internal model of the system and easily selects the decision they predicted as the outcome. However, if the metric does not align with the expectation of the designer, then the designer may need to reevaluate their process for how a decision was derived. Typically, design reasoning is a comparison of the goal of the task to the determination of new metrics.

In an educational context, novice engineers interact on teams to design these engineering systems. The teams are directed internally by an identified student leader or manager. Externally, the course instructor or facilitator may provide guidance on student performance and guide students to alternate approaches to decision-making, if necessary.

If design decisions are done well in any design, then decisions will be justified by the results of the design tasks. Further, observed from a disciplinary-oriented approach, if design decisions are done well, then the disciplinary-oriented metrics will be used to justify decisions within tasks. That is, as a decision is made within a discipline-oriented task, the goals, preferences, and constraints of that decision will be explicitly used to justify the outcome of the task. Finally, if design knowledge coordination is effective, then a variety of metrics from across the disciplines will be used to justify decisions, and the overall impact of a decision beyond any one discipline will be described.

2.4 Framework for Characterizing Design Knowledge Coordination within an Engineering Design Process

An aerospace engineering design process can be characterized by how much the design process applies each of the constructs of goals, tasks, metrics, and decisions. As discussed in the previous section, three approaches are identifiable using the design knowledge coordination framework: a basic approach, a disciplinary-oriented approach, and a coordinated approach. Table 4 summarizes these different approaches a designer can take in making engineering design decisions

Table 4. Framework for characterizing design knowledge coordination within an engineering design process

	Basic Approach	Discipline-Oriented Approach	Coordinated Approach
Goal	Defines a general design goal	Design goals are decomposed into more specific goals for each discipline	Identifies trade-offs between discipline-oriented design goals
Tasks	Defines tasks and subtasks Incorporates an order and hierarchy to task decomposition	The tasks and subtasks have an order and hierarchy that align with engineering disciplines	Recognizes the links between tasks and subtasks Iterates across the tasks to update information about the design
Metrics	Uses metrics to complete tasks and subtasks	Within each discipline, there are critical metrics guiding the decisions and tasks	Maintains consistent values for metrics across the different disciplines
Decision	Justifies decisions through completion of design tasks	Decisions are justified through discipline-oriented metrics	Describes the overall impact of a particular decision Incorporates a variety of metrics from other disciplines to justify decisions

Thus the discussion of goals, tasks, metrics, and decisions can be framed to distinguish between a ‘basic’ approach to design, a ‘discipline-oriented’ approach to design, and the ‘coordinated’ approach to design. The basic approach to design corresponds to the lowest effort of design reasoning. In this approach, the designer uses some structure to organize their design problem but doesn’t move beyond the structure to consider the disciplinary impacts of their design decisions. In particular, the design tasks are not connected together in any meaningful fashion. Instead, the designers follow a prescribed approach and limit their decision-making to the immediate impact. Design decisions are justified using this immediacy reasoning. For example, in the design of an aircraft a designer might follow some prescriptive method to systematically design the vehicle. They might start with a general formula to estimate the size of the aircraft followed by calculating the size of the engine that would be required.

The next approach adds a discipline-oriented perspective to the design process. In this perspective, the designer breaks down the tasks into discipline-oriented boundaries. This is similar to the structure that larger companies use to subdivide the work into discipline-oriented design teams. Each design team focuses on their component of the design. For example, with the aircraft example, a designer might divide the design process into designing the wings, fuselage, engine, structures, and controls/electronics. Each discipline would be isolated from the other disciplines and later fit together to complete the design. Justifications and trade-offs would be focused on within-discipline aspects of the design. A pure discipline-oriented design perspective would be an extreme case of a siloed design, where design decisions may be optimized within each discipline but lack the integration for the total vehicle to be optimized across domains.

Thus, the coordinated perspective brings a cross-disciplinary lens to the design process. This perspective integrates design considerations across the disciplines. While many of the tasks might be divided by discipline, considerations are made to connect the design tasks and to transfer cross-disciplinary information across the tasks. Additionally, metrics are used to maintain consistent information about the design across the disciplines. Decisions incorporate a justified using reasoning that extends beyond the immediate impact and cross-disciplinary trade-offs are considered when comparing decision options

The subsequent chapters of this thesis use this framework to evaluate features that support or hinder the presence of design knowledge coordination within the engineering design process.

CHAPTER 3 - DESIGN KNOWLEDGE COORDINATION IN AUTHORITATIVE TEXTS ON CONCEPTUAL AEROSPACE ENGINEERING DESIGN

This chapter examines an authoritative text on the aerospace engineering design process to identify indicators of design knowledge coordination. Chapter 2 outlined a framework for design knowledge coordination in the context of engineering design. This chapter uses that framework to describe the design knowledge coordination inherent to aerospace engineering conceptual design.

3.1 Conceptual Design in Aerospace Engineering

Aerospace engineering design can be characterized by many different representations of the engineering design process, as noted in Chapter 1. The main process that will be used here follows Roskam (1990's) model of conceptual design. Conceptual design answers basic questions related to aircraft sizing, performance, and configuration. Advanced technology infusion is also considered within conceptual design to address performance gaps. This phase of design is commonly covered in aerospace engineering capstone design courses with students producing a high-level design 'on paper.' While the students do not physically fabricate an aircraft, the conceptual design process allows students to integrate their disciplinary knowledge through mathematical representations of aircraft performance and system design. The resulting aircraft design is intended to exhibit a students' ability to integrate technical design decisions across the complete design of an aircraft.

Three classic texts [Aircraft Design by Roskam (1990), Fundamentals of Aircraft and Airship Design by Nicolai and Carichner (2010), and Aircraft Design –A Conceptual Approach by Raymer (2006)] use a similar approach to describe the aerospace engineering conceptual design process. Their description of conceptual design involves dividing the process into a hierarchy of higher-lever and lower-level tasks. As the designer moves through the process, more knowledge about the design is gained. Within each task, critical metrics guide the quantitative evaluation of design decisions and justify the designer's reasoning.

3.1.1 Description of High-Level Tasks in Conceptual Design

Overall, a summary of the high-level tasks is described by Anderson (1999):

1. Define Requirements and Outline Mission
2. Perform Initial Aircraft Sizing
3. Determine Critical Performance-Based Metrics
4. Determine Initial Configuration and Layout of Aircraft
5. Improve Aircraft Weight Estimation and Configuration
6. Conduct a Performance Analysis
7. Optimize the Design

While this process is outlined in a linear fashion, in practice it is not a linear process. The decisions made within disciplinary-oriented subtasks feeds back into earlier decisions to update information about the design. For example, the designed aircraft's weight is initially estimated using historical trends on similar aircraft weights. This weight is iteratively updated as more information about the aircraft is gained. Roskam (1990) describes the conceptual design process using an iterative and complex flow chart. Similarly, Raymer (2006) incorporates a simplified flow chart of high-level design tasks, as shown in Figure 6.

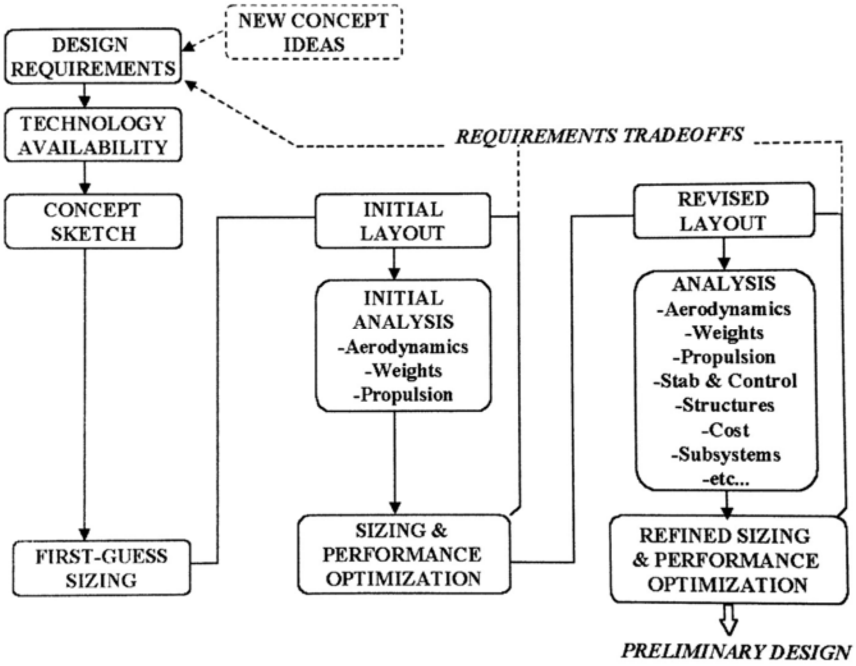


Figure 6. Raymer's description of the aircraft conceptual design process (Raymer, 2006, p. 9)

The conceptual design process starts with defining the aircraft system requirements and outlining the mission parameters. This phase of the design process uses the Request for Proposal (RFP) to define the specific requirements of the aircraft. These requirements include information about the performance capabilities of the aircraft as well as manufacturing and cost constraints. Outside of the RFP, other information about the design is gathered using information from the stakeholders (e.g. users, maintainers, regulators) as well as information about the environmental context (e.g. expected takeoff conditions). The general mission that the aircraft must be able to complete is also defined by the requirements, such as the typical cruise distance, altitude, and speed, and any special maneuvers, emergency fuel reserves, and landing and takeoff distances.

The requirements are then used to calculate an initial weight estimate for the aircraft. This initial weight estimate gives guidance on how large the aircraft must be to successfully carry a specified payload through the entire mission. The takeoff weight is an indicator of the maximum weight of the aircraft and gives an indication as to how much thrust and lift must be generated to successfully achieve flight. Beyond the requirements, some assumptions must be made at this phase of design about the performance capabilities of the aircraft. These estimates are made with the assistance of the text as well as through external references (e.g. information gathered about similar aircraft).

Following the initial weight estimate, the designers use mathematical relationships to determine critical performance-based metrics, such as thrust to weight ratio, wing loading, and maximum lift coefficient. Thrust to weight and wing loading are determined by analyzing a variety of flight conditions of the aircraft. For example, the designer can calculate the relationship of wing area to the lift generated at takeoff and can consider these relationships at other points in the mission, such as on cruise, landing, and in an evasive maneuver. The designer plots these relationships and determines the most efficient design point for the aircraft. The selection of a 'design point' entails the designer picking a minimum thrust to weight ratio and a maximum wing loading value. These performance-based metrics are required to continue through the design process and complete a more comprehensive design and analysis of the aircraft's performance capabilities.

Next, the layout of the aircraft is defined using an analysis of the aircraft requirements as well as information about the stakeholder needs. This layout leads into the selection and sizing of many aircraft components, such as high lift devices, wing planform size, and fuselage size. Once the aircraft has been sized and more information is known about the components, the weight estimate is refined. Then, the performance analysis phase applies a detailed investigation of the capabilities of the current aircraft design, where each component is compared to the required capabilities of the aircraft. If any one component or performance-based metrics is not sufficient, the designer must go back and re-design. This redesign can be for the component or for the whole aircraft. Once the performance of the aircraft has been validated, the designer can return to any piece of the design and further optimize the aircraft for maximum performance and efficiency.

In each of the seven components, or high-level tasks, the subtasks, metrics, and decisions can also be identified. Because of the complexity of the conceptual design process, an abbreviated form of the analysis results is presented in the next section using the framework for structuring knowledge management within engineering.

3.2 Design Knowledge Coordination in AE Design

The framework for design knowledge coordination (Table 5) was applied to an authoritative text detailing a process for conceptual design within aerospace engineering: Roskam (1990). The text was examined for indicators of how design knowledge should be structured and coordinated (e.g. tasks, goals, metrics, and decisions). This examination was conducted by first defining the high-level tasks detailed in the texts. Once the high-level tasks were defined, each task was broken into subtasks, and the metrics central to the tasks and subtasks were identified. The decisions that resulted from each subtask could then be identified. From this breakdown, design knowledge coordination in the conceptual design process can be discussed. Note, Roskam's aircraft design tasks generally align with the tasks presented in other authoritative texts. However, the terminology and order of tasks may differ between the various texts.

Table 5. Design knowledge coordination in engineering design

	Coordinated Perspective
Goal	Identifies trade-offs between discipline-oriented design goals
Tasks	Recognizes the links between tasks and subtasks Iterates across the tasks to update information about the design
Metrics	Maintains consistent metrics across the different disciplines
Decision	Describes the overall impact of a particular decision Incorporates a variety of metrics from other disciplines to justify decisions

3.2.1 Analysis Approach

Qualitative methods were used to identify indicators of design knowledge coordination within the conceptual design process. A coding scheme was developed using a strategic analysis of the literature, discussed in chapter 2. The coding scheme's dimensions of *goals, tasks, metric,* and *decisions* were applied to the Roskam (1990) text. The text was reviewed for those indicators of design knowledge, and a post-hoc analysis summarized the indicators of coordination using chapter 2's outline of a coordinated perspective of design (Table 4).

3.2.2 Description of High-Level Tasks in Conceptual Design

This analysis placed the metrics from each mathematical model listed in Roskam into an Excel spreadsheet, along with its high-level and subtask classification, and this list was analyzed for cross-disciplinary features. A full description of the authoritative text's design process is in Appendix A. Specifically, the metrics were analyzed for the number of high-level tasks and subtasks they appeared within. Then, the high-level tasks and subtasks were categorized by discipline to see the cross-disciplinary nature of each metric and to identify tasks that require integration across disciplines.

Ultimately, 44 metrics were identified in the process as being cross-disciplinary (Table 6 and Table 7). These metrics reflect where design knowledge coordination is required to link together tasks spanning disciplines. For example, the primary function of the coefficient of lift and coefficient of drag (C_L and C_D) is within aerodynamic analyses. However, these values are also used to analyze structural properties through a V-n diagram that defines the aircraft flight envelope's limits for velocity given structural load capabilities. Additionally, C_L and C_D are used in the performance analysis and to determine whether the vehicle has stable flying qualities. The breakdown of coordination-enabling metrics shows that metrics related to velocity and weight are the most critical in conceptual design. This intuitively makes sense, because both values determine the inherent performance capabilities of the aircraft and drive subsequent decisions on aircraft design.

Table 6. Metrics in the authoritative text that share information across and within disciplines, sorted by high-level task

Critical metrics	Subtasks
Weight (Takeoff, Payload, Fuel, Crew, Empty)	First Weight Estimate, Class II Weight Est, Sensitivity Studies, Structural Arrangement, Perform Preliminary Cost Analysis, Sensitivity Studies, Procurement Cost, Airfoil Selection and Planform Shape, Analyze Aircraft Stability, Prepare Constraint Diagram, Operations & Maintenance Costs, Fuselage Layout , Development Cost
Wing Area	Analyze Aircraft Stability, Class II Weight Est, High-Lift Devices, Estimate Drag Polar, Preliminary Sizing of Empennage, Prepare Constraint Diagram, V-n Diagram
Velocity (Approach, Cruise, Dive, Manuever, Max, Stall)	First Weight Estimate, Analyze Aircraft Stability, Class II Weight Est, V-n Diagram, Prepare Constraint Diagram, Structural Arrangement, Operations & Maintenance Costs, Procurement Cost
#Crew per Aircraft	Class II Weight Est, Fuselage Layout, Outline Mission requirements, Operations & Maintenance Costs
Aspect Ratio of the Wing	Airfoil Selection and Planform Shape, Analyze Aircraft Stability, Estimate Drag Polar, Class II Weight Est, Prepare Constraint Diagram
CD (CD, CD0)	Analyze Aircraft Stability, Estimate Drag Polar, V-n Diagram, Prepare Constraint Diagram, Airfoil Selection and Planform Shape
CL (CL, CLAlpha, CLMax)	Airfoil Selection and Planform Shape, Analyze Aircraft Stability, Prepare Constraint Diagram, Estimate Drag Polar, High-Lift Devices, V-n Diagram
Air Density	Analyze Aircraft Stability, Class II Weight Est, V-n Diagram, Prepare Constraint Diagram
Load Factor (n, nult)	Class II Weight Est, Analyze Aircraft Stability, Prepare Constraint Diagram, V-n Diagram, Structural Arrangement
Range (R, R Cruise)	Analyze Aircraft Stability, First Weight Estimate, Sensitivity Studies, Outline Mission requirements
Mach	First Weight Estimate, Fuselage Layout
#Engines	Class II Weight Est, Operations & Maintenance Costs, Overall Configuration Selection
Wing Span	Airfoil Selection and Planform Shape, Analyze Aircraft Stability, Preliminary Sizing of Empennage
Taper Ratio	Airfoil Selection and Planform Shape, Class II Weight Est, Preliminary Sizing of Empennage, High-Lift Devices
Oswald’s Efficiency Factor	Airfoil Selection and Planform Shape, Analyze Aircraft Stability, Prepare Constraint Diagram, Estimate Drag Polar
Specific Fuel Consumption	Analyze Aircraft Stability, First Weight Estimate, Sensitivity Studies
Leading Edge Sweep	Airfoil Selection and Planform Shape, Analyze Aircraft Stability, Class II Weight Est

Table 6. Metrics in the authoritative text that share information across and within disciplines, sorted by high-level task (Cont'd)

Critical metrics	**Subtasks**
Takeoff and Landing Field Length	Analyze Aircraft Stability, Outline Mission requirements, Prepare Constraint Diagram
Type of Landing gear	Fuselage Layout, Overall Configuration Selection, Preliminary Landing Gear Configuration
Angle of Attack	Airfoil Selection and Planform Shape, Analyze Aircraft Stability
Aspect Ratio of the Horiz Tail	Analyze Aircraft Stability, Preliminary Sizing of Empennage
Aspect Ratio of the Vert Tail	Class II Weight Est, Preliminary Sizing of Empennage
c coefficient (weight sizing)	Estimate Drag Polar, Sensitivity Studies
Mean Chord	Airfoil Selection and Planform Shape, Preliminary Sizing of Empennage
Coefficient of friction	Airfoil Selection and Planform Shape, Estimate Drag Polar, Prepare Constraint Diagram
Climb Gradient	Analyze Aircraft Stability, Prepare Constraint Diagram
Coefficient of Moment	Airfoil Selection and Planform Shape, Analyze Aircraft Stability
Cost (Operation, Acquisition, Life Cycle Cost)	Outline Mission requirements, Overall Cost, Operations & Maintenance Costs, Procurement Cost
Drag	Analyze Aircraft Stability, Prepare Constraint Diagram
Endurance	Analyze Aircraft Stability, Sensitivity Studies
Fuel Fraction Reserves	First Weight Estimate, Sensitivity Studies
Altitude	Analyze Aircraft Stability, Prepare Constraint Diagram
K	Airfoil Selection and Planform Shape, Structural Arrangement
Length of Fuselage	Class II Weight Est, Fuselage Layout
Lift to Drag Ratio	First Weight Estimate, Prepare Constraint Diagram, Sensitivity Studies
Lift	Analyze Aircraft Stability, Structural Arrangement
Materials	Procurement Cost, Structural Arrangement
Rate of Climb	Analyze Aircraft Stability, Prepare Constraint Diagram
Horiz Tail Area	Class II Weight Est, Preliminary Sizing of Empennage
Vert Tail Area	Class II Weight Est, Preliminary Sizing of Empennage
Sweep Vert Tail	Class II Weight Est, Preliminary Sizing of Empennage
Wetted Wing Area	Estimate Drag Polar, Prepare Constraint Diagram
Thrust	Analyze Aircraft Stability, Prepare Constraint Diagram
Wing Loading	Prepare Constraint Diagram, V-n Diagram

Table 7. Metrics in the authoritative text that share information across and within disciplines, sorted by discipline

Critical metrics	Number of Cross-Discipline Integrations	Mission and Requirements	Weight Calculation	Performance Estimation	Configuration	Aerodynamics	Structures	Stability	Cost	Propulsion	Landing Gear	Within-Task Elements
Weight (Takeoff, Payload, Fuel, Crew, Empty)	7		X	X	X	X	X	X	X			X
Wing Area	6		X	X	X	X	X	X				X
Velocity (Approach, Cruise, Dive, Maneuver, Max, Stall)	5		X	X			X	X	X			X
#Crew per Aircraft	4	X	X		X				X			
Aspect Ratio of the Wing	4		X	X		X		X				X
CD (CD, CD0)	4			X		X	X	X				X
CL (CL, CLAlpha, CLMax)	4			X		X	X	X				X
Air Density	4		X	X			X	X				
Load Factor (n, nult)	4		X	X			X	X				X
Range (R, R Cruise)	4	X	X	X				X				
Taper Ratio	4		X		X	X		X				X
Mach	3		X		X				X			
#Engines	3		X		X				X			
Wing Span	3				X	X		X				
Oswald’s Efficiency Factor	3			X		X		X				X
Specific Fuel Consumption	3		X	X				X				
Leading Edge Sweep	3		X			X		X				
Takeoff and Landing Field Length	3	X		X				X				
Thrust	3			X				X		X		
Type of Landing gear	2				X						X	
Angle of Attack	2					X		X				

Table 7. Metrics in the authoritative text that share information across and within disciplines, sorted by discipline (Cont'd)

Critical metrics	Number of Cross-Discipline Integrations	Mission and Requirements	Weight Calculation	Performance Estimation	Configuration	Aerodynamics	Structures	Stability	Cost	Propulsion	Landing Gear	Within-Task Elements
Aspect Ratio of the Horiz Tail	2		X					X				
Aspect Ratio of the Vert Tail	2		X					X				
Angle of Attack	2					X		X				
Aspect Ratio of the Horiz Tail	2		X					X				
Aspect Ratio of the Vert Tail	2		X					X				
c coefficient (weight sizing)	2			X		X						
Mean Chord	2					X		X				
Coefficient of friction	2			X		X						X
Climb Gradient	2			X				X				
Coefficient of Moment	2					X		X				
Cost (Operation, Acquisition, Life Cycle Cost)	2	X							X			X
Drag	2			X				X				
Endurance	2			X				X				
Fuel Fraction Reserves	2		X	X								
Altitude	2		X	X								
K	2					X	X					
Length of Fuselage	2		X		X							
Lift to Drag Ratio	2		X	X								X
Lift	2						X	X				
Materials	2						X		X			
Rate of Climb	2			X				X				
Horiz Tail Area	2		X					X				
Vert Tail Area	2		X					X				
Sweep Vert Tail	2		X					X				
Wetted Wing Area	2			X		X						
Wing Loading	2			X			X					

3.2.3 Define Requirements and Outline Mission

The first phase of any conceptual design process is to define and decompose the requirements. Initially, a document calling for design proposals, such as an RFP, is given as a guide for the system's requirements. This document contains information about the aircraft's mission and performance requirements. These requirements include details dictating aircraft performance reflected through metrics such as range, payload weight, cruise altitude, takeoff distance, maximum velocity, service ceiling, and program cost

For example, an RFP given by the 2014-2015 AIAA Foundation Undergraduate Team Aircraft Design Competition specified that the designed aircraft was to be a Next Generation Strategic Airlift Military Transport capable of carrying a maximum of 300,000 pounds of payload. The RFP also specified that the aircraft was to be able to carry a payload weighing 120,000 pounds a range of 6,300 nautical miles without refueling. Guidelines such as the ones from the 2014-2015 AIAA RFP give the engineering designers a set of metrics to bound their aircraft design.

Table 8 has an example of the breakdown of this phase of conceptual design. For a complete list of metrics in the conceptual design process and their full name, please reference Appendix B.

Table 8. Design process decomposition within the requirements definition

High-level Task	Define Requirements and Outline Mission
Decision	Mission parameters, Technologies
Subtasks	Outline mission requirements
	Select technologies for integration
Metrics	Cruise Rqmt, #Crew per Aircraft, Type of Payload, W Pay, V Cruise, V Max, V Loiter, V Ldg, R Cruise, R Max, Endurance time, TOFL, LFL, Cost Dev, Cost Acq, Cost O&S, LCC, Maintenance Hrs per Flight Hour, Service Ceiling, Landing Roll

From the requirements definition, this information is used to plan a typical mission for the aircraft. Information about the mission typically incorporates the same information as identified in the requirements. However, the engineers are able to take this information and plan a specific path that the aircraft should be capable of flying. An example of an aircraft mission as outlined in the 2014-2015 AIAA RFP is shown in Figure 7. This mission was generated by students participating in a aerospace engineering senior design course.

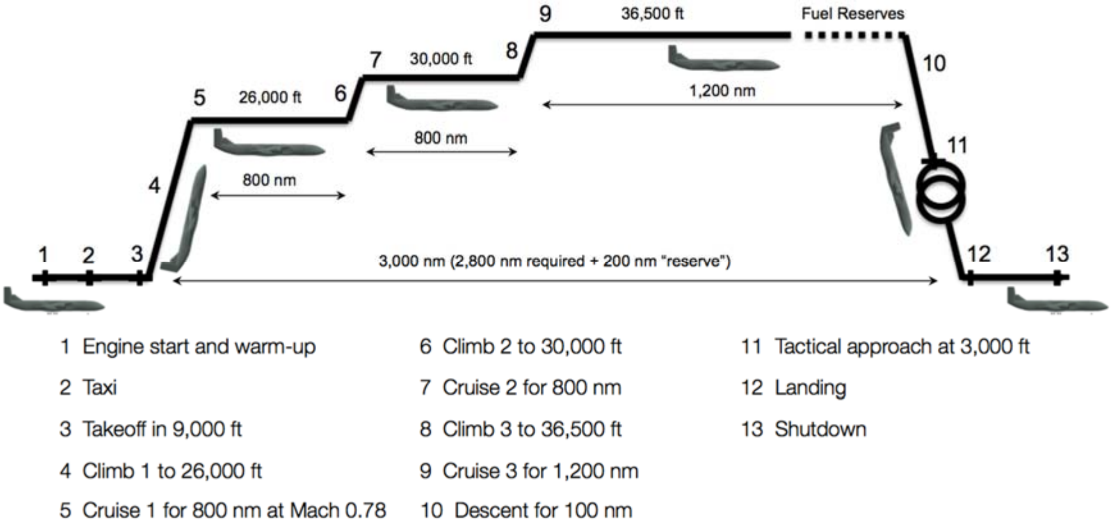


Figure 7. Mission profile of aircraft

Within a coordinated perspective, this phase of the conceptual design process connects to the other phases by acting as a guide for future decisions. The metrics that are stated in the requirements definition will ultimately be referenced later in the design, and iterated on to ensure that the design meets the requirements. The requirements act as project goals, defining the constraints and criteria of a successful design. A basic approach to design would discuss the goals, but not present the goals in any meaningful context to how they relate to specific requirements within disciplines. A discipline-centric perspective of the requirements definition phase would break apart the requirements into disciplines and discuss the impact of the requirements within the disciplines, but would not make connections across the disciplines. A coordinated perspective of design moves beyond the within-discipline perspective to provide cross-disciplinary perspective on the goals. It would also include a discussion from the designer regarding any trade-offs inherent to the requirements between disciplines.

3.2.4 Perform 1st Estimation of Weight

For aircraft design, most decisions are made based on the aircraft weight. Thus, the aircraft weight is an essential metric in design knowledge coordination that connects the different steps within the conceptual design process. This high-level task is the first opportunity to estimate the weight. This estimation will then be iteratively updated through subtasks and through future high-level tasks.

The empty weight of an aircraft is determined as the sum total of the weight of individual components of the aircraft (e.g. weight of the wing structure, propulsive systems, fuselage structure, and internal systems). The gross takeoff weight of the aircraft (or maximum weight) is a function of the empty weight, payload weight, and the amount of fuel needed to carry the aircraft a specific distance.

In an initial calculation or estimation of the weight, the weights are estimated using historical values from similar aircraft. Next, a more detailed calculation of the empty and takeoff weights is performed using mathematical models in the design texts. Many values in this equation are estimated or assumed using suggestions from the text as well as from researched historical values. The resulting weight estimation is compared to similar aircraft to ensure that the value is within a reasonable and justifiable range.

Since the gross takeoff weight is affected by the amount of fuel required to fly a specific distance, a balanced fuel and distance requirement is calculated using the maximum payload weight. The outcome of the first weight estimation is not only an estimation for the empty and takeoff weight of the aircraft, but also an estimation for the amount of fuel the aircraft would need to carry.

Another component of the weight estimation task is the inclusion of expected performance gains from incorporating technologies. At this point, engineering designers outline the technologies they expect to incorporate on the aircraft, and the impact of those technologies to reducing (or increasing) the aircraft's weight. An estimation of the shift in the aircraft's weight is captured through an "eta" value. This value is multiplied by the weight estimation to show the change in the weight due to technologies.

Table 9. Design process decomposition within the initial weight estimation

High-level Task	Initial Aircraft Sizing
Decision	W_allow, W_Calc, WTO, WEmpty, Fuel Volume,
Subtasks	Historical Regression of Weight
	First Weight Estimate
	Sensitivity Studies-- Takeoff Weight Sensistivity to: Payload Weight, Range, Engurance, Speed, SFC, and L/D
Metrics	Year, W_Similar AC, WTO, W Empty, W OE, W Fuel, WPay, WTFO, W Crew, W Empty Manuf, W Fixed Equip, DWeight Calc, WTO Guess, W Fuel Reserves, W Fuel Used, WF, WF Segment, L/D, SFC, R Cruise, W Empty Allow, W Empty TO, W Empty Calc, W Empty Est, A Intercept, B Slope, FF Reserves, FFAvg, MFF Climb, MFF Cruise, MFF Decent, V Max, R, L/D Cruise , M Cruise, VCruise Segment, L/D Cruise Segments, Endurance, MFF, FF TFO, c coef, D Weight Eqn

3.2.5 Determine Critical Performance-Based Metrics

The performance of an aircraft is determined by several critical metrics including the maximum lift coefficient, lift to drag ratio, wing loading (W/S), and thrust to weight ratio (T/W). These metrics serve several functions in later tasks. The wing loading (W/S) and thrust to weight ratio (T/W) will be used to update the initial weight estimation as well as to calculate wing area and wing aspect ratio. The lift to drag ratio (L/D) and lift coefficient (CL) will be used in other tasks and disciplines, such as the aerodynamics calculations and stability analysis.

Thus, before a more detailed analysis of aircraft performance can be made, these metrics must first be calculated. An initial value for the maximum lift coefficient metric is determined using historical data of similar aircraft. Following, a Class I Drag Polar Convergence is performed using an estimation of other performance-based metrics (such as wing loading and coefficient of friction).

Sensitivity analyses show the relationship of takeoff weight to other metrics, such as the lift to drag ratio and the thrust specific fuel consumption, and refine their estimates when not much information is known about the aircraft. For example, in determining the lift to drag ratio, plotting takeoff weight against lift to drag shows a parametric reduction in takeoff weight as lift to drag increases. Ideally, a designer would be able to maximize lift to drag and minimize the takeoff weight. But, because of the negative relationship, an optimal metric value is selected. Other metric values can also be selected through trade studies, such as the optimal cruise velocity (by varying range and mach number) and the optimal cruise altitude (by varying range and altitude)—it depends on what information is known and what information is unknown.

Other subtasks are performed to find the wing loading and thrust to weight ratio. This information ultimately impacts the size of the wing and the type of engine required to achieve optimal aircraft performance. After gaining an initial estimation of the size of the aircraft, the engineering designers must start to refine their calculations, and determine the values for performance metrics of the aircraft. These metrics will feed into the next phase of the design process where many things are determined about the aircraft, such as the required wing planform size, the airfoil characteristics, a rubberized size of the engine, the control surfaces size, and optimal payload placement for a balanced aircraft, among many other aspects of the design.

Table 10. Design process decomposition within the determination of the critical performance-based metrics

High-level Task	Determine Critical Performance-Based Metrics
Decision	ClmaxTO, Lift, CD0, Drag polar, SWing, MTOW, Treq, W/S, T/Wmin
Subtasks	Estimate Drag Polar
	Prepare Constraint Diagram: Stall Speed, Takeoff, Landing, Climb requirements, Time to climb, Manuever
Metrics	CD, CD0, CL, AR Wing, SWing, Equivalent parasite area, e, Swet, a coef, b coef, c coef, d coef, dCD0, Cf, V Stall, CLMax, Density Air, W/S, CLMax TO, CLMax Ldg, TOFL, WTO, VTO, T/W TO, Ground Friction Coefficient, Pilot Technique, TOP, Air Density Ratio, BPR, V Approach, WLdg, Decelleration Method , Flying Qualities, W/S Ldg, WTO/S, CGR, V, L/D, CDi, ROC, T/W, L/D Max, Thrust, Drag, W, h, n, nMax

3.2.6 Determine Configuration and Layout of Aircraft

In conceptual design, determining the configuration and layout is the first point when many detailed decisions are incorporated into the design of the aircraft. Additionally, this task is inherently cross-disciplinary, as designers are simultaneously making decisions about the aircraft related to areas such as structures, aerodynamics, stability, etc. This high-level task requires careful consideration of the design goals to set target values for metrics. Additionally, metrics that are determined or updated within each subtask must be consistently updated throughout the entire design process.

An overall configuration of the aircraft is selected using a quantification of the criteria for the pre-defined requirements (e.g. figures of merit). The first subtask in determining and configuration and layout of the aircraft involves selecting major component arrangements for the aircraft, such as high or low wing, the type of tail, the number of engines and the engine location. These selections may change in a later phase of the conceptual design process, but an initial definition of the configuration opens the design space to determining more detailed components of the aircraft design.

After choosing a general configuration of the aircraft, the designers are able to use earlier estimates of metrics to decide on the size of the aircraft layout. For example, the aerodynamic performance of the aircraft is driven by the determination of the Class I Drag Polar and its metrics. Once the designers have performed a Class I Drag Polar Analysis, the wing planform, wing placement, airfoil type, and high-lift devices can be decided. Additionally, other information can be used to size the empennage of the aircraft.

Subsystems are also selected and incorporated in this high-level task. At this point, the subsystems do not have to be detailed, but the engineering design team does need an understanding of what subsystems will be required and if there will be any advanced technologies incorporated in the design of the aircraft.

Once the various components of the aircraft have been decided, the designers perform a Class I stability and control analysis to determine if the aircraft is statically stable. Typically, this subtask in the conceptual design process requires many iterations. The designers will need to move components and adjust the aircraft configuration until the system is fully balanced. The landing gear will also be selected and placed in this subtask.

Table 11. Design process decomposition within determining the configuration and layout of aircraft

High-level Task	Determine Initial Configuration and Layout of Aircraft
Decision	A/C Type, #Engines, # Fuselages, Engine Type, Engine Disposition, Wing Configuration, Empennage Configuration, Ldg Gear Type, Structural Wing Configuration, Wing/Fuselage Arrangement, Maximum Thickness Ratio of the Airfoil, Location of tmax, camber, AR, Sweep Wing, Taper Ratio Wing, incidence angle, twist angle, dihedral angle, lateral control surface size and layout, Type of High-Lift Devices, HLD Area, Location of HLD, Arrangement of Cargo, Flightdeck Layout, Cabin Layout, Fuselage Radius, Fuselage Length, Location of Vertical Tail, Location of Horizontal Tail, SVert Tail, SHoriz Tail, c rudder, S Aileron, S Elevator, c Elevator, c Aileron, AR Vert, AR Horiz, Sweep Vert, Sweep Horiz, ct/cr Vert, ct/cr Horiz, Dihedral Angle Vert, Dihedral Angle Horiz, iVert, iHoriz, Type of landing Gear, Location of Landing Gear, Number of Tires, Tire size
Subtasks	Overall Configuration Selection
	Airfoil Selection and Planform Shape
	High-Lift Devices
	Fuselage Layout
	Preliminary Sizing of Empennage
	Preliminary Landing Gear Configuration
Metrics	FOM, Stakeholders, Type of AC, Similar AC, #Engines, #Fuselages, Type of Engine, Engine Placement, Wing Config, Config Empennage, Type of LG, AR Wing, CD0, e, CLalpha, CLMax, W Wing, ct/Cr, t Airfoil Center, rLE, Camber, K, Vol Fuel Wing, t/c max, M Crit, c Mean, Cf, Cm, CL, D Wave, CD LE, M, dNose Flap, LE Suction, Cm a/c, AoA0L, CLmin, CDmin, Cd Section, Sweep LE, Max t line, Cp, Cl Section, Cm Section, AoA, W, bWing, Sweep Wing, iW, Spanwise Twist, Gamma W, Sweep c/4, CLMax TO, CLMax Ldg, clmax t, clmax r, Swet Flaps, SWing, Location of Flaps, Flap to Chord Ratio, d Flaps, DCLMax due to Flaps, DCl due to Flaps, dAoA Flaps, Re, Type of Flaps, Type of Cargo, h cargo, w cargo, l cargo, #Crew per Aircraft, Crew Seating Arrangement, Crew Seat Angle, Over-Nose Viewing Angle, Over-Side Viewing Angle, Tip-Over, Turnover Angle, Wing Carry-Through Volume, Vol Fuel Fuse, Type of Fuel Tank, Type of Avionics, W Avionics, Volume Avionics, Empennage Area per SWing, W Empennage per Area, CD0 Fuse, cf Fuselage, Cdpmin Fuse, lf/df, D Wave Fuse, d fuse, l fuse, M Cruise, Tail Vol Ratio Horiz, Tail Vol Ratio Vert, Location of Vert Tail, Location of Horiz Tail, SVert Tail, SHoriz Tail, crudder, SAileron, SElevator, cElevator, cAileron, AR Horiz Tail, Sweep Vert Tail, Sweep Horiz Tail, ct/cr Vert Tail, ct/cr Horiz Tail, Dihedral Angle Vert, Dihedral Angle Horiz, iVert Tail, iHoriz Tail, l Horiz, Location of LG, #Tires, Tire size,

3.2.7 Improve Aircraft Weight Estimation

The fifth phase of the conceptual design process updates and improves the aircraft weight estimation. Now that more information is known about the aircraft design, the designer can begin to breakdown the aircraft into individual components and systems, and calculate a more precise weight based on that knowledge. The updated weight estimation is initiated by calculating the structural demands on the aircraft through a V-n diagram. Next, the Class II weight estimation breaks the aircraft into many components. The weight is approximated using mathematical relationships for each component. For example, the weight of the structural components of the aircraft is found using the previously calculated size of the wing (aspect ratio and area) as well as information generated in the V-n diagram. Weights are also found for the empennage, fuselage, fuel system, propulsion system, flight control system, electrical system, avionics, oxygen systems, furnishings, auxiliary power unit, cargo handling, operational items, weapons, flight test instruments, ballast, and paint.

Once the weight has been found for each component, the designers outline the specific structural arrangement of the interior of the aircraft. In this subtask, the designers have to decide the number and size of structural support devices, such as stringers inside the wing.

The aircraft center of gravity (cg) is calculated using the component weight breakdown as well as an approximation of the location of each component. When calculating the aircraft center of gravity, the designer may have to move items around the aircraft to appropriately balance the weight distribution. This subtask provides a more detailed understanding of how items, such as the payload and interior systems, will be laid out in the aircraft.

Finally, with all the information that was generated in updating the aircraft weight and interior systems positions, the designer can create a 3D model of the vehicle. At this point, the designer will also need to go back to previous steps of design and update information that was improved through this task. For example, the aircraft weight is used to find information about the drag characteristics. The work performed in previous phases of the conceptual design process is updated to match the new knowledge about the design. The parameters found in the previous stages have given improved knowledge about the design. At this point, the designers can do a detailed weight breakdown by the components. This also leads to an improved estimation for how much fuel is required to fly the specified mission.

Table 12. Design process decomposition within improving the aircraft weight estimation

High-level Task	Improve Aircraft Weight Estimation and Configuration
Decision	Wempty, Structural Components and Arrangement, Interior Arrangement
Subtasks	V-n Diagram
	Class II Weight Estimation
	Structural Arrangement
	Locate Component CG
	Finalize 3D Model and Three-View
Metrics	V Stall, V Cruise, V Dive, V Manuever, WTO/S, Density Air, CNMax, CD, CLMax, K V-n, LLF, n, V Stall neg, Gust Load Factor, Gust Velocity, Airplane Mass Ratio, SWing, n Ult, V, AR Wing, M Max, WTO, t/c, ct/cr, Sweep LE, SHoriz Tail, bHoriz Tail, lt, t Horiz, cHoriz, hT/hV, SVert Tail, AR Vert Tail, ct/cr Vert Tail, Sweep Vert Tail, SRudder, K Inl, Density Air, l Fuse, h Fuse, W Fuel, Kfsp, W Engine Controls, W Engine Starting System, W Oil System, W Engine, #Engines, #Crew per Aircraft, M Dive, Materials, Lift, W, Safety, V Approach, V Max, MTOW, W Ldg Max, W OE, k, Gust, Mission Profile, J Materials, G, Stress, Strain, W Components, x AC Components, Moments of Inertia, alat,

3.2.8 Conduct a Performance Analysis

The performance analysis of the aircraft is where the configuration is examined for whether current aircraft design can meet the requirements. The design goals must be referenced again and compared to the known metrics of the current design. If there is a disparity in performance, the design must be iterated and updated. From a coordinated perspective, this task is a check on performance and requires consistent metrics to be integrated within the design analysis.

The propulsion system is analyzed for its ability to meet the required thrust capabilities. Additionally, if there any advanced propulsive technologies, they are investigated for impact on the design at this point. Special considerations, such as technology development timeline and interaction with other aircraft components are also investigated.

The structural capabilities of the aircraft are analyzed by examining the strength of the aircraft materials in extreme gust, velocity, and applied load conditions. This subtask requires the team to know the type of materials that will be incorporated on the aircraft as well as the relative strength of those materials. If advanced materials are to be incorporated in the design (such as composites), those are analyzed for strength at this point. A V-n diagram allows the designers to examine the relationship of velocity to loads on the aircraft.

The stability and control of the aircraft is important to knowing if the aircraft is capable of flying without major disturbances due to instability. This subtask in the conceptual design process requires engineers to breakdown the static and dynamic stability characteristics along each of the aircraft's axes. If the aircraft is found to be unstable in any of these cases, the engineers will need to readjust their design or incorporate a new system to account for the instabilities in the aircraft design.

Performance and flight mechanics are analyzed for aircraft performance in various flight conditions. In this analysis the engineering designers create a series of mathematical models demonstrating how the aircraft will behave in different conditions. Additionally, this phase of the conceptual design process includes a detailed analysis of the total program cost to develop, test, manufacture, and operate the aircraft. An approximation of the aircraft cost is generated by breaking the cost calculations into multiple subtasks, including calculating the development cost, procurement cost, and the operations and maintenance cost. If the cost is noted as overly high, the designers may need to do a more detailed evaluation to see what factors are impacting the high cost.

Table 13. Design process decomposition within conducting a performance analysis

High-level Task	Conduct a Performance Analysis
Decision	N/A – Evaluating Performance Capabilities
Subtasks	Analyze Aircraft Stability
	Evaluate Maintenance and Accessibility
	Perform Preliminary Cost Analysis
	Development Cost (Reference RAND)
	Procurement Cost (use term Cost Estimating Relationships)
	Operations & Maintenance Costs
	Overall Cost
Metrics	AR Wing, AR Horiz Tail, bWing, b flapped wing, alat, avert, cWing, SFC, cbeta, CD0, CD, CGR, Chinge, chinge0, chinge AoA, chinge beta, chinge dctl, Clp, Clr, Clbeta, Clda, Cldr, CL, CL0, CLalpha, Clde, Clw flaps, Cmac flaps, Cmacwf, Cm, Cm0, CmAoA, Cmdctrl, Cmde, Cmq, Cnp, Cnr, Cnbeta, CnbetaB, Cnda, Cndr, Cride, CTx, Cyp, CYr, Cybeta, Cyda, Cydr, dT, Drag, e, Endurance, fmp, fto, Fa, Fr, Fs, Fty, Gearing Ratio, h, hL, hTO, HM, Ixx, Iyy, Iyymg, Izz, Gust Parameter, lh, Lift, Sweep LE, Lift Horiz, Gust Force, Lift WF, ClT, Macwf, n, Roll rate, Pm Total, Pn Total, Ps, V, Density Air, R, ROC, RoD, Rloop, Turn Radius, LFL, TOFL, SWing, Time, Thrust, TR, Troll, TD, V Approach, V Stall, VTD, W, Fuel Flow Rate, xac, xachoriz, xacwf, xcg, ln, lm, zDrag, zmg, zThrust, AoA, Beta, Flight Path Angle, dCtrl , Downwash Angle, W Airframe, W Empty, V Max, #Aircraft Test, Type of Airframe Material, NRE, NRT, Cost Dev & Support, Cost Flt Test, RE100, RML100, RMM100, RQA100, W Structures, #AC, Cost Engr, Cost Tooling, Cost Manuf, Cost Qual Ctl, Tmax Engine, M Max, TiT, W Avionics, $/W Avionics, #Eng Hrs, #Tooling Hrs, #Manuf Hrs, Materials, #QC Hrs, #Flight Test, LCC, Cost Acq, Cost Operation, Cost Total, CPI, $/Hr, Price/Unit_Sim AC, Cost by Material, Cost Fuel, Cost per Crew Member, Depreciation of Money, Cost Maintenance, Landing Fees, Cost of Administration, Flt Hrs per Year, Cost Fuel Projected, #Crew per Aircraft, Utilization, Cost Labor, MMH/FH, V Cruise, WTO, Cost Materials, Cost Engine, #Engines, Cost_Similar AC, Cost R&D, Cost O&S, Cost Production

3.2.9 Optimize the Design

The final phase of the conceptual design process optimizes the design. Within this task, the designer must note areas where the design does not meet the previously determined goals and requirements. Those areas must be updated and optimized until the aircraft satisfies the engineering goals.

Ideally, each task would have iteration embedded within itself. Additionally, if there were any disparities between the design goals or the estimated metrics, the aircraft design may have to be iterated to meet the requirements. The design optimization is also an opportunity for designers to reflect on their design decisions, including the impact of each of their design decisions on important metrics and the trade-offs underlying each decision.

3.3 Design Knowledge Coordination in Aerospace Engineering Conceptual Design

Throughout the previous discussion of the conceptual design process, indicators of coordination were identified and discussed in the context of the design problem. Considering the three-tier structure of approaching a design problem, the design process can be characterized as both a coordinated and as an uncoordinated process. The level of coordination is dependent on the designer making connections between the disciplines and using cross-disciplinary justifications to support decisions.

Table 14. Framework for characterizing design knowledge coordination within an engineering design process

	Basic Approach	Discipline-Oriented Approach	Coordinated Approach
Goal	Defines a general design goal	Design goals are decomposed into more specific goals for each discipline	Identifies trade-offs between discipline-oriented design goals
Tasks	Defines tasks and subtasks Incorporates an order and hierarchy to task decomposition	The tasks and subtasks have an order and hierarchy that align with engineering disciplines	Recognizes the links between tasks and subtasks Iterates across the tasks to update information about the design
Metrics	Uses metrics to complete tasks and subtasks	Within each discipline, there are critical metrics guiding the decisions and tasks	Maintains consistent values for metrics across the different disciplines
Decision	Justifies decisions through completion of design tasks	Decisions are justified through discipline-oriented metrics	Describes the overall impact of a particular decision Incorporates a variety of metrics from other disciplines to justify decisions

The conceptual design process is inherently a structured process. Roskam (1990), as well as other traditional design texts (Raymer, 2006; Nicolai & Carichner, 2010), outline a very structured process of design. Design knowledge coordination is not explicitly noted in these texts. However, design knowledge coordination inferred in the organization and structure of the conceptual design process.

The text discusses methods of defining goals at the start of the design process. These methods are intended to create a hierarchical decomposition of the requirements of the designed aircraft. At one level, a designer might specify a general goal ("Aircraft should be able to fly a long distance and carry heavy payload"). This non-specific, high-level design goal does not discuss the specific requirements of the system and would make performing a coordinated and integrated design process difficult. Further, the design goals described by the text only require discipline-oriented metrics of success. This approach would allow a designer to work toward design goals within individual disciplines and integrate their design solutions later in the design process.

A fully coordinated design process would consider the discipline-oriented metrics as well as the cross-disciplinary trade-offs of the design goals. For example, one requirement from the RFP might be to design a heavy, cargo aircraft that can fly long distances. Another requirement given by ultimate aircraft purchasers might be that the aircraft be able to takeoff and land at most airports. While those two requirements don't directly reference the same metrics, a closer look at them shows the conflicting trade-off of designing an aircraft that can carry a heavy load a long distance (requiring a longer takeoff and landing field length) and an aircraft that can land at most airports (limited to average runway distance for takeoff and landing). This coordinated perspective of the design requirements would come from the detailed requirements analysis as well as the designer's intuition from prior experience.

The tasks in the authoritative text are specified in an ordered and hierarchical manner. Additionally, the high-level tasks were defined such that the subtasks have a cross-disciplinary decision-making aspect to their completion. For example, within the phase to "Determine initial configuration and layout of aircraft," the designer examines factors from structures, aerodynamics, propulsion, and landing gear design. The simultaneous completion of these tasks requires designers to exchange information about the design as the work through the mathematical models. It also integrates the designers' thinking to brainstorm across the discipline boundaries, instead of working within one boundary before moving to the next discipline.

The information that is shared between within and across discipline tasks is exchanged using metrics. An analysis of the metrics within the authoritative text concluded that there are 44 ‘critical metrics’ that share the most information across tasks (Table 6 and Table 7). These metrics influence decisions in a range of disciplines, including aerodynamics, structures, stability, and cost. Further, weight and velocity were seen to have the greatest impact, with influences in most tasks. Several of these metrics not only share information across tasks, but they also share information within the tasks.

Another interesting component of the metrics is the type of metrics and when they are determined. Some metrics are brought into the process through the requirements definition phase, while others are calculated using mathematical modeling or decided during the design process. Those that are brought into the design process through the requirements must be maintained at a consistent value from start to finish, unless the original value is being improved on. Those that are calculated have to be analyzed to see how their calculation impacts the design process and monitored for when their estimates can be refined.

However the metrics are brought into the design process, they must be kept consistent across the disciplines. This could be seen in the high-level tasks with simultaneous subtasks as well as in the optimization phase of design. As more information about the design is gathered, older information must be updated to reflect the design decisions.

Finally, the decisions in the authoritative text’s design process are outcomes of the design tasks. The decisions made in the design process must have a justification for their reasoning.

3.4 Summary

In this chapter, the previously developed framework was used to characterize constructs of design knowledge coordination in the conceptual design process. An authoritative text of conceptual design was used to identify indicators of design knowledge coordination in aerospace engineering. This section of the research answers research question 1: To what extent does AE design require coordination and integration of knowledge about a design?

By providing indicators of design knowledge coordination within an authoritative example of the aerospace engineering design, this chapter (1) isolates factors in the conceptual design process that support design knowledge coordination and (2) creates a model of comparison suitable for evaluating novice strategies for design knowledge coordination. The next portion of this research compares the authoritative text's implicit design knowledge coordination with indicators of design knowledge coordination exhibited by novice aerospace engineering designers in a capstone design course.

CHAPTER 4 - DESIGN KNOWLEDGE COORDINATION BY NOVICE AEROSPACE ENGINEERING DESIGNERS

This chapter will answer the second research question: How do novice aerospace engineers coordinate and integrate knowledge about a design? In the previous chapters, a framework of design knowledge coordination was presented and subsequently used to characterize the conceptual design process described in authoritative texts in aerospace engineering education. This chapter in contrast applies the framework to describe and evaluate novice aerospace engineers' strategies for design knowledge coordination.

4.1 Research Design and Method

A multiple case study method was employed using observations of student teams (Yin, 1994). This examination characterizes the presence of specific behaviors within a given context. This is both a strength and a limitation of the research method, as this framework is applied to observations of authentic behaviors, but, thus, also subject to the idiosyncrasies of the studied institution and the teams observed (Case & Light, 2011). This approach can be contrasted to the positivist perspective where an evaluation is made of the general application of a specific intervention. Such an evaluation typically entails a randomized, controlled study that demands controls on the participants' environments and tasks that were not possible in this research.

To structure and systematize this method, the framework developed in Chapter 2 is again applied here. Specifically, the goals, tasks, metrics, and design decisions employed by the student teams are identified overall, with particular attention to those that serve as observable indicators of design knowledge coordination (or indicators of a basic design approach lacking in coordination). This characterization of observed behavior is then compared to the characterization of conceptual design in authoritative texts established in Chapter 3.

4.1.1 Site and Sample

The research was conducted with students and instructors participating in an aerospace engineering senior design capstone course at a large public, research institution. The senior design capstone course spanned two-semesters, fall 2014 and spring 2015. The data incorporated in this section of the thesis primarily focuses on student teams' observed design process in the spring semester's collaborative design project.

As described by the department handbook, the purpose of the capstone course is to develop an understanding of design methodology through lectures and applications. The course largely follows the aircraft design process laid out in Roskam (1990). Prior to taking the two course sequence, the students have completed the majority of coursework required for degree completion in six technical areas: aerodynamics, propulsion, structures and materials, structural dynamics and aeroelasticity, fluid mechanics and control, and performance and design.

In the first, fall, semester of the course, the students had individually completed four mini-projects related to aircraft sizing and layout, with each assignment building on content from previous assignments. The mini-projects and final design report followed a Request for Proposal (RFP) specified by the American Institute of Aeronautics and Astronautics (AIAA) Undergraduate Individual Aircraft Design Competition. The RFP asked students to individually design an uninhabited long range strike vehicle. The five projects were distributed throughout the semester and progressed with a lecture schedule established by the co-instructors. The AIAA RFP for this individual design competition is in Appendix C.

The second, spring, semester of the course observed here incorporated a team design project and followed the requirements specified by a different AIAA Undergraduate Team Aircraft Design Competition. This challenge asked students to collaborate within their team to design a conceptual layout of a next generation airlift military support. The AIAA RFP for the team design competition is also in APPENDIX C. The student teams were encouraged, but not required, to submit their project to the national AIAA design competition.

Fifty-one students were registered for the capstone design course at the start of the fall 2014 semester, and all students agreed to participate in the full study. At the start of the spring 2015 semester, the students self-selected design teams, resulting in eight design teams ranging in size from six to eight team members. Three of the eight teams were selected in consultation with the course instructors as illustrative case studies of different approaches to design.

In this spring semester, the student teams primarily worked independent of formal course instruction. Material that was not covered in the fall semester lectures, such as cost analysis, subsystem layout, and computational fluid dynamics, was included in a small number of hour-long lectures spread throughout the spring semester. Most of the students' activities focused on their design activities. The student teams met with the instructors weekly for 30-45 minute informal design reviews. At the midpoint of the semester, a midterm design review based on an hour-long student presentation provided an explicit point where instructor feedback was given. Likewise, a final design review was conducted at the end of the semester with an hour-long presentation followed by instructor feedback. The students were given a week to incorporate the instructors' feedback into their final report detailing the aircraft design. The final, written design report for each team was submitted at the end of the semester.

4.1.1.1 Team Selection

The eight design teams were initially down-selected to five teams at the start of the second, spring semester using three indicators. First, as an indicator of aggregate team performance, the course grade in the previous fall semester was calculated using the guidelines from the syllabus. The students' grades were based on a weighted average of four mini-projects and a final project. The course average weighted the four mini-projects as 70% of the overall course grade and the final project as 30% of the overall course grade:

$$Course\ Grade = .7\left(\frac{Score_{p1} + Score_{p2} + Score_{p3} + Score_{p4}}{4}\right) + .3\left(Score_{Final\ Project}\right)$$

Each team's average course grade was calculated by summing the team member's individual scores and dividing by the number of team members.

Second, individual students' course grade in the previous fall semester was used to determine the number of 'high' and 'low' performing students on each team in the spring semester. A student was considered 'high performing' if their course grade was in the top quartile of overall course grades and 'low performing' if their course grade was in the bottom quartile of overall course grades. The top quartile was determined for those students who had a course grade higher than 87.5%. The bottom quartile was determined for those students who had a course grade lower than 71.5%.

Third, indicator of external factors that impact team motivation was determined using students' submission (or non-submission) to the AIAA Undergraduate Team Aircraft Design Competition. The project for the spring semester was based on the AIAA's Undergraduate Team Aircraft Design Competition. Thus, students were encouraged, but not required, to submit their final project to AIAA's national competition. Three of the eight teams in the senior design course declared at the start of the second, spring semester that they would submit their final project to the AIAA competition. One of the teams that chose to submit their design to the national competition was included in the case study analysis. The other two observed teams did not submit their project to the national competition.

Table 15 details the three selection criteria: each team's average course grade, the percentage of team members in the top and bottom quartiles, and their participation (or non-participation) in the AIAA competition. The Teams 1-5 were originally selected for observation throughout the spring semester. Teams 1-3 were further down selected for inclusion in the detailed case study analysis using input from unstructured interviews with the instructors.

Table 15. Teams in dark grey were included in full case study analysis. Teams in light grey were observed, but not included in the analysis.

Team Number	Number of Team Members	Average Course Grade in the Fall	Low	High	Participating in AIAA National Competition
Team 1	7	85.8	14%	57%	No
Team 2	6	76.7	33%	50%	Yes
Team 3	6	80.6	17%	0%	No
Team 4	6	68.7	50%	17%	No
Team 5	6	86.9	17%	33%	Yes
Team 6	6	85.1	17%	33%	No
Team 7	6	81.2	17%	0%	No
Team 8	8	78.7	38%	38%	Yes

In summary, the teams that were selected represent the highest and lowest scoring teams in the previous fall semester, as well as the teams with the highest and lowest percentage of ‘high’ and ‘low’ performers in the previous fall semester. The selected teams also include teams with the declared motivation to enter the AIAA national competition.

4.1.1.2 Team Demographics

At the start of the Fall 2014 semester, the students were given a brief survey where they were asked to list their gender and ethnicity as well as outline any prior design experiences, work experiences, or undergraduate research. Their responses are shown in Table 16.

Table 16. Description of team demographics

	Total # Members	#Females	#African American or Hispanic Members	# With Prior Design Experience	# With Industry or Undergraduate Research Experience
Team 1	7	2	2	2	7
Team 2	6	0	0	2	3
Team 3	6	1	2	1	5

Pertaining to demographics, Team 1 and Team 3 had a fairly diverse team composition, with both women and underrepresented minorities participating on the teams. The students with previous design experience noted that they participated in the aerospace engineering department's Design, Build, Fly club. The Design, Build, Fly club participates in an annual competition to design and fabricate an unmanned, radio controlled aircraft. The students with industry experience traditionally participated in the university co-op or internship program.

4.1.2 Data Collection

The data were collected with approval from the Institutional Review Board (see Appendix D). The data collected included video and audio recordings of two formal design reviews for each team (mid-semester and end-of-semester) as well as observer notes recorded at weekly informal design reviews, and observer notes from one observation of an outside class team-meeting. The first formal design review was a midterm evaluation of student teams' progress. The midterm review consisted of a 30-45 minute presentation and, if there was time, was followed by questions and feedback from the instructors. The midterm evaluation was not graded and was an opportunity for the students to get formative feedback on their aircraft design. The midterm design review also gave the instructors a qualitative understanding of which teams were on-track with their aircraft design and which student teams were underperforming. The students were told ahead of the presentation that they would ideally achieve a specific stage of design prior to the midterm. Those that had not reached that stage of design, or had reached that stage with a poor aircraft design, were considered under-performing teams. The midterm presentations were both videotaped and audio recorded. Additionally, any presentation materials (e.g. PowerPoint presentations) were gathered for the data collection.

The second formal design review was a final evaluation of the student teams' design. This was also the last opportunity for the instructors to give the design teams formative feedback about the aircraft design before the students submitted the final report. This review consisted of a 45-60 minute presentation and, if there was time, was followed by questions and critiques from the instructors. The final design review was not formally graded using a rubric, but instructors did use this presentation as an opportunity to provide critical feedback that students were expected to incorporate in their final design project report. Presentations were both videotaped and audio recorded. Additionally, any presentation materials were gathered for the data collection.

In addition to the two formal design reviews, the student teams met with the instructors on a weekly basis to give an informal update on their aircraft design progress. The researcher recorded observation notes during these informal reviews. The researcher also attended one outside team meeting where the instructors were not present. The researcher noted the general method for organizing the meeting, the team members who organized and managed the team progress, and typical team meeting practices. By attending one of these meetings, the researcher was able to gain insights on how the team coordinated their design process independent of instructor influences. Table 17 has a brief summary of the data that was collected and Table 18 has a list of the identifiers used for the team members and instructors, which does not reflect their actual names.

Table 17. Detailed overview of analyzed design discussions

Meeting	Meeting Purpose	Data Type
Midterm Design Review	Formative feedback from the instructors at the midpoint of the semester	Video, Audio, Transcript, Presentation Slides
Final Design Review	Project evaluation and formative feedback from the instructors at the end of the semester	Video, Audio, Transcript, Presentation slides
Weekly Informal Reviews	Weekly progress updates on the student teams' aircraft designs. Instructors provide formative feedback on incremental progress.	Observer notes
Outside Class, Team Meeting	One team meeting outside of class time, where the instructors were not present. In general, the teams discussed team members' progress on design tasks and any issues that might have arisen within completing the tasks.	Observer Notes

Table 18. Identifying names for course instructors and team members

Entity	**Name**
Instructors	August, Rusty
Team 1	Rocco, Astrid, Damien, Mauro, Rachel, Spencer
Team 2	Buck, Calvin, Gary, Maximo, Ward
Team 3	Alexandra, Asa, Demitri, Garth, Peter, Sanford

4.1.3 Data Analysis

In analyzing the presentations, an a priori coding scheme was used to code the presentation transcripts and project artifacts, including the design review presentation slides. The a priori coding scheme follows the same framework for coordinating design knowledge, developed in Chapter 2.

Table 19. Coding scheme for classifying designers' structured approach to engineering design

Constructs of Design Knowledge	Details
Goal	Derived from the project users and/or requirements and are used to direct engineering tasks.
Tasks	Dictate the direction and future content of overall work within the complex engineering design process
Metrics	Representation of information about the design that is available to or needed by the designer
Decisions	Outcome of a task

Table 19 defines the codes applied in the analysis. In coding the conversations, the researcher read through each transcript multiple times and recorded indicators of each dimension of the coding scheme as they were evident within the transcripts. The text's authoritative design process was used as a guide for the level of depth that was desired in coding the transcripts. Additionally, while the metrics were fairly evident through quoted text, the text's design process was used as a comparison to identify tasks and subtasks in the students' processes.

As an example:

> *"…we started looking into the mission profile. We looked at the RFP and we designed a mission profile so that it would fit all the requirements… Now, looking at our mission profile, you may think that some of these altitudes may seem kind of random, some these velocities may seem kind of randomly picked out of a hat, but no, they were actually calculated using different criteria. What we did was started looking at our specific range due to Mach number and our tools; we started varying that, and we saw that there was a curve with a peak. At that peak, or 'sweet spot', we determined that at Mach .78 we would maximize our range. So, we decided to use that Mach before all of our cruise segments." Rocco (Team 1, Midterm)*

Table 20 is an example of how the coding scheme is filled out in the analysis spreadsheet for this specific case. In this quote, Rocco clearly states that the subtask is to outline the "mission profile" (or the path the aircraft will be designed for). One of decisions that as made at this point included the Mach number (or velocity) of the aircraft. This metric was determined by using an analysis that incorporated the altitude and range, comparing the specific range and Mach number. Here, the decision was dependent on the teams understanding of how the Mach number and range varied at different altitudes.

Table 20. Example coding scheme

High-Level Task	Subtask	Decision	Metric
(Stated earlier in transcript) Define Mission Requirements and Outline Mission Parameters	Define Mission Profile	Mach Number	Mach Number
			Altitude
			Range
			Velocity

Interrater reliability was evaluated using two rounds of comparison analysis. The first interrater reliability analysis compared the codes of two researchers, the primary researcher and a second researcher. The second researcher was familiar with qualitative coding research methods and was asked to code two of the transcripts (Team 1 final design review and Team 3 midterm design review) for evidence of student 'metrics.' Before starting their analysis, the researcher was given a statement describing what constitutes as a 'metric':

> *Metrics are a representation of information about the design that is available to or needed by the designer. Metrics are identified as more information is revealed about the design. Some examples of metrics in the design of an aircraft are: mean takeoff weight, coefficient of lift, figures of merit, and wing span.*

The first interrater reliability analysis resulted in a 37% agreement rate. The differences were discussed among the two researchers. The primary differences in coding were related to the level of depth that was expected. The primary researcher was very detailed, noting items such as multiple uses of the same metric in different tasks as well as various forms of the same metric (e.g. Mach number and maximum Mach number). 91% of the coding differences were attributed to a metric (or detailed distinctions of the same metric) being omitted by the second researcher. The second researcher was not aware of the level of depth required by the analysis. Once the common understanding of depth within the coding scheme was achieved, agreement was reached on all of the differing codes.

Due to the low reliability of the first analysis, another interrater reliability analysis was conducted with a third researcher. In this evaluation, the outside coder was initially given the authoritative text design process as a representation of the level of depth and type of analysis that was desired. The researcher was given the same two transcripts as the first reliability check (Team 1 final design review and Team 3 midterm design review). In the second interrater reliability analysis, the two researchers achieved a level of 90% agreement across two transcripts when coding for metrics. The differences were discussed until agreement on all codes was achieved.

This third researcher also coded for identifiable tasks in the transcripts. Compared with the primary researcher 85% agreement was achieved. Differences were discussed until agreement was reached.

As the observations and analysis were completed, a research notebook was maintained and any high-level themes that emerged throughout the research period were recorded. Finally, peer debriefing with multiple research partners offered an opportunity to discuss any researcher bias within the results and any competing hypotheses.

After the completing the detailed coding of transcripts, a high-level analysis examined indicators of design knowledge coordination. Specifically, the framework developed in Chapter 2 (reprinted in Table 21) was used to examine the teams' goals tasks, metrics, and design decisions for indicators of design knowledge coordination. Throughout the next part of this chapter, this framework will be used to guide descriptions of each teams' design process, compared to the authoritative text's design process, as well as to comparisons between teams.

Table 21. Framework for characterizing design knowledge coordination within an engineering design process

	Basic Approach	Discipline-Oriented Approach	Coordinated Approach
Goal	Defines a general design goal	Design goals are decomposed into more specific goals for each discipline	Identifies trade-offs between discipline-oriented design goals
Tasks	Defines tasks and subtasks Incorporates an order and hierarchy to task decomposition	The tasks and subtasks have an order and hierarchy that align with engineering disciplines	Recognizes the links between tasks and subtasks Iterates across the tasks to update information about the design
Metrics	Uses metrics to complete tasks and subtasks	Within each discipline, there are critical metrics guiding the decisions and tasks	Maintains consistent values for metrics across the different disciplines
Decision	Justifies decisions through completion of design tasks	Decisions are justified through discipline-oriented metrics	Describes the overall impact of a particular decision Incorporates a variety of metrics from other disciplines to justify decisions

4.2 Observable Indicators of Novice Engineers' Design Knowledge Coordination

Qualitative coding of the three teams' transcripts and artifacts identified the observable indicators of the student teams' design knowledge coordination. This section details these indicators for each of the three teams.

4.2.1 Team 1's Design Knowledge Coordination

Overall, Team 1 mostly used a coordinated approach similar to that in the authoritative text (Table 22). For the observed tasks, metrics, and decisions, Team 1 continuously leveraged a coordinated approach to describing their process and making integrated decisions. However, the goals were not as coordinated in that Team 1 failed to reference multi-disciplinary and cross-task trade-offs within their goals. The full set of data from the observation and analysis of Team 1 is located in Appendix E. This section describes key themes in this team's design process.

Table 22. Overview of Team 1's approach to design knowledge coordination in the conceptual design process

	Summary of Observations	Categorization of Design Knowledge Coordination
Goals	Integrated goals into the decision making process within specific disciplines and tasks, but did not consider trade-offs of goals across disciplines and tasks	Discipline-Oriented Approach
Tasks	Followed a cross-disciplinary, hierarchical task breakdown and aligned tasks in the authoritative text	Coordinated Approach
	Incorporated an integrated approach to task completion through metric use to link disciplines together	
Metrics	Used a variety of metrics and explained their reasoning for including specific metrics in their analysis in a cross-disciplinary context	Coordinated Approach
Decisions	Justified decisions using both quantitative mathematical modeling and qualitative consideration of trade-offs between design options	Coordinated Approach

Team 1 integrated goals into the decision making process within specific disciplines and tasks, but did not consider trade-offs between goals across disciplines and tasks

Team 1 primarily evaluated the goals within particular disciplinary boundaries. They did not evaluate the trade-offs between these goals across the disciplines. After recognizing the quantitative performance goals given by the RFP. Further, goals that were discussed in a multi-discipline and integrated perspective were typically qualitative and difficult to verify if they had been met.

Team 1 used the project RFP to define verifiable goals for project completion. These goals established quantifiable requirements that must be met for successful aircraft design and were primarily performance-based. Throughout their design process, the team referenced these requirements within design subtasks as a benchmark for design decisions, inputs to the mathematical model, and metrics such as wing area and takeoff weight. When stating their requirements, Team 1 framed them in the same language as the RFP:

> *"So, a really quick summary of what RFP is, so I'm just going to hit a couple of the high points that we are going to talk about during our presentation. We are designing next generation strategic airlift military transport, that will go into service in 2030. They are requesting from us that we build 120 units. The RFP says that we need to have a maximum range of 6300 nautical miles, with a payload of 120,000 pounds. The maximum takeoff of payload should be 300,000 pounds, and we should be cruising at a Mach number of at least 0.6. Another important requirement is that we need to take off in a field length of most 9000 feet, and the other very important requirement is our cargo capacity. We are instructed that we should carry 44,463 liter master pallets, or one Wolverine Heavy Assault Bridge. We'll talk about how we hit most of these requirements, all of these requirements, as we go through the presentations," Rocco (Team 1, Midterm Presentation)*

Throughout the presentation, eight performance requirements were explicitly used as metrics by Team 1: cargo carried, payload weight, CLMax, flight altitude, Mach, range, and takeoff field length. Of those performance-based metrics, two were used outside of the performance analysis. Both the payload weight and the takeoff field length were used in the performance analysis and in analyzing the propulsion system capabilities. Other, non-performance-based, requirements, such as the number of aircraft to be built, the entry into service date, and the cost of the aircraft, were used across disciplines to examine technology integrations and system costs.

As an example of a performance-based requirement, in determining the wing loading value (which then leads to determining the wing area), the team referenced the takeoff field length goal that was stated in the RFP, "We were trying to keep within the takeoff field length of 9000 ft. that was required by the RFP," Rocco (Team 1, Final Presentation). As another example, Team 1 evaluated their aircraft's performance capability by constructing a Payload-Range diagram. Construction of the diagram and evaluation of the aircraft's capabilities were done by considering the maximum and nominal payload weights as well as the nominal mission range:

> *"So, we started off at a maximum payload of about 300,000 pounds from the RFP, and as we move further to the right, we continued to decrease the payload as we increased the fuel, until we reach a maximum range of about 8300 nautical miles with no payload on our aircraft. One of the requirements from the RFP was that we would have to fly about 6300 nautical miles, with a 120,000 payload, which is what is shown in the red dot right there," Astrid (Team 1, Final Presentation)*

Outside of the RFP, Team 1 also incorporated goals determined from a Stakeholder Analysis. These goals set the preferences of the customer and generally focused on qualitative indicators of success, such as designing an aircraft that was 'more efficient' and at 'lower cost':

> *"We wanted to figure out exactly what was important to these stakeholders, and how important these particular things were. So, we put up a list, and we started ranking them again, one through five, to try and determine what our main driving factors are going to be. Just like before, we determined that the cost, the storage, the maintenance—these were some of the key players on our design." Rocco (Team 1, Final Presentation)*

While the quantitative requirements, defined using the RFP, were used as verifiable indicators of a successful design, it was more difficult to verify if the qualitative requirements were satisfied. Often, the students would state that a technology or other improvement would meet an abstract aspect of the stakeholder's preferences. However, the stakeholders' preferences were largely omitted from making design decisions and instead used to justify a decision after it had been made:

> *"Then, we're going to replace the hydraulic actuators in our aircraft to electromechanical actuators. This would help to reduce maintenance costs, but we'd also have a drawback of increasing operation costs. Just in general, the benefits from using these different types of technologies was that we'd be reducing drag of our aircraft, improving fuel efficiency, and in some cases reducing the total weight of the aircraft, but with a few drawbacks of increasing costs which we'll tell you about later into the cost analysis process, and maybe increasing the complexity of some of the systems." Damien (Team 1, Final Presentation)*

In the previous quote, Damien comments that the general benefits are "reducing drag…improving fuel efficiency, and…reducing the total weight." These improvements in the design are related to quantified aircraft performance and could be verified through mathematical models. Conversely, the drawback of "increasing the complexity" is implicitly related to stakeholder preferences and is a qualitative indicator of aircraft design. The complexity of an aircraft's design is difficult to verify without first operationalizing.

Team 1's tasks followed a cross-disciplinary, hierarchical breakdown and aligned with the tasks in the authoritative text

In comparing the authoritative text's tasks to Team 1's tasks (both midterm and final presentation task models), Team 1 closely matched the authoritative text's task breakdown, as shown in Table 23. The primary differences are in the level of detail within high-level tasks. For example, in the configuration task, the students performed an additional task to identify stakeholders and integrate their considerations into their design requirements. The text did not examine stakeholder concerns (Coso, 2014). On the other hand, the text includes a task with a detailed component breakdown to estimate the aircraft weight. However, Team 1 did not complete this step of the design process. They did iterate on the aircraft's weight as they gained more information about the design.

Table 23. Task outline of Team 1 compared to the authoritative model

Team 1		Authoritative Design Process	
Task	**Detailed Task**	**High-Level Task**	**Detailed Task**
Define Requirements	Outline Aircraft Requirements	Define Requirements & Outline Mission	
Select Aircraft Configuration	Identify Stakeholders and Needs		
	Preliminary Configuration Selection		Overall Configuration Selection
Outline Mission	Outline Mission Profile		Outline Mission Requirements
	Sensitivity Studies		Sensitivity Studies
Initial Aircraft Sizing	Historical Weight Regression	Initial Aircraft Sizing	Historical Regression of Weight
	Select technologies		Technology Selection
	First Weight Estimate		First Weight Estimate
	Class I Drag Polar	Determine Critical Performance-Based Metrics	Estimate Drag Polar
	Class II Drag Polar		
	Constraint Sizing		Evaluate Aircraft Constraints
Determine Initial Configuration and Layout of Aircraft	Size Fuselage	Determine Initial Configuration and Layout of Aircraft	Fuselage Layout
	Size Cargo Bay		
	Wing Configuration		Wing Planform Shape
	Airfoil Selection		Airfoil Selection
	Select High-lift Devices		High-Lift Devices
	Preliminary Sizing of Empennage		Preliminary Sizing of Empennage
	Calculate weight and Balance (CG Build-up)		Locate Component CG
	Design landing gear		Preliminary Landing Gear Configuration
	Select engine		
Conduct a performance analysis	Payload/Range diagram		
		Improve Aircraft Weight Estimation and Configuration	Class II Weight Estimation
	V-ndiagram		V-n Diagram
	Calculate stability and control	Conduct a performance analysis	Analyze Aircraft Stability
	Choose subsystems		
	Structure & Manufacturing		Structural Arrangement
	Perform Cost analysis		Perform Cost Analysis
	Finalize 3-D Model & Three-View		Finalize 3D Model and Three-View

By following the authoritative text's task division, Team 1 integrated disciplines within the high-level tasks through the subtasks. For example, an alternate approach might have been to isolate "Aerodynamics" as a task and have all the subtasks work toward an aerodynamic decision, such as the airfoil design or high-lift devices. However, this separation would make it more difficult to integrate cross-disciplinary considerations when evaluating design decisions. By instead imbedding "aerodynamics" in a high-level task for determining the entire aircraft configuration, Team 1 was able to integrate considerations from multiple areas of design into their decision-making process.

One approach to integrating cross-disciplinary concerns and coordinating design decisions is by aligning team member responsibilities with tasks and disciplines. Team 1 aligned member responsibilities along discipline boundaries (Table 24). Because of their task breakdown, this division meant that individuals were working together across discipline boundaries within each task. The format of Team 1's meetings also supported this approach. The team met three times a week for two hour blocks, and would jointly work on tasks, instead of working on them independently outside of meetings. Any questions that arose while working on a task could be answered in real time as the task was being completed. The team member responsibilities evolved slightly throughout the semester as the team grew to learn more about the project and the required activities for completing the project. However, the team consistently identified member roles along general task and discipline boundaries in both the midterm and final design reviews.

Table 24. Breakdown of Team 1's member roles as described in the midterm and final presentations

Name	Midterm Responsibility	Final Responsibility
Rocco	Team Leader	Team Leader
Spencer	Aerodynamics	Subsystems/Aerodynamics
Rachel	Structures	Structures
Astrid	Propulsion	Chief Engineer
Emmett	Aerodynamics	Aerodynamics
Mauro	Systems	Cost Analysis/Technologies
Damien	Weight and Balance	Weight & Balance

Team 1 incorporated an integrated approach to task completion through metric use to link together disciplines.

An important component of design knowledge coordination within the AE design process is being able to view the process as integrated, rather than a piecewise and siloed process with each task being isolated from the other tasks. In describing their process, Team 1 made explicit links between the tasks by using prior tasks and decisions as a foundation for moving to a new task. For example, in the midterm presentation, Team 1 noted moving from a subtask where the selected the aircraft's Mach number, to using that Mach number in the next subtask to select the aircraft's altitude: "And then, we took that Mach number, we did another trade study for altitudes," Damien (Team 1, Midterm Presentation). Thus, in the design review presentations tasks were described as an integrated process rather than in isolation.

Another way of incorporating an integrated and coordinated perspective in the design process is to use common metrics between the tasks. These common and shared metrics maintain consistent information about the design as well as connect cross-disciplinary considerations when making design decisions. These metrics can be shared within disciplines or across disciplines. In a coordinated process, metrics are shared across disciplines. Team 1 repeated 23 metrics across disciplines (Table 25) in both the midterm and final presentations. Seventeen of these 23 metrics are the same as the authoritative text's shared metrics. All of the metrics that are repeated are listed in Appendix E, with a breakdown of the disciplines. For example, in both the midterm and final presentation, the Mach number and coefficient of lift used in multiple tasks. These values are critical indicators of aircraft performance and indicate if the design meets performance requirements. Many other metrics that are used within multiple tasks represent a general description of the aircraft and aircraft performance, rather than being limited to a specific discipline. The wing area is a design parameter initially that is determined by a detailed analysis of aircraft requirements and constraints. Later, the wing area is used to determine make other decisions, such as the type of airfoil and inclusion of a system to enhance aircraft stability and maneuvering.

Table 25. Critical metrics shared across two or more disciplines by Team 1

Critical metrics	# Shared Disciplines	Included in Authoritative Text
Weight (Empty, Components, Technology, Payload, Takeoff, Requirement)	6	X
Altitude	5	X
Cost (O&S, Maintenance)	4	X
Mach	4	X
Area of Wing	3	X
Cargo	3	
Center of Gravity	3	
Coefficient of LIft (CL, CLMax, CL Landing)	3	X
Efficiency of Fuel Burn	3	
Range	3	X
Specific Fuel Consumption	3	X
Takeoff Field Length	3	X
Technology Factor	3	
Anhedral of Wing	2	
Angle of Attack	2	X
Entry into Service	2	
Fuel Fraction	2	X
Length of Fuselage	2	X
Rate of Climb	2	X
Thrust	2	X
Velocity	2	X
Wing Loading	2	X
Wing Span	2	X

Team 1 used a variety of metrics to explain their design process and explained their reasoning for including each metric

Team 1 references 341 metrics combined over the midterm and final presentation (Table 26). Of these metrics, 45 of them are acknowledged in the students' slides but not verbally described or explained. Of the 45 metrics that aren't verbally referenced, 42 metrics are in the final presentation and are related to very detailed design information, such as specific airfoil criteria and landing gear load limits. The metrics that are verbally referenced in the presentations are associated with a variety of disciplines, design tasks, and design decisions. Most of these metrics are used to describe the process by which the students used to justify a particular decision. Other metrics reference design goals and requirements. A third group of metrics reference design information about common aircraft that can be used to compare Team 1's aircraft decisions. Fifty of the metrics are information about similar aircraft design parameters.

Table 26. Number of metrics by Team 1's presentation

Total Number of Metrics Referenced Overall	341
Number of Metrics Referenced in the Midterm	146
Number of Metrics Referenced in the Final	279
Number of Metrics Referenced in Both the Midterm and Final Presentation	84

Team 1 matches 79 of the authoritative text's 389 metrics, or 20.6% of the authoritative text's metrics. Of those metrics that aren't referenced by Team 1, several of the metrics are very specific to a particular aircraft's design, such as stability coefficients and the hinge moment. However, several metrics that were not referenced are critical parameters of aircraft design, such as lift to drag ratio, sweep of the wing, and takeoff aircraft weight.

Team 1 justified decisions using both quantitative mathematical modeling and qualitative consideration of trade-offs between design options

Team 1 used primarily mathematical models to justify their design decisions. With a majority of their design decisions, the team members explained their process for deriving the value, and then summarized the decision with a justification for why that value was an appropriate decision. In the following example, after calculating an optimal value for wing loading and thrust loading, the team member justified their decision by comparing the derived value to historical values from similar aircraft:

> *"So, you see from the constraint diagram, we have a design selection for aircraft of 132,000 square feet for our wing loading and 0.24 thrust loading and these are just again to compare with similar aircrafts; listed are the C5, C17, and Antonov 225. Antonov is a little bit big, but it's just to give us a rough estimate of where we stand with our vehicle," Damien (Team 1, Midterm Presentation)*

In some instances, Team 1 noted trade-offs for the decisions that they were making. Typically, these trade-offs were more qualitative in nature (e.g. increased complexity). In one instance, Rocco reasoned through not adding a more complicated pitch control system due to the complexity and cost of the system:

> *"Other solutions that we looked at and that we were considering was having a pitch feedback control system for the elevator, but that would then add complexity and cost that we thought would just be unnecessary, since the time to double was so big," Rocco (Team 1, Final Presentation)*

As another example of Team 1’s cross-disciplinary approach to decision-making, when designing the wing area from the constraint sizing task, they included a constraint outside of the mathematical model pertaining to the maximum hangar size currently available for aircraft of this type, “We looked at the wing area that we obtained from our constraint sizing and then from that, we were able to get a wing span based on hanger sizes that we looked at, and then get an aspect ratio." Damien (Team 1, Final Presentation). While their aircraft could have had a higher wing area (leading to enhanced performance), this constraint traded aircraft performance for infrastructure constraints.

4.2.2 Team 2's Design Knowledge Coordination

Team 2's approach to the design process was similar to Team 1's approach (Table 27). Team 2 selected their aircraft configuration as a more advanced 'flying wing' aircraft variant. The flying wing configuration meant that the systems were tightly integrated due to the structural integration of the wing, fuselage and empennage: the wing, fuselage, and empennage all act as one system. Thus, Team 2's design inherently required design knowledge coordination for effective design of the aircraft. The full set of data from the observation and analysis of Team 2 is located in Appendix F. This section describes key themes in this team's design process.

Table 27 Overview of Team 2's approach to design knowledge coordination in the conceptual design process

	Summary of Observations	Categorization of Design Knowledge Coordination
Goals	Imposed goals outside of the RFP that consider the context and stakeholders of the designed aircraft	Coordinated Approach
Tasks	Used a discipline-oriented approach to decomposing the tasks	Discipline-Oriented Approach
	Incorporated an integrated approach to task completion through metric use to link disciplines together	Coordinated Approach
Metrics	Used a variety of metrics, but did not always explain their reasoning for including specific metrics in their analysis in a cross-disciplinary context	Discipline-Oriented Approach
Decisions	Justified decisions using both quantitative mathematical modeling and qualitative supporting arguments, across disciplines	Coordinated Approach

Team 2 imposed goals outside of the RFP that consider the context and stakeholders of the designed aircraft

Similar to Team 1's approach, Team 2 initially discussed the requirements by outlining the performance specifications of the vehicle defined by the AIAA RFP. This discussion outlined requirements for the aircraft's range, weight, and climb conditions. The team then moved beyond the immediate requirements specified by the RFP to define requirements that are imposed by the context of the aircraft's use. These requirements considered constraints on the vehicle size due to storage capabilities: "wing-span to be less than the C5, as it's the largest span, and the air force fleet going bigger than that could require new infrastructure," Gary (Team 2, Midterm). They also discussed other requirements, such as the airport limitations and desired efficiency improvements. They also explicitly compared the vehicle to the C5 and discussed how this would replace the aging aircraft: "So with that in mind you are trying to match it or exceed all the C5 capabilities." Gary (Team 2, Midterm)

Cross-disciplinary goals were integrated throughout the design process and used to justify design decisions across discipline-oriented tasks. For example, within the aerodynamic analysis, Team 2 specified that the design of the airfoil was constrained by the size of the cargo bay, which is sized from the defined cargo dimensions:

> *"And then comes the airfoil design. Airfoil dominates the aerodynamics. And in terms of blended body airfoil design there are lots of challenges. Such as first we need to introduce the trim moment because we don't have a tail to control trim. So we need a smaller pitching down moment to help trim. Then we have physical constraints because you have to put the cargo bay inside the center body, so we need to make sure there's enough space to fit, so the tail should be designed in a specific shape, because we want to put a cargo door." Ward (Team 2, Final Presentation)*

Team 2 used a discipline-oriented approach to decomposing the tasks.

In the final presentation, Team 2 presented a discipline-oriented approach to the design process, as shown in Table 28. This approach separates high-level tasks by discipline area (Aerodynamics, Structures, Stability, Propulsion, and Primary Systems). In the observed team meeting, this structure was apparent in how the team organization was coordinated. The team leader would run through each discipline and systematically get updates on what had been accomplished. The team would discuss any issues an individual was having within their discipline and brainstorm potential solutions. After all the discipline leads had reported, the team would break apart to independently work on their tasks that were each usually focused on one discipline.

Table 28. Task breakdown presented by Team 2 in the final presentation

High-level task	Detailed-task
Identify mission objectives	Outline Aircraft Requirements
Configuration Selection& Sizing	Configuration Analysis
	Estimate Weight Trend
	Baseline Sizing
	Technology Impacts
	Sizing Update
	Constraint Sizing
Analyze Aerodynamics	Calculate Total Drag
	Baseline Aerodynamics
	Trade Studies
	Update Calculations
	Airfoil Design
	Spanwise Chord and Twist
	CFD
	Drag Polar Update
	Select Cruise Condition
	Summarize Mission
Design Advanced Propulsion System	Examine Propulsion Fuel Savings
Analyze Static Stability & Design Rudders	CG Buildup
	Sizing the Rudders
	High-Lift Devices
	Stability Characteristics
Structural Layout	Chose Materials
	I-Beam Analysis
	Cargo Bay Floor Analysis
	Load Test
	Wing Structure Configuration
Select and Design the Primary Systems	Size the Cargo Bay
	Landing Gear
	Calculate Fuel Tank Fill and Dimensions
Performance Analysis	Payload Range
	Flight Envelope: V-n Diagram
	Takeoff Performance
	Engine Out Performance
Cost Analysis	Technology Risk
	Fly Away Cost
	Operational Costs

Similar to the task breakdown in the final, the member responsibilities were divided by discipline, Table 29. These individual responsibilities shifted from the start of the semester to the final presentation. This division allowed the pairings to work within the discipline-oriented tasks. Further, the Team Lead, Gary, floated between the discipline groups and provided assistance where necessary. Often, this translated into a "wheel-and-spoke" model of project management: Gary was the center point of information, and all decisions flowed through him before moving to other team members within other disciplines.

Table 29. Team 2 member responsibilities

	Midterm	Final
Gary	Sizing/Layout	Team Lead, Stability and Control
Ward	Flight Systems, Sizing/Layout, CAD	Aerodynamics, Structures
Calvin	Structure, Flight Systems	Structures, Aerodynamics
Dane	Propulsion, Aerodynamics	Propulsion, CAD/Interiors
Buck	Aerodynamics, Structure	Stability and Control, Subsystems
Maximo	CAD	CAD/Interiors, Propulsion

Team 2 incorporated an integrated approach to task completion through metric use to link together tasks

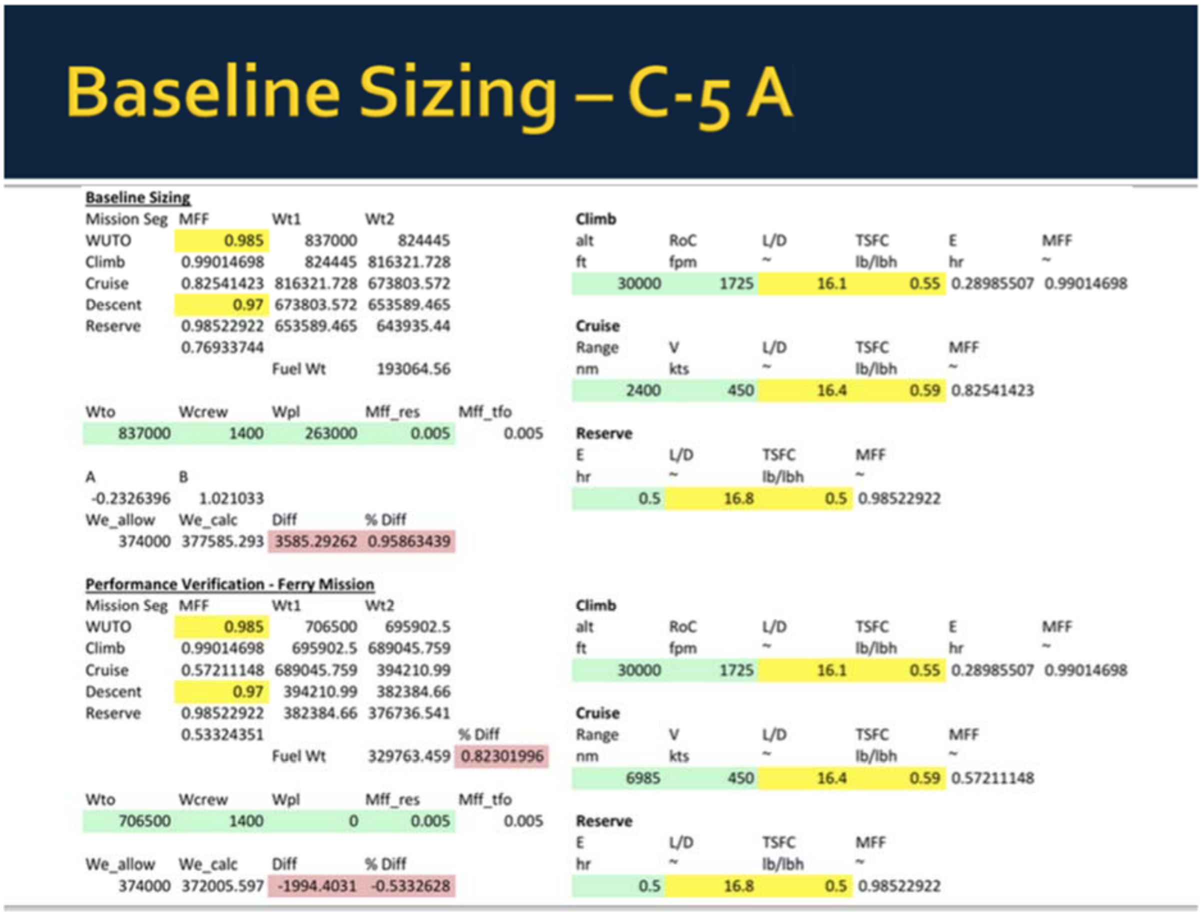
Team 2 used 27 metrics in multiple tasks (Table 30). Of those 27 metrics, 10 were the same as the authoritative text. The metrics that were repeated across tasks in Team 2's design process were less based on performance than Team 1's metrics. This is expected given the differences in tasks and design focuses: Team 2 focused on the designing separate technical components for their aircraft, such as an advanced airfoil. Another example is Team 2's reference to "Fuel Savings." This metric was used to discuss the improvement in fuel consumption from integrating new technologies. The Fuel Savings referenced the improvement from using aerodynamic technologies, structural technologies, and propulsive technologies. All of the metrics that are repeated are listed in Appendix F, with a breakdown of the disciplines.

Table 30. Critical metrics shared across two or more disciplines by team 2

Critical metrics	# Shared Disciplines	Included in Authoritative Text
Weight (W Technology, W Empty)	7	X
Cost (Flight Test, Fuel, Maintenance, Operation)	4	X
Range	4	X
Fuel Savings	4	
Coefficient of Friction	3	X
Drag	3	X
Altitude (h, h Cruise)	3	X
Lift to Drag Ratio	3	X
Mach	3	X
Takeoff Field Length	3	X
Wing Span	2	
Center of Gravity	2	
Coefficient of Lift	2	X
Cargo Bay Dimensions	2	
Entry into Service Date	2	
Figures of Merit	2	
Load Classification Number	2	
Landing Gear Track	2	
Location of Elevator	2	
Pugh Matrix	2	
Safety	2	
Spanwise Twist	2	
Tail Volume Ratio	2	
TOPSIS Output	2	
Thrust Specific Fuel Consumption	2	
Turn Radius	2	
Empty Weight to Takeoff Weight	2	

Team 2 used a variety of metrics, but did not always explain their reasoning for including specific metrics in their analysis in a cross-disciplinary context

Team 2 referenced 396 metrics combined over the midterm and final presentation. Of these metrics, 81 (20.5%) of them are in the students' review presentation slides but not verbally described or explained, notably involving a copied-and-pasted spreadsheet of the students' mathematical Excel model. Thus, Team 2 occasionally overloaded their presentation with metrics, while verbally quickly covering the high-points of the design process instead of providing an in-depth discussion of how specific values were deduced. As an example, Figure 8 shows one of the presentation slides. The mathematical relationships are shown on the slide with no explanation of how these relationships feed into the process or which values are the most important for making decisions about the aircraft.



Baseline Sizing – C-5 A

Baseline Sizing

Mission Seg	MFF	Wt1	Wt2
WUTO	0.985	837000	824445
Climb	0.99014698	824445	816321.728
Cruise	0.82541423	816321.728	673803.572
Descent	0.97	673803.572	653589.465
Reserve	0.98522922	653589.465	643935.44
	0.76933744		
		Fuel Wt	193064.56

Wto	Wcrew	Wpl	Mff_res	Mff_tfo
837000	1400	263000	0.005	0.005

A	B
-0.2326396	1.021033

We_allow	We_calc	Diff	% Diff
374000	377585.293	3585.29262	0.95863439

Climb

alt	RoC	L/D	TSFC	E	MFF
ft	fpm	~	lb/lbh	hr	~
30000	1725	16.1	0.55	0.28985507	0.99014698

Cruise

Range	V	L/D	TSFC	MFF
nm	kts	~	lb/lbh	~
2400	450	16.4	0.59	0.82541423

Reserve

E	L/D	TSFC	MFF
hr	~	lb/lbh	~
0.5	16.8	0.5	0.98522922

Performance Verification - Ferry Mission

Mission Seg	MFF	Wt1	Wt2	
WUTO	0.985	706500	695902.5	
Climb	0.99014698	695902.5	689045.759	
Cruise	0.57211148	689045.759	394210.99	
Descent	0.97	394210.99	382384.66	
Reserve	0.98522922	382384.66	376736.541	
	0.53324351			% Diff
		Fuel Wt	329763.459	0.82301996

Wto	Wcrew	Wpl	Mff_res	Mff_tfo
706500	1400	0	0.005	0.005

We_allow	We_calc	Diff	% Diff
374000	372005.597	-1994.4031	-0.5332628

Climb

alt	RoC	L/D	TSFC	E	MFF
ft	fpm	~	lb/lbh	hr	~
30000	1725	16.1	0.55	0.28985507	0.99014698

Cruise

Range	V	L/D	TSFC	MFF
nm	kts	~	lb/lbh	~
6985	450	16.4	0.59	0.57211148

Reserve

E	L/D	TSFC	MFF
hr	~	lb/lbh	~
0.5	16.8	0.5	0.98522922

Figure 8. Presentation slide from Team 2 midterm presentation

Team 2 matches 90 of the authoritative text's metrics, or 23.4% of the authoritative text's metrics (Table 31). Some of the metrics that matched between the two samples include the lift to drag ratio, Mach number, multiple cost factors, the coefficient of drag, the span of the wing, and the takeoff weight. These metrics represent general information about the design that characterize performance capability and outline the aircraft design. Team 2 made a concerted effort to include a detailed aerodynamic analysis in their design process. Thus, many aerodynamic metrics are included in the analysis and were used throughout the design process.

Table 31. Number of metrics by Team 2's presentation

Total Number of Metrics Referenced Overall	349
Number of Metrics Referenced in the Midterm	165
Number of Metrics Referenced in the Final	259
Number of Metrics Referenced in Both the Midterm and Final Presentation	75

Team 2 justified decisions using both quantitative mathematical modeling and qualitative supporting arguments across disciplines

Team 2 framed their decisions within the mathematical model of aircraft performance and justified their decisions using a combination of historical data and qualitative information. Many of the decisions that Team 2 presented were followed by a qualifier that explained why that decision was appropriate:

> *"So we have to choose our own design mission. We use the payload of 300,000 pounds and for range of 3500 nautical/miles and this is a nice number because one it exceeds the max payload range of C5, which is just shy of 3000 nautical/miles and 3500 is the distance that the airports uses for en route planning which includes island hopping in the pacific," Gary (Team 2, Midterm Presentation)*

In this example, Gary discussed the team's decision for a range of 3500 nautical miles. This decision is justified through an understanding of distances that aircraft would have to fly on a typical route. In another example, the team discussed how their values differ from traditional values. They justified their reasoning by pointing to the advanced technology, composites that they are integrating in their aircraft: "We have each [rib at] 50 inches in pitch, traditional aircraft with aluminum, typically between 18 to 22 inches. Composite materials are stronger and light weight so you can spread them out some more." Calvin (Team 3, Final Presentation). The justifications of these decisions are rooted in the immediate impact of each design decision.

The team also discussed the larger impact of decisions by integrating cross-disciplinary considerations. For example, when designing the cargo bay, Team 2 discusses how the length of the cargo bay will impact the stability analysis. They ultimately chose to incorporate a longer fuselage to mitigate negative stability effects, "We chose a longer configuration as opposed to a wider configuration, which is used by NASA's analysis, because we thought that having a longer cargo bay would help us if we wanted to move the wings forward and back for CG balancing," Maximo (Team 2, Final Presentation)

4.2.3 Team 3's Design Knowledge Coordination

Team 3 had a basic approach to the design process with low evidence of design knowledge coordination (Table 32). When dividing their project into tasks, Team 3 had trouble creating a hierarchical structure to the task decomposition and recognizing how decisions could be imbedded within high-level tasks. Additionally, Team 3 strictly followed a prescriptive method to design, which often made their approach tightly structured with little integrated decision-making. The team was able to reference a variety of metrics in different disciplines, but failed to connect those metrics to their overall cross-disciplinary decision-making process. The full set of data from the observation and analysis of Team 3 is located in Appendix G. This Appendix has the full detailed design process, as well as evidence for the tasks and decisions that were identified in the design process. This section describes key themes in this team's design process.

Table 32. Overview of Team 3's approach to design knowledge coordination in the conceptual design process

	Summary of Observations	Categorization of Design Knowledge Coordination
Goals	Defined a generic design goal, but did not perform a detailed requirements analysis or integrate goals into decision-making process	Basic Approach
Tasks	Task breakdown lacked clear organization and hierarchy	Did Not Meet Criteria for Basic Approach
	Did not show a strong connection between tasks	
Metrics	Referenced metrics as an indicator aircraft performance and capabilities within tasks, but did not fully explain metric's in the context of the design problem	Basic Approach
Decisions	Did not justify decisions or explain their decisions in context of the aircraft design.	Basic Approach

Team 3 did not perform a detailed requirements analysis or integrate goals into decision-making process

Similar to the other two teams, Team 3 discussed the RFP as the primary source of information for determining their project goals:

> *"First off is the RFP summary and mission requirements. Our design objective is to design a strategic aircraft airlift military transport with an assumed entry into service of 2030. We have two key requirements. The first one is 120,000 pound payload over a 6300 nautical mile range. And the second requirement is to carry a 300 000 pound payload." Alexandra (Team 3, Midterm Presentation)*

However, in the midterm, Team 3 gave a shallow description of the project goals, outlining four requirements (entry into service date, payload weight, range, and maximum payload weight) as opposed to Team 1 and 2's detailed requirements analyses, including nine requirements each. Additionally, the team identified the stakeholders in their presentation, but they never outlined how the stakeholders impact the design, nor did they integrate any of the stakeholder's concerns into the design decision-making process:

> *"So our main stakeholders are the US Department of Defense. The US Air Force are the ones who mostly use the C5 right now. And also the FAA. And also other stakeholders we should consider are Pilots, Flight Crews, Maintenance Personnel, Aircrew Loadmasters, Aircraft Manufacturers, and taxpayers." Alexandra (Team 3, Midterm Presentation)*

Team 3's interpretation of the RFP and lack of stakeholder integration were a contributor to the team's confusion on design project expectations and led to multiple points of feedback from the instructors at the end of the midterm and final presentations. In the end, the design that was presented by Team 3 in the midterm and final did not fully meet the requirements defined by the RFP.

Task breakdown lacked clear organization and hierarchy

Team 3 did not have a clear task/subtask structure in their midterm presentation and no hierarchy could be noted in classifying the tasks (Table 33). This lack of hierarchy led to significant differences in their design process from that given in the authoritative text. Team 3's description of tasks had little background information on what accomplishments were achieved through the tasks as well as how the tasks connected to an overarching project goal. There was no transition provided in the verbal presentation to connect the tasks together. For example, the team followed the technology selection task with a discussion of the weight sizing. In moving from one task to the next, there was no clear signal that a new task had been started or how the previous task connected with the next task:

> *"The CF6 produces up to 61 000 and so four engines, two under each wing that's enough to provide the thrust that we need.*

> *Case one and case two are the two different mission requirements we had to meet. The 120 000 for 6300 nautical miles. And case two later on we'll show that we picked the 2000 nautical miles for 300 000 pounds of payload. So we're just detailing out what we're calling case one and case two. This is the weight sizing spreadsheet." Garth (Team 3, Midterm Presentation)*

Table 33. Task breakdown for Team 3's midterm presentation

Tasks
Requirements
Identify Stakeholders
Baseline Aircraft
Mission Profile
Configuration Selection
Technology Selection
Weight Sizing
Specific Range Plots
Drag Polar
Select Range
Constraint Analysis
Outline Cargo
Sizing the Fuselage
Wing Sizing

The explanation of the design process in the final presentation was structured more similarly to the authoritative text and had clear hierarchy and organization (Table 34). However, the final task order was missing some of the detailed components of the aircraft design process, such as the airfoil analysis and the V-n diagram.

Table 34. Task breakdown for Team 3's final presentation compared to the authoritative text

High-level task	Detailed Task	High-Level Task	Detailed Task
Define Requirements & Outline Mission	Outline RFP	Define Requirements & Outline Mission	Outline aircraft Requirements
	Stakeholder Identification		
			Overall Configuration Selection
			Outline Mission Requirements
			Sensitivity Studies
Configuration Selection	Figure of Merit Analysis		
		Initial Aircraft Sizing	Historical Regression of Weight
Technology Identification			Technology Selection
Sizing	Weight Sizing		First Weight Estimate
	Drag Polar	Determine Critical Performance-Based Metrics	Estimate Drag Polar
	Constraint Sizing		Evaluate Aircraft Constraints
Physical Design	Cargo Design	Determine Initial Configuration and Layout of Aircraft	Fuselage Layout
	Fuselage Design		Wing Planform Shape
	Wing Design		Preliminary Sizing of Empennage
	Empennage Design		Preliminary Landing Gear Configuration
	Landing Gear Design		Airfoil Selection
			High-Lift Devices
Weight and Balance and Stability	Calculate the center of gravity		Locate Component CG
		Improve Aircraft Weight Estimation and Configuration	Class II Weight Estimation
			V-n Diagram
	Stability Calculations	Conduct a performance analysis	Analyze Aircraft Stability
Cost			Structural Arrangement
	Parametric Cost		Overall Cost
	Operation & Support		Development Cost
	Total Cost Summary		Procurement Cost
			Operations & Maintenance Costs
			Finalize 3D Model and Three-View

The team chose to not assign any discipline or task-oriented responsibilities to the team members. Instead, they stated they had a Project Manager and two Chief Engineers. The specific responsibilities of each team member were not clearly stated in either presentation.

Team 3 did not show a strong connection between tasks

An analysis of Team 3's metrics identified 17 metrics as cross-task, where 8 of them matched with the authoritative text (Table 35). The majority of the metrics were shared among tasks pertaining to the weight calculation and sizing calculation. All of the metrics that are used in multiple tasks are listed in Appendix G, with a breakdown of the disciplines.

Table 35. Critical metrics shared across two or more tasks by Team 3

Critical metrics	# Shared Tasks	Included in Authoritative Text
Weight	6	X
Altitude	3	X
Mach	3	X
Number of Engines	2	
Aspect Ratio of the Wing	2	X
Cargo	2	
Technology Factor	2	X
Lift to Drag Ratio	2	X
Loading Style	2	
Mission Profile	2	
Range	2	X
Specific Range	2	
Time to Climb	2	
Thrust Required	2	X
Thrust Specific Fuel Consumption	2	
Type of Wing	2	
Velocity	2	X

Team 3's approach to integrating the tasks demonstrated that they were unable to fully coordinate decisions between the tasks. Despite the large number of metrics in their presentations, Team 3 did not demonstrate awareness of the connections between the high-level tasks within the conceptual design process.

Through Team 3's presentation, the tasks appeared to be segmented, with each task performing a function independent of the overall project. For example, one task balanced the aircraft's weight by shifting components forward and backward until the aircraft was estimated to be stable. In discussing this task, the team mentioned moving the tail and the wing, but they didn't discuss how those movements might have impacted their original design parameters for the tail and wing or other aspects of the design:

> *"Throughout this process we are using AVL to find stability, and in the process we had to move our wing back and forth on the fuselage with all this change. The vertical and horizontal tail went lower and changes from the main wing. As we did this we fulfilled the stability requirements but then had to check and make sure that the longitude and lateral tip over case was arrived at and did not have any issues with either. The longitudinal tip over is basically when the aircraft has a CG over or behind the main landing gear so mostly tips backwards, and the lateral tip over is the same but with side to side so both the wings may end up hitting the ground. And the ground clearance refers to whenever you take off and actually rotate and your tail kind of does not rub the ground." Garth (Team 3, Final Presentation)*

Referenced metrics as an indicator aircraft performance and capabilities within tasks, but did not fully explain metrics in the context of the design problem

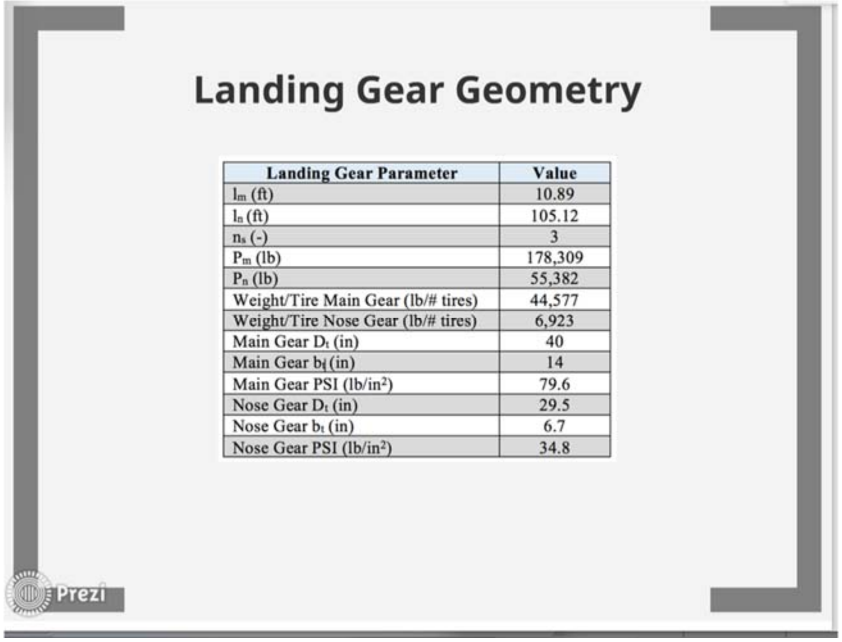
Team 3 included 318 metrics in their midterm and final presentations (Table 36): 154 metrics in the midterm presentation, and 224 metrics in the final presentation, where 60 of those metrics were the same between the two presentations. 95 metrics matched the authoritative text, or 24.7% of the authoritative text's metrics. This breakdown is similar to the inclusion of metrics by Team 1 and Team 2. The major difference in Team 3's metrics inclusion is their use of metrics as a validation that their aircraft meets specific performance criteria without a discussion of the metric beyond its immediate, task-oriented impact. For example, in discussing their performance analysis, Team 3 mentioned selecting Mach numbers and altitudes. However, they never extended beyond the selection of those metrics to show how they fit into the aircraft design process. They also didn't breakdown these values to show how they fit into the discipline-oriented context of design:

> *"This is to the right from the window we just showed. This is the cruise segment breakdown for the step cruise climb. Our L/D's, once again, are right around 20. These TSFC values, again, incorporate our engine technologies. We show how we obtain the Mach number for each one. But, our Mach numbers are .72 for the first two cruise segments and Mach .74 for the third segment. The altitudes for the segments are 34 000 feet, 39 000 feet, and 42 000 feet. We obtained those by doing the specific range plot analysis for each segment." Asa (Team 3, Midterm Presentation)*

Table 36. Number of metrics by Team 3's presentation

Total Number of Metrics Referenced Overall	318
Number of Metrics Referenced in the Midterm	154
Number of Metrics Referenced in the Final	224
Number of Metrics Referenced in Both the Midterm and Final Presentation	60

While the team presented a similar number of metrics to the authoritative text as Team 1 and 2, they used a more general approach to state metrics with very little background information. Further, 199 (62.6%) of the metrics were verbally included in the presentations and 119 (37.4%) were included on the slide presentation, but not stated verbally. An example of a slide with rich metric details, but few verbal explanations, is in Figure 9. With this slide, Alexandra explicitly mentioned the weight per nose gear and weight per main gear metrics. However, no explanation is given about how these values were developed nor are the other values discussed within the context of this task: “So, as I said, we have three struts at the main landing gear. These are just the weight per nose gear is 6,923 pounds and the weight per main gear is 44,577 pounds.” Alexandra (Team 3, Final Presentation)



Landing Gear Geometry

Landing Gear Parameter	Value
l_m (ft)	10.89
l_n (ft)	105.12
n_s (-)	3
P_m (lb)	178,309
P_n (lb)	55,382
Weight/Tire Main Gear (lb/# tires)	44,577
Weight/Tire Nose Gear (lb/# tires)	6,923
Main Gear D_t (in)	40
Main Gear b_t (in)	14
Main Gear PSI (lb/in^2)	79.6
Nose Gear D_t (in)	29.5
Nose Gear b_t (in)	6.7
Nose Gear PSI (lb/in^2)	34.8

Figure 9. Presentation slide from Team 3 final presentation

Team 3 did not justify decisions or explain their decisions in context of the aircraft design.

Team 3 often stated design decisions without justifying or explaining their reasoning. For example, in calculating the lift to drag ratio, Asa stated that their resulting ratio is a ‘good’ value. However, no evidence was provided to support why that number is appropriate for this design.

> *This is our final spreadsheet we came up with a takeoff weight of 648,000 pounds. The L/D's, cruise will be on the next slide, Climb L/D and all the other are hovering around 20. Which we thought was pretty good."*
>
> *Asa (Team 3, Midterm Presentation)*

As another example, in discussing the metrics that defined cruise altitude, Mach and range, Asa described the specific range as 'high.' "We found that at 42,000 feet at Mach .72 we had a high specific range," Asa (Team 3, Midterm Presentation). Yet, no follow-up reasoning was given to show how the high specific range value impacts their design decisions. Would the high specific range be a desirable feature of the aircraft? Or should the cruise metrics be updated to reflect a more appropriate specific range?

4.3 Comparison of Design Knowledge Coordination by Different Teams of Novice Engineers

The three teams that were evaluated for the case study each applied a different approach to the design process. As a result, the observable indicators of their design knowledge coordination also varied (Table 37).

Table 37. Overview of all three case study teams' approaches to design knowledge coordination in the conceptual design process

	Team 1	**Team 2**	**Team 3**
Goals	Integrated goals into the decision making process within specific disciplines and tasks, but did not consider trade-offs of goals across disciplines and tasks (Discipline-Oriented Approach)	Imposed goals outside of the RFP that consider the context and stakeholders of the designed aircraft (Coordinated Approach)	Defined a generic design goal, but did not perform a detailed requirements analysis or integrate goals into decision-making process (Basic Approach)
Tasks	Followed a cross-disciplinary, hierarchical task breakdown and aligned with the authoritative design process's tasks (Coordinated Approach)	Used a discipline-oriented approach to decomposing the tasks (Discipline-Oriented Approach)	Task breakdown lacked clear organization and hierarchy (Did Not Meet Criteria for Basic Approach)
	Incorporated an integrated approach to task completion through metric use to link disciplines together (Coordinated Approach)	Incorporated an integrated approach to task completion through metric use to link disciplines together (Coordinated Approach)	Did not show a strong connection between tasks (Did Not Meet Criteria for Basic Approach)
	Used task definitions to assign team member roles and responsibilities (Coordinated Approach)	Used task definitions to assign team member roles and responsibilities (Coordinated Approach)	Did not assign team member roles and responsibilities (Did Not Meet Criteria for Basic Approach)
Metrics	Used a variety of metrics and explained their reasoning for including specific metrics in their analysis in a cross-disciplinary context (Coordinated Approach)	Used a variety of metrics, but did not always explain their reasoning for including specific metrics in their analysis in a cross-disciplinary context (Discipline-Oriented Approach)	Referenced metrics as an indicator aircraft performance and capabilities within tasks, but did not fully explain metric's in the context of the design problem (Basic Approach)
Decisions	Justified decisions using both quantitative mathematical modeling and qualitative consideration of trade-offs between design options (Coordinated Approach)	Justified decisions using both quantitative mathematical modeling and qualitative supporting arguments, across disciplines (Coordinated Approach)	Did not justify decisions or explain their decisions in context of the aircraft design. (Basic Approach)

4.3.1 Goals

In determining the goals of the design project, the high-coordinating team (Team 2) extended their requirements analysis beyond the RFP document. Their analysis resulted in goals that crossed disciplines and considered the context and stakeholders of the designed aircraft. The low-coordinating team (Team 3) defined generic goals, using only the RFP.

In integrating the goals into the design process, the high-coordinating team (Team 2) integrated these goals across disciplines. When discussing design reasoning, Team 2 considered the impact of cross-disciplinary constraints. Conversely, the low-coordinating team (Team 1) only considered the goals within tasks and disciplines.

4.3.2 Tasks

Teams 1 and 2 exhibited design knowledge coordination through their task decomposition. Both teams used a hierarchy and order to breakdown the tasks across and within disciplinary boundaries. Conversely, the low coordinating team (Team 3) did not use a clear order or hierarchy to structure their tasks.

Compared to the authoritative text, Team 1 followed the task breakdown detailed in the authoritative text in the midterm and the final design review. In the final design review, Team 2 decomposed their tasks by discipline, leading to a disciplinary-oriented approach to the design process. Team 3’s task breakdown did not match the authoritative text in the midterm design review; in the final design review, Team 3 had aspects some tasks similar to the authoritative text, however not as detailed.

Additionally, indicators of design knowledge coordination were exhibited when the teams used metrics to link the tasks together. Team 1 and 2 used a large variety of metrics to link tasks and disciplines. Team 3 also used a large number of metrics to link tasks and disciplines; however, the links mostly connected the weight calculation and sizing calculation, which are similar disciplines. Thus Team 3 referenced metrics related to aircraft performance within tasks but did not discuss aircraft capabilities across disciplines.

Compared to the authoritative text, Team 1 shared many of the same metrics that the authoritative text used to link tasks (Table 38). Team 2 and 3 shared fewer metrics with the authoritative text.

Table 38. Critical metrics shared across two or more tasks within the authoritative text (AM) and by Team 1 (T1), Team 2 (T2), and Team 3 (T3)

Critical metrics	**AM**	**T1**	**T2**	**T3**
Altitude	X	X	X	X
Mach	X	X	X	X
Range	X	X	X	X
Weight (Takeoff, Payload, Fuel, Crew, Empty)	X	X	X	X
CL (C_L, C_{LAlpha}, C_{LMax})	X	X	X	
Cost (O&S, Operation, Acquisition, Life Cycle Cost)	X	X	X	
Lift to Drag Ratio	X		X	X
Takeoff and Landing Field Length	X	X	X	
Thrust	X	X		X
Velocity (Approach, Cruise, Dive, Maneuver, Max, Stall)	X	X		X
Wing Span	X	X	X	
#Engines	X			X
Angle of Attack	X	X		
Area of Wing	X	X		
Aspect Ratio of the Wing	X			X
Coefficient of Friction	X		X	
Drag	X	X		
Fuel Fraction	X	X		
Length of Fuselage	X	X		
Rate of Climb	X	X		
Specific Fuel Consumption	X	X		
Wing Loading	X	X		
#Crew per Aircraft	X			
Aspect Ratio of the Horiz Tail	X			
Aspect Ratio of the Vert Tail	X			
c coefficient (weight sizing)	X			
CD (C_D, C_{D0})	X			
Climb Gradient	X			
Coefficient of Moment	X			
Density Air	X			
Endurance	X			
Horizontal Tail Area	X			
K	X			
Leading Edge Sweep	X			
Lift	X			
Load Factor (n, n_{ult})	X			
Materials	X			
Mean Chord	X			
Oswald's Efficiency Factor	X			
Taper Ratio	X			
Type of LG	X			
Vertical Tail Area	X			
Vertical Tail Sweep	X			
Wetted Wing Area	X			

Finally, teams that exhibited design knowledge coordination (Teams 1 and Team 2) assigned team member responsibilities and roles according to task definitions. These roles aligned with the team's chosen task decomposition. The team that lacked evidence of coordination in this area, Team 3, did not assign roles or responsibilities to their team members according to the task division.

4.3.3 Metrics

Design knowledge coordination is evident when teams use a variety of metrics to explain decisions and tasks processes. All three teams referenced a variety of metrics in their midterm and final presentations. Compared to the authoritative text, Team 1 matched 79 metrics, Team 2 matched 90 metrics, and Team 3 matched 95 metrics. While Team 3 matched the most metrics with the authoritative text, they exhibited the fewest indicators of design knowledge coordination: The metrics that were included were not discussed beyond the immediate, task-oriented impact. Comparatively, Team 1 and 2 framed their references to metrics primarily within a mathematical context, and explained their process for deriving metric values.

Additionally, Team 1 explicitly referenced critical tasks in their discussion of the design process. They used their understanding of how each metric impacts task completion and decision-reasoning to explain to the instructors why a specific metrics is connected to the design process. Conversely, Team 3 did not integrate design knowledge coordination in that they did not verbally explain which metrics were essential to the design process.

4.3.4 Decisions

Team 1 and Team 2 incorporated design knowledge coordination in their approach to the design process by justifying their decisions using a range of arguments across disciplines. Team 3 appeared to lack design knowledge coordination in that the team did not justify or explain their decision-reasoning.

While Team 1 did include some discussion of trade-offs, their inclusion of trade-offs was not consistent throughout the design process. Further, Team 2 and Team 3 did not consider trade-offs in their decision-making process. Within engineering design, trade-offs present a method for comparing and evaluating various choices for aspects of the design.

These choices might weight designer preferences differently, and it is up to the designer to decide which preference is more important (Lewis, 2006). For example, Team 2 decided to move forward with a more advanced aircraft layout (i.e. a flying wing configuration). This design choice demonstrated that the student designers preferred the advanced design configuration and increased performance capabilities over the increased complexity and increased cost that would be incurred due to the advanced configuration. However, while the trade-offs can be inferred by an expert designer, the students did not explicitly acknowledge the trade-offs that they considered in making the decision to design an aircraft with an advanced configuration. Further, the students did not outline their reasoning for using a flying wing configuration or justify the design decision within their design reviews.

4.4 Summary and Discussion

In this chapter, a case study evaluated student engineering design teams' design knowledge coordination. The findings of this research answer the second research question: How do novice aerospace engineers coordinate and integrate knowledge about a design? Through the case study, the team design processes were compared to the authoritative text as well as compared to the other teams' design processes. The analysis resulted in a summary of indicators of high- and low- design knowledge coordination.

The team design processes can be compared and summarized to outline observable indicators of 'High-Coordination' and observable indicators of 'Low-Coordination' (Table 39). These indicators are generalizations within the specific context and cases discussed through the case study.

Table 39. Indicators of coordination in an aircraft design course

	Indicators of Low-Coordinated Process	Indicators of High-Coordinated Process
Goals	Defines generic goals using single reference	Defines goals imposed by primary requirements document as well as defines goals related to the context and stakeholders of the design problem
	Integrates goals within tasks/disciplines	Integrates goals across disciplines
Tasks	Does not use a clear order or hierarchy to structure tasks	Uses hierarchy and order to decompose tasks across and within disciplines
	Does not connect tasks	Integrates tasks across-disciplines using cross-disciplinary metrics
	Does not assign team member responsibilities or roles	Assigns team member responsibilities according to task definitions
Metrics	References metrics as an indicator of aircraft performance and capabilities within tasks	Uses a variety of metrics to explain decision reasoning in a cross-disciplinary context
	Does not fully explain critical metrics included in the design process	Explains the reasoning and use of critical metrics included in the design process
Decisions	Does not justify decisions or explain their decisions in context of the aircraft design	Justifies decisions using both quantitative mathematical modeling and qualitative supporting arguments, across disciplines

Once validated, these indicators can be used to develop characteristics of educational interventions that support design knowledge coordination strategies. The next chapter (Chapter 5) validates the indicators of high- and low-coordinated processes by triangulating the results with a second study.

As discussed in Chapter 1 and throughout Chapter 2, the intent of this thesis is to analyze and evaluate how the engineering design process explicitly incorporates design knowledge coordination. Overall, the two teams that exhibited the most indicators of design knowledge coordination, Team 1 and Team 2, had the most structured approach to their design process. These teams defined clear goals, tasks, and metrics. They also clearly stated their decisions with justifications that linked back to the goals, tasks, and metrics. The structure used by Team 1 and Team 2 generally followed the structure inherent to the text's authoritative design process. However, Team 2 tended to divide the tasks along disciplinary boundaries.

Conversely, Team 3 had little structure in their presentation of the design process. Team 3's design process lacked a clear definition of goals and tasks. Additionally, the decisions were not always clearly stated nor justified within the context of the team's previously stated goals, tasks, and metrics.

While the teams demonstrated evidence of both high design knowledge coordination and low design knowledge coordination, not every aspect of coordination was consistently observed within the students' design processes. Notably, the teams showed little evidence of considering trade-offs. As discussed earlier, trade-offs should be considered when making many design decisions. Another component of considering trade-offs arises when the designers define the design's requirements and objectives to also account for stakeholder preferences. Typically, within this process the designer will encounter design requirements that conflict one another and must adjudicate the trade-offs within the design requirements and stakeholder needs. Whereas Team 1 and, to some extent, Team 3 outlined the stakeholders in the design reviews, these teams did not connect the stakeholders to the design requirements nor did they consider the requirements trade-offs that arise from the stakeholder analysis.

While the case studies focused on evidence of design knowledge coordination within student teams' design processes, other factors may also impact student design teams' application of the aerospace engineering conceptual design process. For example, the team makeup (e.g. demographics, affect, and prior experiences) may impact how the team approached the engineering design process. However, while there are differences in the breakdown of how many students participated in these activities on each team, the team presentation of their design process and the observability of design knowledge coordination within that process did not appear to be influenced by either the team demographics or the team members' prior experiences.

CHAPTER 5 - STUDENT-CENTERED APPROACH TO INTEGRATING DESIGN KNOWLEDGE COORDINATION IN AEROSPACE ENGINEERING EDUCATION

This chapter investigates student perceptions of design knowledge coordination within the aerospace engineering conceptual design process. The results were compared to the results from Chapter 4 to test for internal validity. The triangulation of Chapter 4's findings with this alternate data source enhances the validity of the results and adds an additional perspective for defining characteristics of educational interventions and resources (Cohen, Manion & Morrison, 2000). Further, triangulation is another way to mitigate researcher bias, in addition to the interrater reliability check discussed previously.

5.1 Research Methods and Analysis

A qualitative analysis of informal focus group discussions explored student perceptions of design knowledge coordination within their capstone design project. Thematic analysis of this data isolated characteristics of the student's perceptions of decision-making in the capstone design process using the design knowledge coordination lens, developed in Chapter 2.

The research subjects and site are the same as discussed in Chapter 4.

5.1.1 Data Summary

In the second (spring) semester, the primary researcher conducted informal focus groups with the three teams included in the analysis in Chapter 4. The focus groups were conducted in the week preceding the final presentations. Thus, most of the teams had finalized their aircraft design but had not yet received the detailed instructor feedback provided after the final presentation. The focus group followed a semi-structured protocol with an introductory task and follow-up questions (see Appendix F). An introduction to the focus group explained the overall task and was verbally stated by the researcher/observer:

> *As a future aerospace design faculty, I hope to be teaching a senior design course. So, I want your perspective on how you view the design process and the most important components of this process. Take five minutes and individually reflect on the process you used this semester in completing your aircraft design. Write this process on the paper I've handed out as if you were having to explain it to another person not in aerospace senior design. Feel free to use any format to convey your process (for example, bullet points, a diagram, a picture).*

The students were then provided white paper, coloring pencils and ink pens, and given five minutes to individually reflect on their team's design process. Once the individual task was completed, the students were asked to collectively negotiate to one common design process that was used by the team. They were encouraged to draw their process on a white board located in the room. As the students discussed their design process, the researcher interjected with clarifying questions as well as questions that probed the team to give more detail about specific tasks within the process. Following the task, the students were asked for their feedback on how the course was progressing and if they had any recommendations for changes they would like to see in the course. Throughout the focus group, the researcher took notes about the students' responses and expanded those notes after the focus group concluded.

5.1.2 Data Analysis

The data were analyzed qualitatively by the primary researcher using thematic analysis techniques to uncover high level themes within the data (Miles & Huberman, 1994), using design knowledge coordination framework to focus their theme characterization. The themes that were generated followed the same coding scheme that was developed in Chapter 2 and used in Chapters 3 and 4. This lens guided the researcher to evaluate the focus group conversations for indicators of *Goals*, *Tasks*, *Metrics*, and

Decisions (Table 40). Additionally, the researcher analyzed for themes related to cross-disciplinary alignment of tasks and decisions, as they pertain to design knowledge coordination.

Table 40. Coding scheme for classifying designers' structured approach to engineering design

Constructs of Design Knowledge	Details
Goal	Derived from the project users and/or requirements and are used to direct engineering tasks.
Tasks	Dictate the direction and future content of overall work within the complex engineering design process
Metrics	Representation of information about the design that is available to or needed by the designer
Decisions	Outcome of a task

Throughout data collection and analysis, a research notebook maintained any high-level themes or observations that emerged to further understand the results and to identify additional categories relevant to design knowledge coordination.

5.2 Results

Qualitative coding of the focus group conversations and artifacts found evidence of the students' perceptions of design knowledge coordination within their capstone design task. The themes that were identified supported many of the themes that were discussed in Chapter 4.

5.2.1 Peer Reviews and Perceptions of Team Dynamics

Before initiating the discussion of Goals, Tasks, Metrics and Decisions, team members' perceptions of their group work were examined. The team dynamics and cohesion differed between teams and may have influenced how the teams approached their design process, particularly from a coordinated perspective. At the end of the semester, the instructors asked the students to grade their team members' individual effort and contributions through a Peer Review. An examination of the Peer Reviews showed a significant difference in how Team 1 and Team 2 viewed their team cohesion compared to how Team 3 perceived their team cohesion. Members of Team 3 rated their peers much lower, on average, than Team 1 and Team 2 (Table 41).

Table 41. Average scores on the Peer Review evaluations submitted by the students at the end of the semester

	Average Score	Lowest Individual Score	Highest Individual Score
Team 1	99%	95%	100%
Team 2	98%	94%	99%
Team 3	84%	69%	97%

Team 1 and Team 2 had very positive team interactions, as is apparent from the high scores that team members assigned to their peers' contribution. Team 1 and Team 2 had very organized team meetings that led to clear communication of design decisions and information about the design. Team 1, in particular, had a unique approach to coordinating team meetings by hosting one to two-hour work sessions three days each week. Within these work sessions, the team members would sit in a common area and work on the design in parallel. As issues or questions arose, the team members could immediately discuss design decisions and quickly resolve confusion about the design.

Conversely, Team 3 had a much lower distribution of scores. This was also reflected in the Focus Group discussion by Team 3's disorganized conversation when discussing their design process. When asked to describe their design process, the team members weren't able to directly attribute specific jobs to one team member. Instead, the team members appeared to have disagreements about who did the work and whether specific members' efforts were a significant contribution to the project. This dynamic was also apparent in the lack of division on the team members' task responsibilities.

5.2.2 Goals

Within a coordinated design process, goals are defined at the start of the design process and used to iteratively incorporate cross-disciplinary information about the design.

Teams 1 and 2 reported performing a detailed analysis of the RFP at the beginning of the design process and iteratively updated those goals throughout the design process: “The RFP was one source” Gary (Team 2, Focus Group). This approach viewed the RFP as a primary roadmap for the design process, and the teams were able to incorporate information from the RFP into their decision-making process: “Being able to translate what we see in the RFP and then deciding what we need to do for each requirement” Damien (Team 1, Focus Group). Team 2 also reported analyzing other requirements imposed by outside factors, such as stakeholders and infrastructure constraints:

> *“There was some operation. There were some derived requirements. Like one of them that we used was limiting the wing span to the span of the C5. Obviously, that's not mentioned in the RFP, but that was one that we self-imposed… because it is the largest wingspan in the Air Force so going larger could make them change infrastructure.” Gary (Team 2, Focus Group)*

Team 3 did not report performing an in-depth requirements analysis and goal definition at the start of the design process: “We did not intimately know [the RFP] until fairly recently,” Garth (Team 3, Focus Group). Their lack of a detailed goal definition phase hindered the group’s ability to incorporate a multidisciplinary, coordinated design process by limiting their ability to see how the cross-disciplinary constraints impacted design decisions. Additionally, the team reported using the RFP as a reference for when they were missing information, rather than a guide for a complete design: “Rather than fully understanding it at the beginning, we kind of just went back to it whenever we needed something” Asa (Team 3, Focus Group). Team 3 openly recognized that they should have performed a more in depth analysis of the requirements: “If we were describing to someone what we did, step 2 would be read the RFP. It doesn't matter if we actually did it” Peter (Team 3, Focus Group).

Within the higher-coordinating teams, as the students reported making more decisions about the design, they iteratively incorporated information from the design goals: “After doing the constraint sizing, we knew the design point. Then, based on that we knew other values like the wing and the fuselage we had to pick. This is where we went and looked at the RFP again” Gary (Team 2, Focus Group). Team 1 also reported comparing their design decisions to the design goals: “when we were going through this process we kept going back to the RFP, to make sure we were on track. Sometimes we would make design decisions, then we would be like 'wait, how does this help the RFP?'… Every time we made a decision, we would keep going back to the RFP to make sure we were doing the right thing” Damien (Team 1, Focus Group).

These findings align with the findings in Chapter 4 for high-coordinating and low-coordinating behaviors on design teams (Table 42).

Table 42. Indicators of high- and low-coordination pertaining to design goal definition and integration

Indicators of Low-Coordinating Behaviors	Indicators of High-Coordinating Behaviors
Defines generic goals using single reference	Defines goals imposed by primary requirements document as well as defines goals related to the context and stakeholders of the design problem
Integrates goals within tasks/disciplines	Integrates goals across disciplines

5.2.3 Tasks

Teams with more a more organized approach to coordinating design tasks were able to reflect on their design process

In discussing their design process, Teams 1 and 2 reported defining tasks in an organized manner. In presenting these tasks, both Team 1 and Team 2 reported using a structure similar to the structure presented in Roskam (1990). Figure 10 shows the process that Team 1 drew on the whiteboard. In their decomposition of the tasks, the team broke the process into an ordered process that included collaborative organization tasks. Figure 11 shows the process drawn by Team 2 on paper. Team 2's process description goes into more detail on the individual discipline breakdowns and shows how each discipline feeds into the next phase of design.

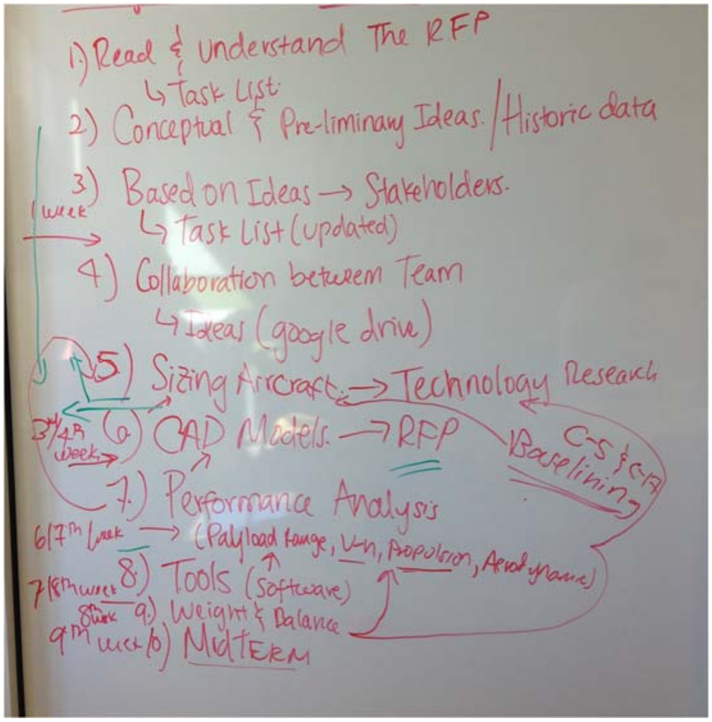


Figure 10. Task structure presented by Team 1 in the focus group

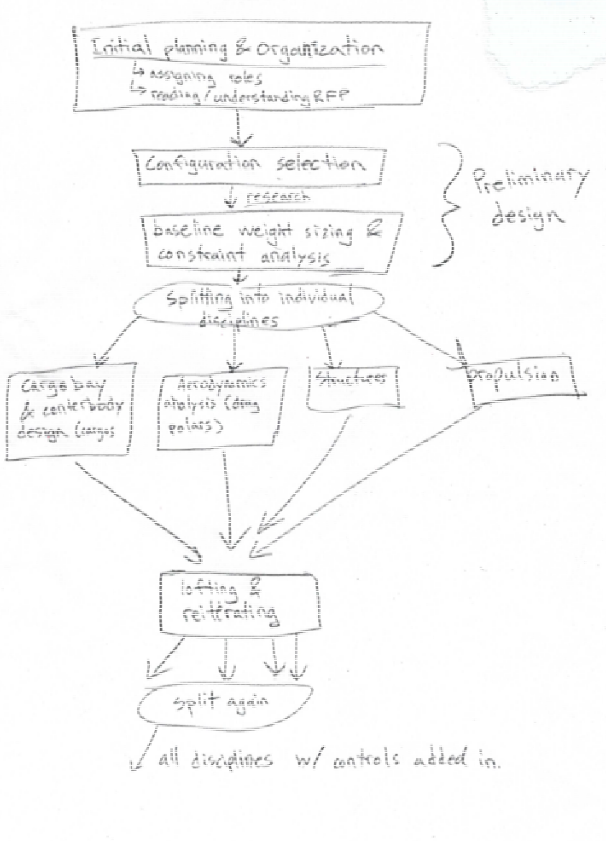


Figure 11. Task structure presented by Team 2 in the focus group

Team 3 reported recognizing the use of the Roskam text’s design tasks within the aircraft design process, but were unable to describe how they implemented these tasks: “I think we knew what the steps were, we didn't understand how to do the steps very well” Asa (Team 3, Focus Group). In particular, Team 3 noted their desire for a resource that would outline the steps within the design process: “It would be helpful, these steps we're writing here should be printed out on paper and given to students. This is this design process. You're out there on your own and you don't know what depends on what or what to iterate on” Garth (Team 3, Focus Group).

Assigned team member responsibilities maintained consistent task work throughout the design process.

By assigning team member responsibilities, Teams 1 and 2 reported maintaining a consistent workflow: “At the very beginning, each person had an assigned task… So after each meeting we discussed 'Okay. They had this feedback for us. We still have this to do and based on those tasks we would say whose discipline does that fall under?’” Maximo (Team 2, Focus Group). However, the tasks that were initially assigned evolved as the students learned more about how to apply the design tasks: “In our first meeting we all just divided up. I feel like that was a bit premature because as we all went on everything changed… Three weeks out everything changed” Rocco (Team 1, Focus Group) The tasks were assigned according to the interests of the team members: “Ideally we all ended up doing the part of the process that we were interested in” Gary (Team 2, Focus Group). The students’ familiarity may have led to them being more knowledgeable within specific design tasks: “Once we started working on things, it was like 'oh! I think I'm more familiar with this’” Astrid (Team 1, Focus Group)

Additionally, the students reported that the task structure allowed them to work on tasks in parallel: “I was doing research on structural elements of the cargo bay while he was doing research on layouts” Dane (Team 2, Focus Group). This may have allowed the teams to work on multiple tasks simultaneously, but created the need to iterate on decisions to update information across tasks. Additionally, as more knowledge about the design was defined, the teams reported needing to iterate on the design to update this information: “As we did more analysis on airfoil selection and CFD that Spencer was working on… we went back to the CAD model and updated it” Damien (Team 1, Focus Group).

The team that did not assign team member responsibilities reflected that they didn’t understand the project well enough to divide the work into equal tasks: “We certainly didn't understand how to do the steps well enough to split them up evenly” Asa (Team 3, Focus Group). This mirrors the previously discussed observation that Team 3 did not have an organized task structure. One member of Team 3 was fairly hostile to the idea of collaborating in a design project: “In the real world, you're not really collaborating with everyone. Somebody assigned that task to you and that's what you have to do” Alexandra (Team 3, Focus Group). This team may have had internal issues preventing them from fully coordinating within their design project.

Team 3 recognized the need to work simultaneously but reported an inability to organize the tasks in a manner that allowed for the parallel workflow: “We had a bottleneck on our process. Until we finished the weight sizing we couldn't do anything else” Asa (Team 3, Focus Group).

These results align with Chapter 4’s findings about tasks. The teams exhibiting higher evidence of design knowledge coordination reflected on the design process using a clear order and hierarchy to their task structure, incorporated cross-disciplinary metrics to connect tasks, and assigned team member responsibilities according to task definitions (Table 43).

Table 43. Indicators of high- and low-coordination pertaining to design Task definition and integration

Indicators of Low-Coordination	Indicators of High-Coordination
Does not use a clear order or hierarchy to structure tasks	Uses hierarchy and order to decompose tasks across and within disciplines
Does not connect tasks	Integrates tasks across-disciplines using cross-disciplinary metrics
Does not assign team member responsibilities or roles	Assigns team member responsibilities according to task definitions

5.2.4 Metrics

Metrics were kept consistent across disciplines throughout the different tasks in the design process

The teams that coordinating within their design process explicitly noted instances when changing one metrics would impact another metric, and they would have to go through and update multiple values in their mathematical models: “In one case we would change the technology factor, which would change the sizing, which would change the technology factor” Rocco (Team 1, Focus Group). Consistency of within-discipline metrics is important to maintain a discipline-oriented design process. But, consistency across disciplines impacts design knowledge coordination: “The cargo bay size. Originally we had it 42 by 80-something. Then Ward said 40 by 80 and that was good enough. But, when we added that extra five feet it changed the airfoil. So we had to go back and scratch the cargo bay a bit” Gary (Team 2, Focus Group). By noting that changes in the airfoil impacted structural metrics, Team 2 maintained consistent values in their design.

As the teams worked on their design project, many of the decisions were reported as being made using an extensive spreadsheet with mathematical models. The use of this spreadsheet sometimes caused inconsistencies in the metrics: “All our spreadsheets last semester weren't exactly right” Asa (Team 3, Focus Group). Team 3 also noted the difficulties with maintaining consistent metrics in a ‘living document’: “It's so difficult to have a living document. You can't have 6 people working on it at the same time” Alexandra (Team 3, Focus Group). Additionally, instead of going through an integrated process, Team 3 reported modifying design parameters manually to meet the expected values: “Being completely honest, there are some numbers in here that we have to fudge. Because something went wrong along the way. Our numbers for the cruise climb segments, we're still getting numbers that I feel don't make sense” Asa (Team 3, Focus Group). The alterations were made within the disciplines; however, it was unclear if the impact of changing the values was integrated across disciplines.

This finding aligns with Chapter 4’s findings on metrics. The teams that exhibited high-coordinating behaviors when the students reported integrating metrics across disciplines. Additionally, a new characterization of high and low-coordinating behaviors offered by the focus group analysis is the role of iteration in maintaining consistent task values. This suggests that design knowledge coordination is enhanced when students understand how metrics are impacted through iteration (Table 44).

Table 44. Indicators of high- and low- coordination pertaining to design metric usage.

Indicators of Low-Coordination	Indicators of High-Coordination
References metrics as an indicator of aircraft performance and capabilities within tasks	Uses a variety of metrics to explain decision reasoning in a cross-disciplinary context
Does not fully explain critical metrics included in the design process	Explains the reasoning and use of critical metrics included in the design process
Manually updates metrics without consideration for cross-disciplinary impacts	Iterates on the design to update metrics consistently

5.2.5 Decisions

Teams 1 and 2 reported considering decisions through a cross-disciplinary reasoning and trade-offs. For example, in discussing the design of the cargo bay, Team 2 noted the tight interdependencies of the cargo bay, fuselage shape, and wing design: “Designing the cargo bay really constrained what we were going to do. Since we had a blended wing body we had to design the rest of the fuselage shape and wings around that. We had to decide really early how big we wanted it to be” Maximo (Team 2, Focus Group).

In making cross-disciplinary decisions, Teams 1 and 2 reporting discussing issues in their outside class team meetings and collectively brainstorm solutions: “We would bring an issue to the weekly meeting, brainstorm as a group, discuss possible solutions, then the discipline lead would try to implement the solutions so it worked” Gary (Team 2, Focus Group). Team 1 reported the most extreme approach to group decision-making: They would meet three times each week for two hours and work on their individual design tasks in a common space.

Conversely, Team 3 reported being unsure about how they were to justify their decisions: “I didn't know that we couldn't assume this. Or that we needed justifications for all this." Peter (Team 3, Focus Group). Ultimately, Alexandra summarized their design process by commenting on the unexpected complexity they experienced in the capstone course: "This is just so much more complex" Alexandra (Team 3, Focus Group).

The findings from the focus group analysis on decisions align with the findings in Chapter 4. Teams 1 and 2 described a cross-disciplinary decision-making process, while Team 3 was unable to describe a process for justifying their design decisions (Table 45).

Table 45. Indicators of high- and low- coordination within the decision-making process

Indicators of Low-Coordination	Indicators of High-Coordination
Does not justify decisions or explain their decisions in context of the aircraft design	Justifies decisions using both quantitative mathematical modeling and qualitative supporting arguments, across disciplines

5.3 Summary and Discussion

The students' perceptions of high- and low- design knowledge coordination are similar to those observed indicators presented in Chapter 4. These indicators can be used to create characteristics of educational interventions that support design knowledge coordination, as discussed in Chapter 6. A summary of the indicators of design knowledge coordination are presented in Table 46.

Table 46. Indicators of coordinating behaviors in an aircraft design course, including behaviors characterized from both the instructors' and students' perspectives

	Indicators of Low-Coordination	**Indicators of High-Coordination**
Goals	Defines generic goals using single reference	Defines goals imposed by primary requirements document as well as defines goals related to the context and stakeholders of the design problem
	Integrates goals within tasks/disciplines	Integrates goals across disciplines
Tasks	Does not use a clear order or hierarchy to structure tasks	Uses hierarchy and order to decompose tasks across and within disciplines
	Does not connect tasks	Integrates tasks across-disciplines using cross-disciplinary metrics
	Does not assign team member responsibilities or roles	Assigns team member responsibilities according to task definitions
Metrics	References metrics as an indicator of aircraft performance and capabilities within tasks	Uses a variety of metrics to explain decision reasoning in a cross-disciplinary context
	Does not fully explain critical metrics included in the design process	Explains the reasoning and use of critical metrics included in the design process
	Manually updates metrics without consideration for cross-disciplinary impacts	Iterates on the design to update metrics consistently
Decisions	Does not justify decisions or explain their decisions in context of the aircraft design	Justifies decisions using both quantitative mathematical modeling and qualitative supporting arguments, across disciplines

As discussed in Chapter 4, the team demographics did not appear to impact the teams' different approaches to design knowledge coordination, with one exception noted here: Team 2 commented that Gary's previous industry experience guided their division of design tasks and member roles and responsibilities. Team 2 modeled their group organization similar to Gary's experiences with industry by dividing the design tasks and roles along disciplinary boundaries. Decisions within disciplinary groupings were communicated to Gary, who tracked the decision and translated major findings to the other team members.

Within large organizations, this approach to task division is beneficial to maintain connections across large technical teams. A Project Manager is responsible for maintaining consistent information across the design and ensuring that decisions made within disciplines are translated across disciplines. The cross-team communication is typically enabled through processes and documentation. While this approach works for large organizations that have many disciplines and subteams, smaller design teams, such as the ones in this study, may benefit from having clearly defined tasks without necessarily requiring them to be divided very deeply. Additionally, the implementation of a Project Manager to communicate decisions across the team members can have both benefits and difficulties: while one person may provide a central handling of design knowledge, adding this additional layer to the organization may have hindered design knowledge coordination by adding another layer of communication before the members could discuss and integrate design decisions across team boundaries.

Related to design knowledge coordination, one can consider design knowledge coordination as either influencing, or being influenced by, the team dynamic. From the view of design knowledge coordination influencing the team dynamic, a lack of understanding how decisions about the design can be coordinated and integrated may have then led to the deterioration of communication and cohesion on the team. Conversely, from the view of design knowledge coordination being influenced by team dynamic, the lack of communication and cohesion would have led to decisions and information not being translated to the design consistently and in a timely manner.

Considering the team dynamics and design knowledge coordination, there was a pattern of the teams with observable indicators of design knowledge coordination having a higher cohesion between the team members. Teams 1 and 2 gave their peer members a higher evaluation score on the Peer Review. Conversely, Team 3 had a lower average score on the Peer Review.

In discussing Team 3's design knowledge coordination, the team members perceived many problems with the communication and coordination among team members. Specifically, there was confusion and misunderstanding about the structure of the design process, including the task definition as well as how the tasks were divided and executed among the team members. The confusion regarding task definition and execution may have been due to the team members lacking positive team interactions to effectively communicate decisions, or it may have also been to the team members lacking the knowledge and skills needed to interact within the design process effectively.

In contrast, Team 1 and 2 discussed their team dynamics in a positive light. Further, the team members were able to easily recognize the structure of the design process, including the design tasks, their team's work division, and the task execution. The teams' functionality within the design process may be attributed to positive team interactions and communications. It may also have been attributed to the team members having a solid understanding of the knowledge and skills needed to interact within the design process effectively.

CHAPTER 6 - CHARACTERISTICS OF EDUCATIONAL INTERVENTIONS THAT SUPPORT DESIGN KNOWLEDGE COORDINATION

Research on engineering education can assist educators as they “articulate reasonable learning objectives, understand students’ growth relative to learning objectives, imagine activities that can be implemented to promote learning, and identify effective assessment measures” (Turns, Adams, Linse, Martin & Atman, 2004, p. 379). Thus, based on the research results in the previous chapters (Figure 12), this chapter discusses learning goals for incorporating a coordinated perspective into aerospace engineering design education. Additionally, this chapter discusses design activities that could be included in design courses to promote the learning goals and support students’ design knowledge coordination. Finally, this chapter describes how design knowledge coordination may be used to evaluate student performance and to design course content. The identified learning goals and design activities are summarized in Table 47.

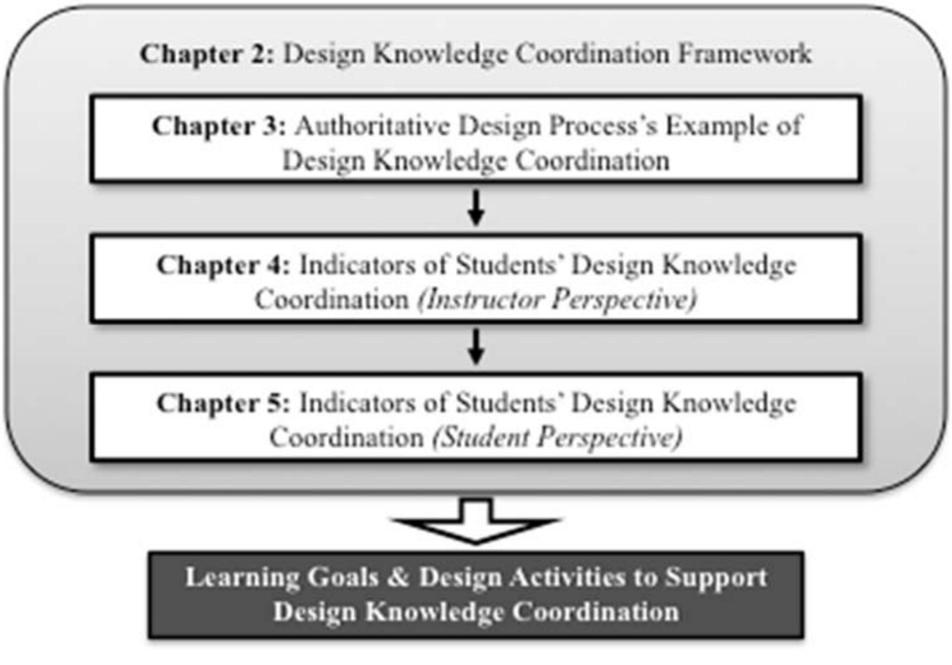


Figure 12. Summary of research leading into the development of learning goals and design activities to support design knowledge coordination.

Table 47. Outline of learning goals and design activities to support design knowledge coordination

	Learning Goals where students…	Design Activities
Goals	° Use multiple reference points to define design goals (e.g. primary requirements, design context, and stakeholders) ° Apply design goals consistently and iteratively throughout the design process to make and validate design decisions	° Requirements Analysis ° Stakeholder Analysis
Tasks	° Define tasks and subtasks with an order and hierarchy ° Recognize the links between tasks and subtasks ° Iterate across the tasks to update information about the design	° Concept Maps
Metrics	° Recognize critical discipline-oriented metrics to required to complete tasks and subtasks ° Maintain consistent values for metrics across the different disciplines	° Design Structure Matrix
Decisions	° Justify decisions through a completion of tasks and consideration of evidence ° Describe the overall impact of a particular decision	° Systems Engineering Decomposition Tools

The learning goals and design activities that are discussed in this chapter are not intended to over-burden the aerospace engineering design course with additional content to the curriculum. Instead, the learning goals and design activities extend current approaches to teaching aerospace engineering design by incorporating aspects of the design knowledge coordination lens within current course activities and assignments.

Additionally, by incorporating the design knowledge coordination lens, the course content and activities may better satisfy ABET student outcomes to have: (c) an ability to design a system to meet desired needs within realistic constraints; (d) an ability to function on multidisciplinary teams; (f) an understanding of professional and ethical responsibility; (g) an ability to communicate effectively; and, (h) an understanding of the impact of engineering solutions in a global, economic, environment, and societal context (ABET, 2016; Dym et al, 2005). That is, through design knowledge coordination, students are not only required to demonstrate a firm grasp of the wide array of disciplinary-based knowledge, but also to use a coordinated perspective to interpret how these disciplines contribute to and integrate within the design of an aerospace system.

6.1 Learning Goals

Learning goals guide student skill development by specifying competency areas for instructional design (Ambrose, Bridges, DiPietro, Lovett & Norman, 2010; Fink, 2003). Thus, learning goals are needed to incorporate the principles of design knowledge coordination into aerospace engineering design curriculum. The following four sub-sections detail learning goals by examining the design knowledge coordination framework (Table 48) and the indicators of low- and high-coordination (Table 49). These learning goals target specifically the design construction in the framework: design goals, tasks, metrics and decisions.

Table 48. Framework for characterizing design knowledge coordination within an engineering design process (Repeated from Table 4, Chapter 2)

	Basic Approach	Discipline-Oriented Approach	Coordinated Approach
Goal	Defines a general design goal	Design goals are decomposed into more specific goals for each discipline	Identifies trade-offs between discipline-oriented design goals
Tasks	Defines tasks and subtasks Incorporates an order and hierarchy to task decomposition	The tasks and subtasks have an order and hierarchy that align with engineering disciplines	Recognizes the links between tasks and subtasks Iterates across the tasks to update information about the design
Metrics	Uses metrics to complete tasks and subtasks	Within each discipline, there are critical metrics guiding the decisions and tasks	Maintains consistent values for metrics across the different disciplines
Decision	Justifies decisions through completion of design tasks	Decisions are justified through discipline-oriented metrics	Describes the overall impact of a particular decision Incorporates a variety of metrics from other disciplines to justify decisions

Table 49. Indicators of coordinating behaviors in an aircraft design course, including behaviors characterized from both the instructors' and students' perspectives (Repeated from Table 46, Chapter 5)

	Indicators of Low-Coordination	Indicators of High-Coordination
Goals	Defines generic goals using single reference	Defines goals imposed by primary requirements document as well as defines goals related to the context and stakeholders of the design problem
	Integrates goals within tasks/disciplines	Integrates goals across disciplines
Tasks	Does not use a clear order or hierarchy to structure tasks	Uses hierarchy and order to decompose tasks across and within disciplines
	Does not connect tasks	Integrates tasks across-disciplines using cross-disciplinary metrics
	Does not assign team member responsibilities or roles	Assigns team member responsibilities according to task definitions
Metrics	References metrics as an indicator of aircraft performance and capabilities within tasks	Uses a variety of metrics to explain decision reasoning in a cross-disciplinary context
	Does not fully explain critical metrics included in the design process	Explains the reasoning and use of critical metrics included in the design process
	Manually updates metrics without consideration for cross-disciplinary impacts	Iterates on the design to update metrics consistently
Decisions	Does not justify decisions or explain their decisions in context of the aircraft design	Justifies decisions using both quantitative mathematical modeling and qualitative supporting arguments, across disciplines

6.1.1 Learning Goals for Design Goals

Within a coordinated approach to design, designers "identify trade-offs between discipline-oriented design goals" (Table 48). The first component of identifying trade-offs between design goals is to define and decompose design goals appropriately. Such design goals need to be defined using requirements from multiple sources (e.g. the requirements document, stakeholder analysis, design context). Within the authoritative text, design requirements are gathered from market analysis as well as initial trade studies comparing the trade-offs between various design options (Roskam, 1990). Thus, the learning goals should direct students to use multiple references when establishing design goals rather than allowing, for example, a narrow fixation on the Request for Proposal alone.

Further, the learning goals should direct students to incorporate the design goals continuously and iteratively across the disciplines. This integration of design goals should also be supported through different design activities in the course. Within the authoritative text, requirements are used to constrain design metrics (e.g. limit the runway takeoff distance) and define performance metrics (e.g. nominal cruise range and velocity). As more information about the design is gained, the performance capabilities should then be compared to the initially defined requirements to confirm that the aircraft is meeting the design specifications.

The design knowledge coordination competencies that the student should learn with respect to design goals are to:

- Use multiple reference points to define design goals (e.g. primary requirements, design context, and stakeholders)
- Apply design goals consistently and iteratively throughout the design process to make and validate design decisions

6.1.2 Learning Goals for Design Tasks

If task definition and decomposition is done well in any design, the tasks and subtasks will be identifiable and they will have an order and a hierarchy. For example, in the design of a traditional, fixed-wing aircraft, the tasks defined by the authoritative text could serve as an example task decomposition for the student design process. These tasks are clearly defined by Roskam (1990) and decompose tasks by design activities, with disciplinary considerations embedded within each high-level task.

Further, if design knowledge coordination is effective, then the links between the tasks and subtasks will be observable. Within the authoritative text, the links between design tasks are maintained through critical metrics. These metrics passed information across tasks as well as across disciplines, creating an integrated design process. The links between the tasks and subtasks allow for iterations within the design process as more knowledge about the design was gained.

The design knowledge coordination competencies that the student should learn with respect to tasks are to:

- Define tasks and subtasks with an order and hierarchy
- Recognize the links between tasks and subtasks
- Iterate across the tasks to update information about the design

6.1.3 Learning Goals for Design Metrics

If metric determination and application is done well in any design, metrics will be apparent in task and subtask completion. Further, observed from a disciplinary-oriented approach, if metric determination and application is done well then the metrics will be defined within the disciplines to guide task/subtask completion and design decisions. The authoritative text used disciplinary metrics to guide tasks centered on analyzing the aircraft through a mathematical perspective. It defined 44 metrics critical to completing multiple tasks and subtasks. These critical metrics should be identifiable within the aerospace engineering design process and incorporated in the decision-making process. The metrics should then be used as supporting evidence for design decisions. This evidence justifying design decisions should be apparent to the designers as well as to external audiences who are interested in learning about the design's features (e.g. the instructors in an educational setting, customers or company executives in industry).

As more information about the design is gained through task completion, the metrics should be aligned across disciplines. For example, in the authoritative text the coefficient of lift is first used to evaluate initial performance characteristics of the aircraft, and then the coefficient of lift is later used to design the airfoil. The metric value for coefficient of lift should be consistent between these two tasks. If these numbers differ, the designer may need to iterate the design to align the metric across tasks, to justify why the initial analysis is still valid.

The design knowledge coordination competencies that the student should learn with respect to metrics are to:

- Recognize critical discipline-oriented metrics to required to complete tasks and subtasks
- Maintain consistent values for metrics across the different disciplines

6.1.4 Learning Goals for Design Decisions

If design decisions are done well in any design, then the decisions will be justified through a completion of design tasks. Accordingly, a learning goal that supports design knowledge coordination is for students to learn to justify decisions through a completion of tasks and, as noted earlier, consideration of the evidence for the decision from the metrics known at that time.

Further, within the design knowledge coordination framework, the overall impact of each local decision should also be related to its global impact on the complete vehicle design. Thus, design courses that support design knowledge coordination should also ask students to describe the overall impact of a critical decisions.

The design knowledge coordination competencies that the student should learn with respect to design decisions are to:

- Justify decisions through a completion of tasks and consideration of evidence
- Describe the overall impact of a particular decision

6.2 Design Activities

The discussed learning goals are guidance for setting expectations for students' design activities and, as necessary, introducing content within aerospace engineering design courses that promote students' development and use of design knowledge coordination. The current capstone design course sequence typically teaches a process similar to the authoritative text. Thus, these learning goals can be integrated within the authoritative texts' design process to support and enhance the curriculum.

However, the capstone course is constrained by the limited time available to teach new content to the students as well as the time available for the students to complete design projects. Consequently, design activities are introduced here as a complement to the design process taught within capstone courses. The students use the design activities as a part of their design process, instead of as separate, additional activities to complete.

The discussed design activities can be used as a complete collection or individually to emphasize aspects of design knowledge coordination to the students. Many of the design activities give the students an integrated perspective of the design process by demonstrating how tasks and metrics are connected across disciplines. This aligns with the current approach to teaching aerospace engineering design while also giving students a coordinated perspective on the context of decision-making in design.

6.2.1 Activities that Support Coordinating Design Goals

The design knowledge coordination learning goals associated with defining design goals are to :

- Use multiple reference points to define design goals (e.g. primary requirements, design context, and stakeholders)
- Apply design goals consistently and iteratively throughout the design process to make and validate design decisions

The learning goals to support a coordinated perspective of design goals are focused on defining and integrating robust design goals throughout the design process. Thus, it is important that the students demonstrate that their design goals consider various aspects of the design and be defined to a level of depth where they can influence design decisions throughout the design process.

While trade-offs are important components to design knowledge coordination, within the case study presented in Chapter 4 and focus group results discussed in Chapter 5, only Team 2 incorporated general aspects of trade-offs related to design goals within their design process. Thus, instructors should incorporate learning goals that explicitly ask students to consider trade-offs within their design requirements. This can be done by asking the students to reference many different types of information to define the design goal and having the students then compare the implications of the different goals, similar to the approach taken when designers implement a requirements definition process and stakeholder analysis.

One approach to defining and integrating robust design goals, used by systems engineers, is the ***requirements definition process***. Within systems engineering, the requirements definition process is a formal component of system design where the designers "identify and express verifiable requirements that state user needs in appropriate terms to guide system concept development" (INCOSE, 2004, p. 99). Requirements are also compared to evaluate interactions between various design components to establish a balanced set of requirements. These requirements are gathered from multiple references, such as from the customer, mission objectives, mission environment, and key performance-based metrics (DAU, 2001).

The systems engineering requirements definition process can be combined with a ***stakeholder analysis*** to fully incorporate stakeholder considerations in the design of an aerospace vehicle. A stakeholder analysis utilizes a highly iterative approach and designers determine the design requirements by engaging in a meaningful dialogue with the system's stakeholders (Gibson, Scherer & Gibson, 2007; Zoltowski, 2010; Coso, 2014). Additionally, stakeholder analysis calls for integrating stakeholder considerations throughout the design process.

An outcome of the requirements definition process and stakeholder analysis is a verifiable and complete list of requirements for the design. Thus, students can incorporate these approaches as a part of their design process by formally and explicitly defining functional and performance requirements of the vehicle, complete with verifiable stakeholder requirements. This design activity aligns with a requirements analysis activity already commonly introduced in the curriculum. However, design knowledge coordination also calls for an evaluation of the completeness of these requirements by examining how they are incorporated in the design. The level-of-depth of the requirements would be dependent on the context of course; within this context, learning goals here emphasize that students' design activities should define requirements such that an outside evaluator can identify how the requirements impacted the design process at each stage of design.

The students' inclusion of detailed design goals and the integration of these throughout the design process is one area of assessment that would be incorporated to evaluate not only students' design knowledge coordination, but also the quality of the design project. The comparison of the initial statement of design goals to the resulting design is one criteria for evaluating the success of the design created by the students.

6.2.2 Activities that Support Coordinating Design Tasks

The design knowledge coordination learning goals associated with defining and decomposing design tasks are to:

- Define tasks and subtasks with an order and hierarchy
- Recognize the links between tasks and subtasks
- Iterate across the tasks to update information about the design

The learning goals for design tasks focus on how the tasks are defined, their integration into the design process, and how they enable iteration within the process. Thus, an approach to supporting design knowledge coordination within the task definition is to have students examine the conceptual design process using a ***design process flow chart***. The design process flow chart is a graphical representation of the relationship between design tasks. This type of flow chart can be compared to a concept map, where the relationships between concepts are visualized (Turns, Atman & Adams, 2000). Within a concept map, concepts are written within nodes, and the nodes are connected with arcs that explicitly describe how the nodes are connected. This type of representation of a system helps students see how larger concepts fit together in the context of the course and how these concepts relate to disciplinary knowledge covered earlier in their course of study (Ellis, Rudnitski, Silverstein, 2004). Thus, by making a design process flow chart, students can similarly see how the design tasks fit together in the context of the design process and how each task relates to individual disciplines as well as to the overall design objectives.

Both Team 1 and Team 2 were able to sketch out their general design process within the focus group discussions. These teams showed a clear understanding of the design tasks and how those tasks fit within the design process. These teams were able to communicate decisions using the design process as a guide for reasoning their design decisions as well as for communicating what information was critical to making the design decisions. A design process flow chart would support similar approaches for students by asking students to map out their design process. Further, these maps could be used to evaluate the teams' understanding of the design process. For example, the instructors might have been able to identify Team 3's confusions within the design process earlier in the semester had they asked the team to map out the design process.

Graphical representations of interdependencies, such as concept maps, have been used to evaluate students' design processes within an educational context (Watson, Pelkey, Noyes, Rogers, 2016) as well as a teaching tool to demonstrate how disciplines connect across courses (Ellis et al. 2004). Thus, within aerospace engineering design courses, a design process flow chart can be used as a teaching tool to demonstrate the different tasks within the conceptual design process and how those tasks link across disciplines.

Within an aerospace engineering design curriculum, a potential integration of design process flow charts into the design course would ask students to map the conceptual design process using a graphical representation of design tasks at the start of their design process, and then reflect on their design process at various points in the semester. At the start of the semester, this would provide an explicit requirement for students to plan their approach to the design process. At a midterm point, the students could be asked to update the flow chart to reflect a more accurate representation of the design tasks as they have evolved. This flow chart could be included in any midterm design reviews and guide how they present their progress to the instructors. At the end of the semester, the students would reflect on the completed process and, again, use the flow chart as a guide when explaining their design process to instructors in their final presentation and report.

From an evaluative perspective, the flow chart would give instructors a starting point for providing formative feedback on the students' design process, including the appropriateness and completeness of the planned tasks. Additionally, the instructors could use the flow chart at the midterm to evaluate if the student team has completed a sufficient number of tasks or if the team is behind the expected design progress, and whether the student team is considering the current linkages between concepts. At the end of the semester, the flow chart could guide an instructors' summative evaluation of the students' design progress.

6.2.3 Activities that Support Coordinating Design Metrics

The design knowledge coordination learning goals associated with using metrics within the aerospace engineering design process are to:

- Recognize critical discipline-oriented metrics required to complete tasks and subtasks
- Maintain consistent values for metrics across the different disciplines

The use of metrics in the design process is generally taught in the context of mathematical models applied during vehicle design (Gainsburg, 2006). Within the aerospace engineering design process, these metrics have typically been taught to the students within previous technical courses. Several of the critical metrics within the authoritative model were taught in multiple courses or used as a foundation for more technical knowledge in the design process. For example, the coefficient of lift is generally included as part of the curriculum in introductory aerospace courses. The coefficient of lift is later used as a part of the aerodynamics courses as well as courses related to flight dynamics and controls.

Mathematical models drive information management within the design process. Designers use the mathematical models as a way to gain more information about the design and to justify design decisions (Gainsburg, 2007; Gainsburg, 2015). One approach to supporting students' use of the appropriate discipline-oriented metrics in the design process is to demonstrate how the mathematical model fits within the context of the design process (Gainsburg, 2015). For example, instead of presenting the different disciplines each as a stand-alone component of the design process (with its own metrics), instructors could describe how specific metrics fit into multiple disciplines. When students understand the mathematical models in the complete context of the design process, then they will be more capable of using the appropriate discipline-oriented metrics to complete tasks and subtasks and integrating these metrics across disciplines. Within the students' understanding of mathematical models, metrics serve as inputs to the model, and the output of the model serves to further identify and refine metrics for subsequent tasks.

Incorporating a ***design structure matrix*** as a part of the aerospace engineering design process supports a coordinated perspective of metric determination and use. As discussed in Chapter 2, the design structure matrix reaches across disciplines and explicates the interdependencies within the task environment (Goel & Pirolli, 1992). This tool also aids in developing an engineering plan to manage information flow within the design work (Steward, 1981).

Requiring students to include a design structure matrix in their presentation and reports on their design process could help them explicitly see the links between tasks and understand what component or metric of the design process supports those task connections. Additionally, iterations within the design process would be captured by the design structure matrix. While Team 1 did not incorporate a design structure matrix in their presentation, they did bring elements of a design structure matrix to their presentation. Team 1 discussed their metrics in a meaningful manner where it was clear that they understood how each metrics impacted their design decisions. A design structure matrix similarly supports an explicit awareness of the metrics required to make design decisions. However, the design structure matrix moves beyond Team 1's approach to also provide a formal method to identifying and defining metrics within the design process.

Consistency in the metrics is maintained through engineering designers' externalization of the mathematical models and decision-making as well as through their organization skills, i.e. organization of the tools that integrate metrics. Student teams could be required to externalize the reasoning for all (or some key subset) of their decisions and specific metric values as a way to document the design process and maintain consistent metrics (English, 2009). Further, the tools used to make decisions should be regularly updated to match the most up-to-date information about the design. The design structure matrix would serve as one method for having student externalize their process. They could also use the matrix as a representation of when they should update and iterate information in the design.

If the student teams provide a design structure matrix, instructors could more easily evaluate which metrics the students used in their model as well as the nature of iteration within the design process. The students' metrics could be compared to the 44 metrics used by the authoritative model to connect tasks. With this approach to evaluating the design process, the instructor could explicitly probe on which metrics were included in the design process and which metrics were not included in the design process.

6.2.4 Activities that Support Coordinating Design Decisions

The design knowledge coordination learning goals associated with design decisions within the aerospace engineering design process are to:

- Justify decisions through a completion of tasks and consideration of evidence
- Describe the overall impact of a particular decision

The last component of design knowledge coordination is making and justifying design decisions. Similar to the rational decision-making model, decision-making within design knowledge coordination is the outcome of a task (or tasks) compared to a specified goal (Badke-Schaub & Gehrlicher, 2003; Jensen & Ahmed-Kristensen, 2010). Thus, as one design activity, instructors should focus on instructing students to make decisions based on a rational process that includes an analysis of the system compared to the goals of the design. Both Team 1 and Team 2 used rational decision-making to justify their design decisions.

Students' understanding the overall impact of a decision could be more explicitly demonstrated with appropriate ***systems engineering methodologies and decomposition tools***. Through systems engineering, the designer can see the impact of decisions as a waterfall effect, where one decision might impact several other future decisions. The impact of decisions is observed through methods such as functional decomposition, work breakdown structures, and the product breakdown structure (DAU, 2001; INCOSE, 2004). While Team 1 and Team 2 did not incorporate a formal systems engineering process, both teams exhibited elements from systems engineering. They decomposed their designed aircraft into functional systems and divided design tasks based on those functions. Additionally, both teams were able to relate their decisions within disciplines back to the intended function of that system. An improvement that systems engineering methodologies offers is the demonstration of connections across disciplines by showing how each piece integrates with the complete system. It also gives a preliminary perspective on the impact of how changes within one component impact other components.

While redesigning the aerospace engineering design course to match the principles taught within systems engineering may not be feasible given the time and content constraints on the course, including elements of systems engineering within the students' design process could streamline some of the design tasks. For example, a functional analysis and allocation uses the requirements output to guide analysis of the design and decision-making from completed tasks. The functional analysis decomposes the design by function and identifies what each function needs to do (e.g. the engine must be capable of providing XX pounds of thrust, as determined by a previous analysis). Additionally, a functional analysis allows the students to perform trade studies to evaluate alternative decisions.

As another systems engineering method, a work breakdown structure defines the complete design process by decomposing it into component-oriented family tree. Within each component, the student design team can allocate performance analyses and track configuration and data management.

The inclusion of these systems engineering tools may require some additional up-front instructions. For example, the instructor might dedicate one, or two, lab sessions in the first semester of a two-semester design course to teach the students a systems engineering toolbox. This lab session could incorporate an aircraft design task and could ask students to analyze the task using systems engineering methods and tools. Then, in the second semester of the course, the students could be required to apply the same systems engineering method and tool in defining their design process to guide their breakdown of the design into components and analyses. Likewise, students could then be required to use the representation in their design process, including in design presentations and reports. The instructor could use the same representation of the design to provide feedback on the students' design process.

6.2.5 Educational Interventions that Support Design Knowledge Coordination Across Goals, Tasks, Metrics, and Decisions

Overall, the learning goals of design knowledge coordination are well-suited to scaffold and structure the different aspects involved within the engineering design process. In a broader sense, the instructor of a capstone design course could present an initial framing of engineering design using goals, tasks, metrics, decisions as lens into the process and discuss how each fits into the overall scheme of aerospace engineering design. While the previous sections discussed design activities that can be used to promote each of the goals, tasks, metrics, and decisions lens, instructors should also consider incorporating teaching methods that support coordination across the goals, tasks, metrics, and decisions. For example, problem-based learning is a learner-centered instructional approach that asks students to solve complex, ill-defined problems independent of formal (i.e. traditional) course instruction (Savery, 2006). One aspect of formal approaches to problem-based learning that impacts students' design knowledge coordination is the role of course instructors (and teaching assistants and any other designated mentors) as a "facilitator" (Pembridge, 2011; Lutz, Hixson, Paretti, Epstein, & Lesko, 2015; McLean, 2003). Within the problem-based environment, the facilitator serves to coach students on their design and critical thinking skills and their interaction as a team. Such facilitation generally focuses on identifying and articulating to the students these aspects of their immediate activities. The facilitation is intended to be formative, i.e., it occurs frequently based on immediate observations to foster student reflection and improvement throughout the course.

Beyond design, aspects of design knowledge coordination can and should also be implemented in other aerospace engineering courses within the overall university curriculum. Efforts to incorporate a coordinated-perspective in other courses can be done by considering how the learning goals for design knowledge coordination influence the course learning goals. Thus, other actions that instructors could take to support design knowledge coordination in more disciplinary courses throughout their curriculum is to continuously connect the technical material taught in their course to the technical material taught in other courses. This could be achieved by adding ‘bookends’ to a semester-long course. At the start of the semester, the instructor would outline the material that was covered in previous courses that directly influences the material taught within their course. And, at the end of the semester, the instructor would ask the students to look forward at the next sequence of courses to see how this material could be used in future coursework. Similarly, another teaching approach might be for instructors to outline specifically where their course would influence the performance of the vehicle (or other aspects frequent to design goals, such as cost) and, correspondingly, fixed-wing design process.

6.3 Implications and Summary

Student learning of design knowledge coordination can be supported through learning goals and design activities that represent the design process as a complete, iterative process, rather than a linear, sequential checklist of tasks. The learning goals were developed using the design knowledge coordination framework and the authoritative text. The design activities were suggested using the learning goals as a basis of curriculum needs. Further, the teams that exhibited high-design knowledge coordination were already implementing many aspects of these design activities.

The discussed design activities and interventions provide a structure for the engineering design process, while accounting for the engineering design context and professional norms. Of note, many of the aspects of design knowledge coordination are supported through systems engineering methods, and these interventions align with those methods. Thus, aerospace engineering design curriculum may benefit by learning goals and design activities incorporating both characteristics of and tools from systems engineering.

While these learning goals and design activities focused on individual pieces of design knowledge coordination, a cohesive picture could also be incorporated in design courses by using the framework as a lens to scaffold and evaluate student design processes. Similar to the approach taken in Chapter 4, the framework characterizes indicators of design knowledge coordination. Thus, in this respect the framework is a tool for classroom and curriculum development.

There is a pendulum swing to consider at this point regarding the amount and type of activities and interventions to incorporate. At one end of the pendulum swing, the incorporation of activities and interventions to support design knowledge coordination may over-scaffold the design process. That is, by providing students the exact steps that must be taken within the design process and the exact pieces of information that must be shared throughout, the students may not experience deep and meaningful learning where they independently discover how to think critically within a design task. At the other end of the pendulum swing, choosing to not integrate activities to support design knowledge coordination may require students to identify the need for design knowledge coordination and methods to achieve it; while this can lead to deeper learning and critical thinking, it is also possible that some student teams (such as Team 3 discussed earlier) may not be able to achieve this learning and experience a successful design.

Thus, design curriculum should be complemented through integration of activities and interventions to support design knowledge coordination. The discussed design activities and teaching methods are intended to promote design knowledge coordination in an aerospace engineering classroom. Students must see the value and usability in the implemented design activities. The value and usability of a design activity is conveyed by integrating the design activity fully into the course curriculum (versus incorporating it as an optional adhoc activity). Design activities should connect directly to the students' ability to conceive analyze, and evaluate design decisions. Further, instructors should evaluate student performance in the design process to the appropriate inclusion of these design activities.

CHAPTER 7 - CONCLUSIONS, FUTURE WORK, & IMPLICATIONS

7.1 Summary of Findings

Design Knowledge Coordination is a structured approach to integrating design considerations across the different disciplines in engineering design framed in terms of the design constructs of goals, tasks, metrics, and decisions. By conducting a systematic evaluation of literature from disparate research areas, a framework for design knowledge coordination was developed. This addressed part of Research Question 1: ***What design knowledge coordination does aerospace engineering require?*** The research approach in Chapter 2 drew together various strands of research to connect findings and develop a characterization of design knowledge coordination. The resulting framework distinguished between three different approaches to structuring an approach to decision-making within engineering design. The first, 'basic' approach represents the lowest effort of decision reasoning and only requires minimal structure and organization. The second, 'discipline-oriented' approach breaks the design process into discipline-oriented boundaries and exchanges information within those boundaries. The third, 'coordinated' approach, brings a design knowledge coordination to the design process.

This framework was then applied to the aerospace engineering conceptual design process to provide insights on the coordination inherent to an authoritative model of aerospace engineering. The application of the framework to an authoritative model addressed the second part of Research Question 1 and placed the framework within the context of the research. This authoritative text can be used to (1) examine current coordinated practices in aerospace engineering and (2) examine for observable indicators of design knowledge coordination by novice aerospace engineering designers.

The research also utilized the design knowledge coordination framework to examine the presence (or lack) of coordination by student teams in an aerospace engineering senior design capstone course. The resulting case study answered Research Question 2: ***How do novice aerospace engineers coordinate and integrate knowledge about a design?*** By examining observed indicators of design knowledge coordination instances of both coordinated and basic (uncoordinated) approaches to design were identified. In Chapter 5, these indicators were verified using a second study incorporating students' perspectives of design knowledge coordination.

Lastly, suggestions for educational interventions were characterized using the design knowledge coordination framework and indicators of high- and low-coordination. The last portion of this research answered Research Question 3: ***What educational interventions can better support novice aerospace engineers' design knowledge coordination***. In Chapter 6, the framework and indicators of high and low-coordination were used to outline learning goals for promoting student use of design knowledge coordination. Following, design activities were presented from the systems engineering literature that support the design knowledge coordination learning goals.

7.2 Contributions of Research

Though effective coordination is required in the successful design of an aerospace vehicle, instruction in design knowledge coordination has yet to be researched in the literature. The findings of this doctoral work contribute to both aerospace engineering design and engineering education research by framing and characterizing design knowledge coordination in the context of aerospace engineering design education. The work detailed throughout this document then relates this authoritative description of design knowledge coordination to observations of student teams and to educational interventions.

7.3 Limitations

Limitations of the methods applied in this thesis include data collection from only a single design course at a single university, and the examination of that course by a single investigator. The bias introduced by the single investigator was mitigated using two techniques. The first technique was to evaluate the inter-rater reliability of the qualitative coding. The second technique was to triangulate the findings of the first qualitative study by analyzing a second data set from the same population and confirming the results of the first study.

Additionally, while the researcher attempted to have a passive role in the course, her presence in the classroom and interactions with the students can be viewed as a potential influence on student behavior. The researcher attempted to mitigate this effect on student behavior by not responding to inquiries on team performance. Additionally, the researcher maintained a notebook of interactions that she had with the students outside of the observations. This notebook was later examined for any stand-out interactions that may have influenced the study's outcome. None were noted.

7.4 Future Work

7.4.1 Engineering Education Research and Application

By incorporating an integrated design perspective into engineering design curricula through coordinated decision-making, this work can assist faculty in preparing their students to interact within a dynamic and complex design environment after graduation. Future studies could further apply the framework to the development of educational interventions, including project requirements, in-class activities, and performance rubrics. These interventions would focus on students' integration of design principles across disciplines and teach students how to manage the integration process.

As a long-term objective, this framework could be used to evaluate curriculum programs across the technical areas. Points of integration within the courses could be identified and made explicit within the learning outcomes of these earlier, discipline-specific courses. Additionally, design projects could be created with the intent of integrating knowledge across the disciplines.

7.4.2 Enhancing Industry Practice

While this work focuses primarily on the development of a framework for design knowledge coordination within aerospace engineering design problems, the findings of this research likely also have broader implications for complex systems design. The design of complex systems involves multiple disciplines, systems integration, and design collaboration, resulting in the need for strategies similar to those outlined in this proposal for aerospace engineering. Thus, this work can be extended to other design areas and integrated into the design process for any complex system. Further, future applications of this work can be used to conduct an evaluation of decision-making processes within professional engineering design teams.

Additionally, this research could be used to capture and document coordinated work practices within complex systems design. The design knowledge coordination framework analyzes aspects of coordination in the design process that may largely be implied within designers work practices. Thus, implicit knowledge of how to integrate systems across disciplines could be documented and made explicit using this framework. The documentation of coordinated practices could then lead to the development of protocols as well as training programs within industry.

APPENDIX A –DESIGN KNOWLEDGE COORDINATION IN CONCEPTUAL DESIGN AUTHORITATIVE TEXTS

A qualitative analysis placed the metrics from mathematical models listed in Roskam into an Excel spreadsheet, along with its high-level and subtask classification, and this list was analyzed for cross-disciplinary features. A full description of the authoritative text's design process is in Table 50.

Table 50. Design knowledge coordination within the authoritative text

Task	Subtask	Decision	Metrics
Define Requirements and Outline Mission	Outline Mission requirements	Mission parameters	Cruise Rqmt
			#Crew per Aircraft
			Type of Payload
			W Pay
			V Cruise
			V Max
			V Loiter
			V Ldg
			R Cruise
			R Max
			Endurance time
			TOFL
			LFL
			Cost Dev
			Cost Acq
			Cost O&S
			LCC
			Maintenance Hrs per Flight Hour
			Service Ceiling
			Landing Roll
	Technology Selection	Technologies	Tech
			TRL

Table 50. Design knowledge coordination within the authoritative text (Cont'd)

Task	Subtask	Decision	Metrics
Initial Aircraft Sizing	Historical Regression of Weight	W_allow	Year
			W_Similar AC
	First Weight Estimate	W_Calc, WTO, WEmpty, Fuel Volume	WTO
			W Empty
			W OE
			W Fuel
			WPay
			WTFO
			W Crew
			W Empty Manuf
			W Fixed Equip
			DWeight Calc
			WTO Guess
			W Fuel Reserves
			W Fuel Used
			WF
			WF Segment
			L/D
			SFC
			R Cruise
			W Empty Allow
			W Empty TO
			W Empty Calc
			W Empty Est
			A Intercept
			B Slope
			FF Reserves
			FFAvg
			MFF Climb
			MFF Cruise
			MFF Decent
			V Max
			R
			L/D Cruise

Table 50. Design knowledge coordination within the authoritative text (Cont'd)

Task	Subtask	Decision	Metrics
			M Cruise
			VCruise Segment
			L/D Cruise Segments
	Sensitivity Studies--Takeoff Weight Sensitivity to: Payload Weight, Range, Endurance, Speed, SFC, and L/D		WPay
			W Empty
			R
			Endurance
			L/D
			SFC
			W Crew
			W Fuel
			WTO
			MFF
			W Fuel Reserves
			WTFO
			FF Reserves
			FF TFO
			c coef
			D Weight Eqn
Determine Critical Performance-Based Metrics	Estimate Drag Polar	ClmaxTO, Lift, CD0, Drag polar	CD
			CD0
			CL
			AR Wing
			SWing
			Equivalent parasite area
			e
			Swet
			a coef
			b coef
			c coef
			d coef
			dCD0
			Cf
	Prepare Constraint Diagram: Stall Speed	SWing, MTOW, Treq, W/S, T/Wmin	V Stall
			CLMax
			Density Air
			W/S
			CLMax TO
			CLMax Ldg

Table 50. Design knowledge coordination within the authoritative text (Cont'd)

Task	Subtask	Decision	Metrics
	Prepare Constraint Diagram: Takeoff		TOFL
			WTO
			VTO
			T/W TO
			CD
			Ground Friction Coefficient
			Pilot Technique
			TOP
			W/S
			CLMax TO
			Air Density Ratio
			Density Air
			BPR
			SWing
	Prepare Constraint Diagram: Landing		V Approach
			WLdg
			Decelleration Method
			Flying Qualities
			Pilot Technique
			V Stall
			W/S Ldg
			WTO/S
			CLMax Ldg
	Prepare Constraint Diagram: Climb Req		CGR
			V
			L/D
			CL
			CD0
			CDi
			CLMax
			AR Wing
			e
			CLMax TO
			CD
			T/W TO
			V Stall
			ROC
			V

Table 50. Design knowledge coordination within the authoritative text (Cont'd)

Task	Subtask	Decision	Metrics
	Prepare Constraint Diagram: Time to Climb		T/W
			L/D
			W/S
			CD0
			AR Wing
			e
			Density Air
			L/D Max
			Thrust
			Drag
			W
			h
			Swet
			Cf
			dCD0
	Prepare Constraint Diagram: Maneuver		n
			CL
			V
			Density Air
			SWing
			nMax
			W/S
			Thrust
			T/W
			CD0
			AR Wing
			e
Determine Initial Configuration and Layout of Aircraft	Overall Configuration Selection	A/C Type, #Engines, # Fuselages, Engine Type, Engine Disposition, Wing Configuration, Empennage Configuration, Ldg Gear Type	FOM
			Stakeholders
			Type of AC
			Similar AC
			#Engines

Table 50. Design knowledge coordination within the authoritative text (Cont'd)

Task	Subtask	Decision	Metrics
			#Fuselages
			Type of Engine
			Engine Placement
			Wing Config
			Config Empennage
			Type of LG
	Airfoil Selection and Planform Shape	Structural Wing Configuration, Wing/Fuselage Arrangement, Maximum Thickness Ratio of the Airfoil, Location of tmax, camber, AR, Sweep Wing, Taper Ratio Wing, incidence angle, twist angle, dihedral angle, lateral control surface size and layout	AR Wing
			CD0
			e
			CLalpha
			CLMax
			W Wing
			ct/Cr
			t Airfoil Center
			rLE
			Camber
			K
			Vol Fuel Wing
			t/c max
			M Crit
			c Mean
			Cf
			Cm
			CL
			rLE
			D Wave
			CD LE
			M
			dNose Flap
			LE Suction
			Cm a/c
			AoA0L
			CLmin
			CDmin
			Cd Section
			Sweep LE
			Max t line
			ct/Cr
			Cp

Table 50. Design knowledge coordination within the authoritative text (Cont'd)

Task	Subtask	Decision	Metrics
			Cl Section
			Cm Section
			AoA
			W
			bWing
			Sweep Wing
			iW
			Spanwise Twist
			Gamma W
			Sweep c/4
	High-Lift Devices	Type of High-Lift Devices, HLD Area, Location of HLD	CLMax
			CLMax TO
			CLMax Ldg
			clmax t
			clmax r
			Swet Flaps
			SWing
			ct/Cr
			Location of Flaps
			Flap to Chord Ratio
			d Flaps
			DCLMax due to Flaps
			DCl due to Flaps
			Cl Section
			dAoA Flaps
			Re
			Type of Flaps
	Fuselage Layout	Arrangement of Cargo, Flightdeck Layout, Cabin Layout, Fuselage Radius, Fuselage Length	Type of Cargo
			h cargo
			w cargo
			l cargo
			#Crew per Aircraft
			Crew Seating Arrangement
			Crew Seat Angle
			Over-Nose Viewing Angle
			Over-Side Viewing Angle

Table 50. Design knowledge coordination within the authoritative text (Cont'd)

Task	Subtask	Decision	Metrics
			Type of LG
			Tip-Over
			Turnover Angle
			Wing Carry-Through Volume
			Vol Fuel Fuse
			Type of Fuel Tank
			Type of Avionics
			W Avionics
			Volume Avionics
			Empennage Area per SWing
			W Empennage per Area
			CD0 Fuse
			cf Fuselage
			Cdpmin Fuse
			lf/df
			D Wave Fuse
			d fuse
			l fuse
			M Cruise
	Preliminary Sizing of Empennage	Location of Vertical Tail, Location of Horizontal Tail, SVert Tail, SHoriz Tail, c rudder, S Aileron, S Elevator, c Elevator, c Aileron, AR Vert, AR Horiz, Sweep Vert, Sweep Horiz, ct/cr Vert, ct/cr Horiz, Dihedral Angle Vert, Dihedral Angle Horiz, iVert, iHoriz	Tail Vol Ratio Horiz
			Tail Vol Ratio Vert
			Location of Vert Tail
			Location of Horiz Tail
			SVert Tail
			SHoriz Tail
			SWing
			c Mean
			bWing
			crudder
			SAileron
			SElevator
			cElevator
			cAileron
			ct/Cr
			AR Vert Tail
			AR Horiz Tail
			Sweep Vert Tail

Table 50. Design knowledge coordination within the authoritative text (Cont'd)

Task	Subtask	Decision	Metrics
			Sweep Horiz Tail
			ct/cr Vert Tail
			ct/cr Horiz Tail
			Dihedral Angle Vert
			Dihedral Angle Horiz
			iVert Tail
			iHoriz Tail
			l Horiz
	Preliminary Landing Gear Configuration	Type of landing Gear, Location of Landing Gear, Number of Tires, Tire size	Type of LG
			Location of LG
			#Tires
			Tire size
Improve Aircraft Weight Estimation and Configuration	V-n Diagram	Wempty	V Stall
			V Cruise
			V Dive
			V Manuever
			WTO/S
			Density Air
			CNMax
			CD
			CLMax
			K V-n
			LLF
			n
			V Stall neg
			Gust Load Factor
			Gust Velocity
			Airplane Mass Ratio
			SWing
			n Ult
			V
	Class II Weight Est: Structural Weight		AR Wing
			M Max
			WTO
			n Ult
			t/c
			ct/cr
			Sweep LE

Table 50. Design knowledge coordination within the authoritative text (Cont’d)

Task	Subtask	Decision	Metrics
			SWing
	Class II Weight Est: Empennage Weight		SHoriz Tail
			bHoriz Tail
			lt
			n Ult
			WTO
			t Horiz
			cHoriz
			hT/hV
			SVert Tail
			M Max
			AR Vert Tail
			ct/cr Vert Tail
			Sweep Vert Tail
			SRudder
	Class II Weight Est: Fuselage Weight		K Inl
			Density Air
			V
			l Fuse
			h Fuse
	Class II Weight Est: Fuel System Weight		W Fuel
			Kfsp
	Class II Weight Est: Propulsion System Weight		W Engine Controls
			W Engine Starting System
			W Oil System
			W Engine
	Class II Weight Est: Other-- Flight Control System Weight, Electrical System Weight, Avionics Weight, Oxygen System, Furnishings, Auxilary Power Unit, Cargo Handlinh, operational Items, Weapons, Flight Test Instruments, Ballast, Paint		WTO
			#Engines
			#Crew per Aircraft
			M Dive

Table 50. Design knowledge coordination within the authoritative text (Cont'd)

Task	Subtask	Decision	Metrics
	Structural Arrangement	Structural Components and Arrangement	Materials
			n
			Lift
			W
			n Ult
			Safety
			V Manuever
			V Approach
			V Stall
			LLF
			V Max
			MTOW
			W Ldg Max
			W OE
			V Cruise
			V Dive
			k
			Gust
			Mission Profile
			J Materials
			G
			Stress
			Strain
	Locate Component CG	Interior Arrangement	W Components
			x AC Components
			Moments of Inertia
	Finalize 3D Model and Three-View		alat
Conduct a Performance Analysis	Analyze Aircraft Stability		AR Wing
			AR Horiz Tail
			bWing
			b flapped wing
			alat
			avert
			cWing
			SFC
			cbeta
			CD0
			CD

Table 50. Design knowledge coordination within the authoritative text (Cont'd)

Task	Subtask	Decision	Metrics
			CGR
			Chinge
			chinge0
			chinge AoA
			chinge beta
			chinge dctl
			Clp
			Clr
			Clbeta
			Clda
			Cldr
			CL
			CL0
			CLalpha
			Clde
			Clw flaps
			Cmac flaps
			Cmacwf
			Cm
			Cm0
			CmAoA
			Cmdctrl
			Cmde
			Cmq
			Cnp
			Cnr
			Cnbeta
			CnbetaB
			Cnda
			Cndr
			Cride
			CTx
			Cyp
			CYr
			Cybeta
			Cyda
			Cydr
			dT
			Drag

Table 50. Design knowledge coordination within the authoritative text (Cont'd)

Task	Subtask	Decision	Metrics
			e
			Endurance
			fmp
			fto
			Fa
			Fr
			Fs
			Fty
			Gearing Ratio
			h
			hL
			hTO
			HM
			Ixx
			Iyy
			Iyymg
			Izz
			Gust Parameter
			lh
			Lift
			Sweep LE
			Lift Horiz
			Gust Force
			Lift WF
			ClT
			Macwf
			n
			Roll rate
			Pm Total
			Pn Total
			Ps
			V
			Density Air
			R
			ROC
			RoD
			Rloop
			Turn Radius
			LFL

Table 50. Design knowledge coordination within the authoritative text (Cont'd)

Task	Subtask	Decision	Metrics
			TOFL
			SWing
			Time
			Thrust
			TR
			Troll
			TD
			V Approach
			V Stall
			VTD
			W
			Fuel Flow Rate
			xac
			xachoriz
			xacwf
			xcg
			ln
			lm
			ln
			lm
			zDrag
			zmg
			zThrust
			AoA
			Beta
			Flight Path Angle
			Sweep LE
			dCtrl
			Downwash Angle
			Density Air
	Evaluate Maintenance and Accessibility		
	Perform Preliminary Cost Analysis		
			W Airframe
			W Empty
			V Max
			#Aircraft Test
			Type of Airframe Material

Table 50. Design knowledge coordination within the authoritative text (Cont'd)

Task	Subtask	Decision	Metrics
	Development Cost (Reference RAND)		NRE
			NRT
			Cost Dev & Support
			Cost Flt Test
			RE100
			RE100
			RML100
			RMM100
			RQA100
			W Structures
			#AC
			Cost Engr
			Cost Tooling
			Cost Manuf
			Cost Qual Ctl
			Tmax Engine
			M Max
			TiT
			W Avionics
			$/W Avionics
	Procurement Cost (use term Cost Estimating Relationships)		#Eng Hrs
			#Tooling Hrs
			#Manuf Hrs
			Materials
			#QC Hrs
			W Empty
			V Max
			#AC
			#Aircraft Test
			LCC
			Cost Acq
			Cost Operation
			Cost Total
			CPI
			$/Hr
			Price/Unit_Sim AC
			W Empty
			Cost by Material
			Cost Operation

Table 50. Design knowledge coordination within the authoritative text (Cont'd)

Task	Subtask	Decision	Metrics
	Operations & Maintenance Costs		Cost Fuel
			Cost per Crew Member
			Depreciation of Money
			Cost Maintenance
			Landing Fees
			Cost of Administration
			#AC
			Flt Hrs per Year
			Cost Fuel Projected
			#Crew per Aircraft
			Utilization
			Cost Labor
			MMH/FH
			V Cruise
			WTO
			Cost Materials
			Cost Engine
			#Engines
			Cost_Similar AC
	Overall Cost		Cost R&D
			Cost O&S
			Cost Production

APPENDIX B – AEROSPACE ENGINEERING METRIC ABBREVIATIONS AND FULL NAMES

A complete list of metrics in the conceptual design process, their abbreviation and their full name, are listed in Table 51.

Table 51. List of metric abbreviations and their full name

Metric Abbreviation	Full Metric Name
#AC	Number of Aircraft Produced
#AC Dev	Number of Aircraft Developed
#Aircraft Test	Number of Aircraft Tested
#APU Gen	Number of APU Generators
#Bogies	Number of Bogies
#Crew per Aircraft	Number of Crew Members Per Aircraft
#Crew per Aircraft	Number of Crew Members
#Crew_C5	Number of Crew Members in the C5
#Eng Hrs	Number of Engineering Hours
#Engines	Number of Engines
#Fuselages	Number of Fuselages
#Man Hours	Number of Man Hours
#Manuf Hrs	Number of Manufacturing Hours
#Manufacturers	Number of Manufacturers
#Pallets	Number of Pallets
#QC Hrs	Number of Quality Control Hours
#Struts LG	Number of Struts on the Landing Gear
#Tires	Number of Tires
#Tires MG	Number of Tires on Main Gear
#Tires NG	Number of Tires on Nose Gear
#Tires per Bogie	Number of Tires per Bogie
#Tooling Hrs	Number of Tooling Hours
#Vert Tails	Number of Vertical Tails
%Al	Percent of Aluminum
%Chord	Percentage of the Chord
%Composites	Percentage of Composites
%Composites AC Component	Percentage of Composites by Aircraft Component
%Composites by Year	Percentage of Composites by Year
%Fuel Used Segment	Percentage of Fuel Used by Segment
%Laminar Flow	Percent Laminar Flow
%Savings per Aircraft	Percentage Savings per Aircraft
%Wempty Sav	Percentage of Empty Weight Savings
$/Hr	Hourly Rate for Aircraft Construction
$/W Avionics	Approximate Cost per Pound of Avionics

Table 51. List of metric abbreviations and their full name (Cont'd)

Metric Abbreviation	Full Metric Name
A Adj	A Adjusted
a coef	a Coefficient
A Intercept	A
A Intercept	A Intercept
A Mat	A Matrix
A Trapezoidal	Trapezoidal Reference Area
AC Geom	Aircraft Geometry
AC Perf	Aircraft Performance
Aft CG	Aft Center of Gravity
Air Density Ratio	Air Density Ratio
Airfoil Type	Airfoil Type
Airplane Mass Ratio	Airplane Mass Ratio
alat	Lateral Acceleration
Altitude_Similar AC	Altitude of Similar Aircraft
Aneh Horiz & Vert Tail	Anehedral Angle of the Horizontal Tail and Vertical Tail
Aneh Wing	Anehedral Angle of Wing
Aneh Wing_Similar AC	Anehedral Angle of Wing of Similar Aircraft
Anew	Updated A Intercept
Angle Front Ramp	Angle of the Front Ramp
Angle Lamina	Angle of the Lamina
Angle Rear Ramp	Angle of Rear Ramp
AoA	Angle of Attack
AoA0L	Angle of Attack at Zero Lift
AR Horiz Tail	Aspect Ratio of Horizontal Tail
AR Vert Tail	Aspect Ratio of Vertical Tail
AR Wing	Aspect Ratio of Wing
Aesthetics	Aesthetics
avert	Vertical Acceleration
B Adj	B Adjusted
b coef	b Coefficient
b flapped wing	Span of the Flapped Wing
B Mat	B Matrix
B Slope	B Slope
Balanced FL	Balanced Field Length
Bank Angle	Bank Angle
Beta	Sideslip Angle
bHigh Lift Dev	Span of High Lift Devices
bHoriz Tail	Span of the Horizontal Tail
BPR	Engine Bypass Ratio
bStabilizer_C5	Span of the Stabilizer of the C5

Table 51. List of metric abbreviations and their full name (Cont'd)

Metric Abbreviation	Full Metric Name
bt MG	bt of the Main Gear
bt NG	bt of the Nose Gear
bVert Tail	Span of the Vertical Tail
bWing	Span of the Wing
bWing	Wing Span
bWing_C5	Span of the Wing of C5
bWing_C5	Wing Span of the C5
c coef	c Coefficient
C Fuse	Coefficient of the Fuselage
c Geom_Similar AC	Geometric chord Length of Similar Aircraft
c Mean	Mean Chord Length
c Span	Spanwise Chord
cAileron	Chord of the Aileron
Camber	Camber
Cant Angle Winglet	Winglet Cant Angle
Cargo	Cargo
Cargo Rqmt	Cargo Requirement
Cargo_C130	Cargo of the C130
Cargo_C17	Cargo of the C17
Cargo_C5	Cargo of the C5
Carving LE	Leading Edge Carving
cbeta	Gear Cornering Coefficient
CD	Coefficient of Drag
Cd BAC1	Coefficient of Drag of the BAC1
Cd CAST102	Coefficient of Drag of the CAST102
CD Components	Coefficient of Drag by Aircraft Components
CD LE	Leading Edge Bluntness
Cd SC(2)0714	Coefficient of Drag of the SC(2)0714
Cd Section	Section Drag Coefficient
CD Segment	Coefficient of Drag by Segment
Cd_Similar Airfoil	Coefficient of Drag of Similar Airfoil
CD0	Profile Drag
CD0 Class I	Profile Drag Class I
CD0 Class II	Profile Drag Class II
CD0 Fuse	Profile Drag of Fuselage
CD0 Horiz Tail	Profile Drag of Horizontal Tail
CD0 Nacelle	Profile Drag of Nacelle
CD0 Vert Tail	Profile Drag of Vertical Tail
CD0 Wing	Profile Drag of Wing
CDi	Induced Drag
CDM	Cruise Drag Multiplier

Table 51. List of metric abbreviations and their full name (Cont'd)

Metric Abbreviation	Full Metric Name
CDmin	Minimum Coefficient of Drag
Cdpmin Fuse	Pressure Drag Coefficient due to Viscous Separation
cElevator	Chord of the Elevator
cElevon	Chord of the Elevon
cf	Coefficient of Friction
Cf Components	Coefficient of Friction of the Components
cf Fuselage	Coefficient of Friction of the Fuselage
cFlaperon	Chord of the Flaperon
CG Components	Center of Gravity of Aircraft Components
CG Empty	Center of Gravity at Empty Weight
CG Fuel	Center of Gravity of the Fuel
CG Overall	Center of Gravity of Aircraft
CG Range	Range of the Center of Gravity
CG Systems	Center of Gravity of Aircraft Systems
CG TO	Center of Gravity of Aircraft at Takeoff
CG_787	Center of Gravity of the 787
CGR	Climb Gradient
Chinge	Coefficient of the Hinge Moment
chinge AoA	Coefficient of the Hinge Moment due to Angle of Attack
chinge beta	Coefficient of the Hinge Moment due to Sideslip Angle
chinge dctl	Coefficient of the Hinge Moment due to Control Surface Deflection
chinge0	Coefficient of the Hinge Moment at Zero Angle of Attack
cHoriz	Chord of the Horizontal Tail
CL	Coefficient of Lift
Cl BAC1	Coefficient of Lift of the BAC1
CL Buffet	Coefficient of Lift Buffet
Cl CAST102	Coefficient of Lift of the CAST102
CL Ldg Req	Coefficient of Lift Required at Landing
Cl SC(2)0714	Coefficient of Lift of the SC(2)0714
Cl Section	Sectional Lift Coefficient
CL Segment	Coefficient of Lift by Segment
Cl_Similar Airfoil	Coefficient of Lift of Similar Airfoil
CL0	Coefficient of Lift at 0
CLalpha	Lift Curve Slope
Clbeta	Rolling Moment due to Sideslip
Clda	Rolling Moment due to Aileron Deflection
Clde	Rolling Moment due to Elevator Deflection
Cldr	Rolling Moment due to Rudder Deflection
Climb Rqmt	Climb Requirement
Climb Rqmt	Climb Requirement per Request for Proposal
CLMax	Maximum Lift Coefficient

Table 51. List of metric abbreviations and their full name (Cont'd)

Metric Abbreviation	Full Metric Name
CLMax Calc	Maximum Lift Coefficient Calculated
CLMax Fowler	Maximum Coefficient of Lift with Fowler Flaps
CLMax Ldg	Maximum Lift Coefficient at Landing
CLMax Ldg Rqmt	Maximum Lift Coefficient at Landing Requirement
CLMax Ldg_Similar AC	Maximum Lift Coefficient at Landing of Similar Aircraft
clmax r	Maximum Sectional Lift Coefficient at the Root
CLMax Rqmt	Maximum Lift Coefficient Requirement
clmax t	Maximum Sectional Lift Coefficient at the Tip
CLMax TO	Maximum Lift Coefficient at Takeoff
CLMax_Var AC	Maximum Lift Coefficient of Various Aircraft
CLmin	Minimum Coefficient of Lift
Clp	Change in Rolling Moment due to Roll Rate
Clq	Change in Rolling Moment due to Pitch Rate
Clr	Change in Rolling Moment due to Yaw Rate
ClT	Rolling Moment due to Thrust
Cm	Coefficient of Moment
Cm a/c	Sectional Pitching Moment Coefficient
Cm LE Slats	Pitching Moment due to Leading Edge Slats
Cm Outboard	Coefficient of Moment Outboard Wings
Cm Section	Section Moment Coefficient
Cm Trim	Moment at Trim
Cmbeta	Coefficient of Moment due to Side Slip
Cmp	Change in Pitching Moment due to Roll Rate
Cmq	Change in Pitching Moment due to Pitch Rate
Cmr	Change in Pitching Moment due to Yaw Rate
Cmw	Pitching Moment
CNMax	Maximum Normal Force Coefficient
Cnp	Change in Yawing Moment due to Roll Rate
Cnq	Change in Yawing Moment due to Pitch Rate
Cnr	Change in Yawing Moment due to Yaw Rate
Config Alt	Configuration Alternatives
Config Empennage	Configuration of the Empennage
Config Selection	Configuration Selection
Config_Similar Aircraft	Configuration of Similar Aircraft
Conversion Rate of $	Conversion Rate of Money
Cost	Cost
Cost Acq	Acquisition Cost
Cost Al	Cost of Aluminum
Cost Al	Cost of Aluminum
Cost Avionics	Cost of Avionics
Cost Avionics per lb	Cost of Avionics per Pound

Table 51. List of metric abbreviations and their full name (Cont'd)

Metric Abbreviation	Full Metric Name
Cost by Material	Cost Breakdown by Material Type
Cost composites	Cost of Composites
Cost Crew	Cost of Crew
Cost Crew Benefits	Cost of Crew Benefits
Cost Crew per Year	Cost of Crew per Year
Cost Crew Salary 20 Years	Cost of Crew Salary over 20 Years
Cost Dev	Cost of Development
Cost Dev & Manuf	Cost of Development and Manufacturing
Cost Dev & Support	Cost of Development and Support
Cost Dev BLI	Cost of Development of BLI
Cost Elements	Cost Elements
Cost Engine	Cost of Engines
Cost Engine	Cost of Engine
Cost Engines per lb	Cost of Engines per Pound
Cost Engr	Cost of Engineering
Cost Flt Test	Cost of Flight Tests
Cost Fuel	Cost of Fuel
Cost Fuel per Gal	Cost of Fuel per Gallon
Cost Fuel Projected	Cost of Fuel Projected
Cost Labor	Cost of Labor
Cost Maintenance	Cost of Maintenance
Cost Maintenance 20 Years	Cost of Maintenance for 20 Years
Cost Maintenance BLI	Cost of Maintenance for BLI
Cost Maintenance Composites	Cost of Maintenance for Composites
Cost Maintenance Labor	Cost of Maintenance Labor
Cost Maintenance per AC	Cost of Maintenance per Aircraft
Cost Maintenance per Year	Cost of Maintenance per Production Year
Cost Manuf	Cost of Manufacturing
Cost Manuf & Materials	Cost of Manufacturing and Materials
Cost Manuf Labor	Cost of Manufacturing Labor
Cost Materials	Cost of Materials
Cost MPS 20 Years	Cost Materials, Parts, Supplied per Flight Hour for 20 years
Cost MPS per Flt Hr per Year	Cost Materials, Parts, Supplied per Flight Hour
Cost MPS per Year in 1999	Cost Materials, Parts, Supplied per Production Year in 1999
Cost MPS per Year in 2015	Cost Materials, Parts, Supplied per Production Year in 2015
Cost O&S	Cost of Operation and Support
Cost Obj	Cost Objective
Cost of Administration	Cost of Administration
Cost Operation	Cost of Operation
Cost per AC	Cost per Aircraft
Cost per AC_C5	Cost per Aircraft of the C5

Table 51. List of metric abbreviations and their full name (Cont'd)

Metric Abbreviation	Full Metric Name
Cost per Crew Member	Cost per Crew Member
Cost Procurement	Total Procurement Cost
Cost Production	Cost of Production
Cost Production Composites	Cost of Production of Composites
Cost Qual Ctl	Cost of Quality Control
Cost R&D	Cost of Research & Development
Cost Salary per Crew	Cost of Salary per Crew
Cost Technician	Cost of Technician Man Hours
Cost Tooling	Cost of Tooling
Cost Total	Total Program Cost
Cost_Similar AC	Cost of Similar Aircraft
Cp	Coefficient of Pressure
CPI	Consumer Price Index
Crew Seat Angle	Seat Angle for the Crew
Crew Seating Arrangement	Crew Seating Arrangement
Crit FL	Critical Field Length
Crit Stresses	Critical Stresses
croot	Root Chord
croot Horiz Tail	Root Chord of Horizontal Tail
croot Winglet	Winglet Root Chord
Crud Drag Factor	Crud Drag Factor
cRudder	Chord of the Rudder
Cruise Rqmt	Cruise Requirement
ct Horz Tail	Tip Chord of the Horizontal Tail
ct Vert Tail	Tip Chord of the Vertical Tail
ct Wing	Tip Chord of the Wing
ct Winglet	Tip Chord of the Winglet
ct/cr	Taper Ratio
ct/cr Horiz Tail	Taper Ratio of the Horizontal Tail
ct/cr Vert Tail	Taper Ratio of the Vertical Tail
ct/cr_Similar AC	Taper Ratio of Similar Aircraft
cWing	Chord Length
cWing_Similar AC	Chord Length of Similar Aircraft
CYp	Change in Side Force due to Roll Rate
Cyq	Change in Side Force due to Pitch Rate
CYr	Change in Side Force due to Yaw Rate
d coef	Coefficient d
d coef	d-Coefficient
D Cruise	Drag at Cruise
D cWing LE Slats	Change in Chord due to Leading Edge Slats
D Elevon Cruise	Deflection of the Elevons at Cruise

Table 51. List of metric abbreviations and their full name (Cont'd)

Metric Abbreviation	**Full Metric Name**
d Elevon TO	Deflection of the Elevons at Takeoff
d Engine Fan	Diameter of the Engine Fan
d Flaps	Flap Deflection
d Flaps LE	Leading Edge Flap Deflection
d fuse	Diameter of Fuselage
d fuse_C5	Diameter of Fuselage of the C5
d fuse_Similar AC	Diameter of Fuselage of Similar Aircraft
d MG	Diameter of Main Gear
d NG	Diameter of Nose Gear
d Static Load	Static Load Deflection
D Wave	Wave Drag
D Wave Fuse	Wave Drag of the Fuselage
Damping Ratio	Damping Ratio
Damping Ratio Rqmt	Damping Ratio Requirement
DAoA	Change in Angle of Attack
dAoA Flaps	Change in Angle of Attack due to Flaps
Data_C5	Data for the C5
Data_X38	Data for the X38
dCD0	Change in Zero Lift Drag Coefficient
DCDi	Change in Induced Drag
DCl due to Flaps	Change in Lift Coefficient due to Flaps
DCLMax due to Flaps	Maximum Change in Life Coefficient Due to Flaps
DCost due to Composites	Change in Cost due to Composites
DCost Operation	Change in Operation Cost
dCtrl	Control Surface Deflection
Deceleration Method	Deceleration Method Used
Density Air	Air Density
Density materials	Density of Materials
Depreciation of Money	Depreciation of Money
Design Obj	Design Objective
Dihedral Angle Horiz	Dihedral Angle of the Horizontal Tail
Dihedral Angle Vert	Dihedral Angle of the Vertical Tail
Dim Airfoil	Airfoil Dimensions
Dim Cargo	Dimensions of Cargo
Dim Cargo	Dimensions of the Cargo
Dim Cargo Bay	Dimensions of Cargo Bay
Dim Cargo Bay_C5	Dimensions of Cargo Bay of the C5
Dim Elevator	Dimensions of the Elevator
Dim Flaps_A340	Dimensions of the Flaps of the A340
Dim Fuse	Dimensions of the Fuselage
Dim Fuse_C5	Dimensions of the Fuselage of the C5

Table 51. List of metric abbreviations and their full name (Cont'd)

Metric Abbreviation	**Full Metric Name**
Dim Fuse_Roskam	Dimensions of the Fuselage from Roskam
Dim Hangar	Dimensions of Hangar
Dim I-beam	Dimensions of I-Beam
Dim Rudder	Dimensions of the Rudder
Dim Tires	Dimensions of Tires
Dim Vert Tail	Dimensions of the Vertical Tail
DInterference	Interference Drag
Distance Btwn Tail Wing	Distance between Tail and Wing
DL/D	Change in L/D
dNose Flap	Deflection of the Nose Flaps
Downwash Angle	Downwash Angle
Drag	Drag
Drag Flaps	Drag of the Flaps
Drag Friction	Drag due to Friction
Drag Ram	Ram Drag
Drag Total	Total Drag
dRudder	Deflection of the Rudder
dSlats	Deflection of the Slats
Dswet BLI	Change in the Wetted Area from Boundary Layer Ingestion Technology
dT	Change in Thrust
DTSFC Eff	Change in TSFC Efficiency
DTSFC GenX	Change in Thrust Specific Fuel Consumption of the GenX
DUlt Load	Ultimate Load Deflection
Dutch Roll	Dutch Roll
DW due to Composites	Weight Reduction due to Composites
DW due to Composites by Component	Weight Reduction due to Composites by Component
DW due to Composites_B787	Weight Reduction due to Composites of the B787
DW due to Tech	Change in Weight due to Technology
DW Floor	Weight Reduction of Floor
DWeight Calc	Difference in Calculated Weight
DWeight Calc_Baseline AC	Difference in Calculated Weight from Baseline AC
e	Oswald Efficiency Factor
e Fuse	Oswald Efficiency Factor of the Fuselage
Eff Aero Tech	Efficiency of Technologies for Aerodynamics
Eff Engine	Engine Efficiency
Eff Fuel Burn	Efficiency of Fuel Burn
Eigenvalues	Eigenvalues
Eigenvectors	Eigenvectors
EIS	Entry into Service Date
Empennage Area per SWing	Ratio of Empennage Area per Wing Area

Table 51. List of metric abbreviations and their full name (Cont'd)

Metric Abbreviation	Full Metric Name
Endurance	Endurance
Endurance time	Endurance time
Engine Data_GE90	Engine Data for the GE90
Engine Placement	Engine Placement
Env Factors	Environmental Factors
Equivalent parasite area	Equivalent parasite area
Error Allowance	Error Allowance
eta	Technology Factor
eta Composites	Technology Factor due to Composites
Ext Moduli Materials	Extensional Moduli of the Materials
Face Stress	Face Stress
FCA	Fuselage Cone Angle
FCA_C5	Fuselage Cone Angle of the C5
FF	Fuel Fraction
FF Reserves	Fuel Fraction of Reserves
FF Segment	Fuel Fraction of Each Segment
FF TFO	Fuel Fraction of the Trapped Fuel and Oil
FF_C5	Fuel Fraction of the C5
FFAvg	Mean Fuel Fraction
Fill Factor	Fill Factor
FL Rqmt	Field Length Requirement
Flap to Chord Ratio	Flap to Chord Ratio
Flight Path Angle	Flight Path Angle
Flt Hrs per AC	Flight hours per aircraft
Flt Hrs per Year	Flight Hours per year
Flt Hrs per Year_C5	Flight Hours per year of the C5
Flying Qualities	Flying Qualities
FOM	Figure of Merit
FOM	Figures of Merit
FOM Grade	Figures of Merit Grade
FOM Score	Figure of Merit Score
FOM Weight	Figures of Merit Weight
Form Factor	Form Factor
Fuel Flow Rate	Fuel Flow Rate
Fuel Obj	Fuel Objective
Fuel per Hr	Fuel Burned per Hour
Fuse Proportions_C5	Fuselage Sizing Proportions of the C5
Fwd CG	Forward Center of Gravity
G	Shear Moduli of Materials
g Force Sim	g Force Simulation
Gamma	Gamma

Table 51. List of metric abbreviations and their full name (Cont'd)

Metric Abbreviation	Full Metric Name
Gamma W	Dihedral Angle of the Wing
Gearing Ratio	Gearing Ratio
Geom Factor Fuel Tank	Geometric Factor of the Fuel Tank
Ground Clearance	Ground Clearance
Ground Clearance Rqmt	Ground Clearance Requirement
Ground Friction Coefficient	Ground Friction Coefficient
Gust Force	Gust Force
Gust Load Factor	Gust Load Factor
Gust Parameter	Gust Parameter
Gust Velocity	Gust Velocity
h	Altitude
h Aft Loading	Height of Aft Loading
h cargo	Height of Cargo
h cargo bay	Height of Cargo Bay
h cargo bay	Height of the Cargo Bay
h cargo bay_C5	Height of Cargo Bay of the C5
h Constraint	Altitude Constraint
h Cruise	Altitude at Cruise
h Fuse	Height of Fuselage
h Fuse Max	Maximum Height of the Fuselage
h I-beam	Height of I-Beam
h LG	Height of the Landing Gear
h Segment	Altitude of Each Segment
h Service_C5	Service Ceiling of the C5
h Tactical Appr	Altitude of Tactical Approach
h Tail_C5	Height of Tail of the C5
HBPR	High Bypass Ratio
High L Dev	High Lift Devices
hL	Obstacle Height for Landing
HM	Hinge Moment
hmax	Maximum Altitude
hmax OEI	Maximum Altitude with One Engine Inoperative
hn	Neutral Point
hT/hV	ratio of Horizontal Trail height to Vertical Tail height
hTO	Obstacle Height for Takeoff
iHoriz Tail	Incidence Angle of Horizontal Tail
iVert Tail	Incidence Angle of Vertical Tail
iW	Incidence Angle of the Wing
J Materials	Torsional Bending Stiffness of Materials
K	K Value
k	Stiffness of Materials

Table 51. List of metric abbreviations and their full name (Cont’d)

Metric Abbreviation	Full Metric Name
K Exp	K Value from Experiment
K Inl	Constant for Inlets in Fuselage
K Model	K Value from Model
K V-n	Constant in V-n Diagram
Kfsp	Pounds per Gallon of Aviation Gasoline
Korn Factor	Korn Factor
l cargo	Length of Cargo
l cargo bay	Length Cargo Bay
l cargo bay	Length of Cargo
l cargo bay_C5	Length of Cargo Bay in the C5
l Center Body	Length of Center Body
l Engine	Length of the Engine
l Flt Deck	Length of Flight Deck
l Flt Deck_C5	Length of Flight Deck of C5
l Front Ramp	Length of the Front Ramp
l fuse	Length of the Fuselage
l fuse_C5	Length of the Fuselage of C5
l Horiz	Distance from the Center of Gravity Location to the Horizontal Tail
l I-beam	Length of I-Beam
L Nose Flaps	Lift from Nose Flaps
l Ramp	Length of the Ramp
l Ramp_C5	Length of the Ramp of the C5
L Slats	Lift from Slats
l TC	Length of the Tail Cone
l_C5	Length of the C5
L/D	Lift to Drag Ratio
L/D Climb	Lift to Drag Ratio in a Climb
L/D Cruise	Lift to Drag Ratio of Cruise
L/D Cruise Segments	Lift to Drag Ratio of Cruise Segments
L/D Max	Lift to Drag Ratio Maximum
L/D Max Exp	Lift to Drag Ratio Maximum, Experimental Value
L/D Max Model	Lift to Drag Ratio Maximum, Model Value
L/D Segment	Lift to Drag Ratio of Each Segment
L/D TO Est	Lift to Drag Ratio, Estimate at Takeoff
Landing Fees	Landing Fees
Landing Roll	Landing Roll
Layout_Similar AC	Layout of Similar Aircraft
Lb	Rolling Moment generated due to Yaw
LCC	Life Cycle Cost
LCN	Load Classification Number
LCN_C17	Load Classification Number of the C17

Table 51. List of metric abbreviations and their full name (Cont'd)

Metric Abbreviation	**Full Metric Name**
Ldg Beta	Landing Beta
LE Suction	Leading Edge Suction
lf/df	Fineness Ratio
lf/df Range	Fineness Ratio Range
lf/df_C5	Fineness Ratio of the C5
LFL	Landing Field Length
LFL_C5	Landing Field Length of the C5
LG Base	Landing Gear Base
LG Spec_C17	Landing Gear Specifications of the C17
LG Track	Track of the Landing Gear
lh	Distance of the Horizontal Tail Aerodynamic Center to the Center of Gravity
Lifespan of AC	Lifespan of Aircraft
Lift	Lift
Lift Horiz	Lift of the Horizontal Tail
Lift WF	Lift of the Wing and Fuselage
LLF	Limit Load Factor
lm	Location of Main Gear
ln	Location of Nose Gear
ln	Location of the Nose Gear
Loading Style	Loading Style
Loading Turnaround Time	Loading Turnaround Time
Location of Ailerons	Location of Ailerons
Location of Elevator	Location of Elevator
Location of Empennage	Location of Empennage
Location of Engine	Location of Engine
Location of Flaps	Location of Flaps
Location of Front Spar	Location of Front Spar
Location of Horiz Tail	Location of Horizontal Tail
Location of LG	Location of Landing Gear
Location of Rear Spar	Location of Rear Spar
Location of TE	Location of the Trailing Edge
Location of the Wing	Location of the Wing
Location of Vert Tail	Location of Vertical Tail
Lr	Rolling Moment due to Yaw Rate
lt	Tail Moment Arm
Lvl 1 Rqmt	Level 1 Requirement
Lvl 1 Rqmt SP	Level 1 Requirement for Short Period Mode
Lvl 2 Rqmt	Level 2 Requirement
Lvl 2 Rqmt DR	Level 2 Requirement for Dutch Roll
Lvl 2 Rqmt RTC	Level 2 Requirement for Roll Time Constant
M	Mach

Table 51. List of metric abbreviations and their full name (Cont'd)

Metric Abbreviation	Full Metric Name
M Crit	Critical Mach Number
M Cruise	Mach at Cruise
M Cruise Max_Similar AC	Maximum Mach at Cruise of Similar Aircraft
M Cruise Rqmt	Mach at Cruise Requirement
M Cruise Segments	Mach Number by Segment
M Cruise_C5	Mach at Cruise of the C5
M Cruise_Similar AC	Mach at Cruise of Similar Aircraft
M DD	Mach Number Drag Divergence
M Dive	Dive Mach
M Max	Maximum Mach Number
M(L/D)	Mach by Lift to Drag Ratio
M(L/D) Baseline	Mach by Lift to Drag Ratio Baseline Value
M(L/D) Max	Mach by Lift to Drag Ratio Maximum
MAC	Mean Aerodynamic Center
MAC	Mean Aerodynamic Chord
Mach <10K	Mach below 10K
Mach >10K	Mach above 10K
Mach Segment	Mach by Segment
Macwf	Pitching Moment about the Wing/Fuselage Aerodynamic Center
Maintenance	Maintenance
Maintenance Hrs per AC	Maintenance Hours per Aircraft
Maintenance Hrs per Flight Hour	Maintenance Hours per Flight Hour
Maintenance Turnaround Time	Maintenance Turnaround Time
Manufacturing	Manufacturing
Materials	Materials
Materials_Similar AC	Materials used by Similar Aircraft
Max d I-Beam	Maximum Deflection of I-Beam
Max Static Load	Maximum Static Load
Max t line	Maximum Thickness Line
MCruise Min	Minimum Mach at Cruise
MFF	Mean Fuel Fraction
MFF Climb	Mean Fuel Fraction for Climb Segment
MFF Cruise	Mean Fuel Fraction for Cruise Segment
MFF Decent	Mean Fuel Fraction for Descent Segment
Mission Duration	Mission Duration
Mission Profile	Mission Profile
MMH/FH	Maintenance Man Hours Per Flying Hour
Moments of Inertia	Moments of Inertia
MTOW	Maximum Takeoff Weight

Table 51. List of metric abbreviations and their full name (Cont'd)

Metric Abbreviation	**Full Metric Name**
MTOW Calc_C5	Maximum Takeoff Weight of the C5 Calculated
MTOW Est	Maximum Takeoff Weight Estimated
MTOW_C5	Maximum Takeoff Weight of the C5
MTOW_Similar AC	Maximum Takeoff Weight of Similar Aircraft
n	Load Factor
n Ult	Ultimate Load Factor
NACA2412 Exp	NACA2412 Experimental Data
Nb	Yaw Moment due to Side Slip
nMax	Maximum Load Factor
Nr	Yaw Moment due to Yaw Rate
NRE	Non-recurring engineering Hours
NRT	Non-recurring tooling hours
Over-Nose Viewing Angle	Over-Nose Viewing Angle
Over-Side Viewing Angle	Over-Side Viewing Angle
P Avail	Power Available to Engine
Pallet Arrangement	Pallet Arrangement
Pallet Capability	Pallet Capability
Pallet Capability RFP	Pallet Capability of Request for Proposal
Pallet Capability_C130	Pallet Capability of the C130
Pallet Capability_C17	Pallet Capability of the C17
Pallet Capability_C5	Pallet Capability of the C5
Performance OEI	Performance Capability at One Engine Inoperative
Phugoid Ratio Ldg	Phugoid Ratio at Landing
Phugoid Ratio TO	Phugoid Ratio at Takeoff
Pilot Technique	Pilot Technique
Pitch Angle Wing	Pitch Angle of the Wing
Pitch Angle Wing Nom	Pitch Angle of the Wing Nominal
Pm	Weight Held by Main Gear
PM Assumed	Profit Margin Assumed
Pm Req	Weight Held by Main Gear Required
Pm Total	Weight Held by Main Gear Total
Pn	Weight Held by Nose Gear
Pn Req	Weight Held by Nose Gear Required
Pn Total	Weight Held by Nose Gear Total
Power Setting Engine	Power Setting of the Engine
Pressure MG	Pressure of Main Gear
Pressure NG	Pressure of Nose Gear
Price/Unit_Sim AC	Price per Aircraft Unit for Similar Aircraft
Ps	Specific Excess Power
Pugh Matrix	Pugh Matrix
R	Range

Table 51. List of metric abbreviations and their full name (Cont’d)

Metric Abbreviation	Full Metric Name
R	Range
R <10K	Range under 10 000 feet
R Airport Base	Range to Airport Base
R Climb	Range of Climb
R Climb Segments	Range of Climb for Each Segment
R Cruise	Cruise Range
R Descent	Range of Descent
R Max	Maximum Range
R Max Pay	Range at Maximum Payload
R Min	Minimum Range
R Obj	Range Objective
R Rqmt	Range Requirement
R Segment	Range by Segment
R_C130	Range of the C130
R_C5	Range of the C5
Range Reserve	Reserve Cruise Range
Ratio Ctl Surface_Similar AC	Ratio of the Control Surface Area of Similar Aircraft
Re	Reynolds Number
RE100	Recurring Engineering Hours for 100 Vehicles
RE100	Recurring Tooling Hours for 100 Vehicles
rLE	Radius of the Leading Edge
Rloop	Loop Radius
RML100	Recurring Manufacturing Labor Hours for 100 Vehicles
RMM100	Recurring Manufacturing Material Cost for 100 Vehicles
RNom	Range of Nominal Scenario
ROC	Rate of Climb
ROC Segment	Rate of Climb by Segment
ROC_C5	Rate of Climb of the C5
RoD	Rate of Descent
Roll rate	Roll rate
RQA100	Recurring Quality Assurance Hours for 100 vehicles
RTC	Roll Time Constant
Running Cost	Running Cost
Safety	Safety
Safety FL	Safety Factor for Field Length
SAileron	Surface Area of the Aileron
Sav Fuel	Fuel Cost Savings
Sav Fuel BLI	Fuel Cost Savings of BLI
Sav Fuel Composites	Fuel Cost Savings of Composites
Savings Composites	Total Cost Savings of Composites
Savings Op BLI	Operation Cost Savings of BLI

Table 51. List of metric abbreviations and their full name (Cont'd)

Metric Abbreviation	**Full Metric Name**
Savings Op Composites	Operational Savings of Composites
Se/Sh	Ratio of Elevator to Horizontal Stabilizer
Selection Criteria	Selection Criteria
SElevator	Surface Area of the Elevator
Service Ceiling	Service Ceiling
SFC	Specific Fuel Consumption
SFC Reduction	Specific Fuel Consumption Reduction
SHoriz Tail	Surface Area of the Horizontal Tail
Similar AC	Similar Aircraft
Size Pallets	Size of Pallets
Slat per Chord	Slat to Chord Ratio
SM	Static Margin
SM_Comm AC	Static Margin for Commercial Aircraft
SP	Short Period
Spanwise Twist	Spanwise Twist
Spiral Mode	Spiral Mode
SR	Specific Range
SR Cruise Segments	Specific Range of Cruise Segments
Sr/Sv	Ratio of Rudder to Vertical Stabilizer
Sref	Reference Wing Area
Sref	Wing Reference Area
SRudder	Surface Area of the Rudder
Stability	Stability
Stability Deriv	Stability Derivatives
Stail	Surface Area of the Tail
Stail Wet	Wetted Tail Area
STail_Similar AC	Surface Area of the Tail of Similar Aircraft
Stakeholder Wants	Stakeholder Wants
Stakeholder Weight	Stakeholder Weights
Stakeholders	Stakeholders
Steering Rqmt	Steering Requirement
Storage	Storage
Stress Floor	Stress Loading of the Floor
Stress Test Load	Stress Test Load
SVert Tail	Surface Area of the Vertical Tail
Sweep c/4	Sweep at the Quarter Chord
Sweep c/4_Similar AC	Sweep at the Quarter Chord of Similar Aircraft
Sweep Horiz Tail	Sweep Angle of the Horizontal Tail
Sweep LE	Sweep of the Leading Edge
Sweep Vert Tail	Sweep Angle of the Vertical Tail
Sweep Wing	Sweep Angle of the Wing

Table 51. List of metric abbreviations and their full name (Cont'd)

Metric Abbreviation	Full Metric Name
Sweep Winglet	Sweep Angle of the Winglet
Swet	Wetted Area of the Wing
Swet Flaps	Wetted Area of the Flaps
Swet/S	Wetted Wing Area by Total Wing Area
SWing	Wing Area
Swing	Wing Area
Swing_C5	Wing Area of the C5
SWing_Similar AC	Wing Area of Similar Aircraft
SWinglet	Winglet Surface Area
t Airfoil Center	Airfoil Thickness at Centerline
t BL	Boundary Layer Thickness
t Core	Thickness of Core
T Engine	Thrust of Engine
t Fuse	Thickness of the Fuselage
t Horiz	Thickness of the Horizontal Tail
t I-beam	Thickness of I-Beam
t Lamina	Thickness of the Lamina
T Max	Maximum Thrust
T_CF6	Thrust of the CF6 Engine
t/c	Thickness to Chord Ratio of the Wing
t/c Horiz Tail	Thickness to Chord Ratio of the Horizontal Tail
t/c max	Maximum Thickness of the Airfoil
t/c Vert Tail	Thickness to Chord Ratio of the Vertical Tail
T/W	Thrust to Weight Ratio
T/W Est	Thrust to Weight Ratio Estimate
T/W TO	Thrust to Weight Ratio at Takeoff
T/W_C5	Thrust to Weight Ratio of the C5
T/W_Similar AC	Thrust to Weight Ratio of Similar Aircraft
Tactical Appr	Tactical Approach
Tail Ground Clearance	Tail Ground Clearance
Tail Ground Clearance Rqmt	Tail Ground Clearance Requirement
Tail Strike Constraint	Tail Strike Constraint
Tail Vol Ratio	Tail Volume Ratio
Tail Vol Ratio Horiz	Tail Volume Ratio of the Horizontal Tail
Tail Vol Ratio Vert	Tail Volume Ratio of the Vertical Tail
TC	Time Constant
TC Rqmt	Time Constant Requirement
TCA	Tail Cone Angle
TCA Range	Tail Cone Angle Range
TD	Time to Double
TD Phugoid	Time to Double for the Phugoid Mode

Table 51. List of metric abbreviations and their full name (Cont'd)

Metric Abbreviation	**Full Metric Name**
TD Rqmt	Time to Double Requirement
Tech	Technologies
Tech Aero	Technologies for Aerodynamics
Thrust	Thrust
time	Time
Time AC Production	Time for Aircraft Production
Time Range	Time of Range Clearance
Time to Climb	Time to Climb
Time Turn Around	Time to Turn Around Aircraft
Time Warmup	Time to Warmup
Tip-Over	Tip-Over
Tip-Over Criteria	Tip-Over Criteria
Tip-Over Criteria Lateral	Tip-Over Criteria Lateral
Tip-Over Criteria Lateral Rqmt	Tip-Over Criteria Lateral Requirement
Tip-Over Criteria Long	Tip-Over Criteria Longitudinal
Tip-Over Criteria Long Rqmt	Tip-Over Criteria Longitudinal Requirement
Tire size	Tire size
Tires Rated Load	Tires Rated Load
Tires Rated Velocity	Tires Rated Velocity
Tires Tread	Tires Tread
TiT	Turbine Inlet Temperature
TLC Rqmt	Takeoff/Landing/Climb Requirement
Tmax Engine	Maximum Engine Thrust
TO Ldg FL	Takeoff and Landing Field Length
TOFL	Takeoff Field Length
TOFL Emergency	Takeoff Field Length for Emergency
TOFL_C5	Takeoff Field Length of the C5
TOP	Takeoff Parameter
TOPSIS Output	Technique for Order of Preference by Similarity to Ideal Solution Output
TR	Thrust Required
TR_Similar AC	Thrust Required of Similar Aircraft
Track Heavy Assault Bridge	Track of Heavy Assault Bridge
Trim Angle	Trim Angle
TRL	Technology Readiness Level
Troll	Roll Time Constant
TSFC	Thrust Specific Fuel Consumption
TSFC Cruise	Thrust Specific Fuel Consumption at Cruise
TSFC Est	Thrust Specific Fuel Consumption Estimated
TSFC Segment	Thrust Specific Fuel Consumption per Cruise Segment
TSFC_CF6	Thrust Specific Fuel Consumption of the CF6

Table 51. List of metric abbreviations and their full name (Cont'd)

Metric Abbreviation	**Full Metric Name**
Turn Radius	Turning Radius
Turn Radius_C17	Turning Radius of the C17
Turnaround Time	Turnaround Time
Turnover Angle	Turnover Angle
tWing Outboard	Thickness of the Outboard Wing
Type of AC	Type of Aircraft
Type of Airframe Material	Type of Airframe Material
Type of Avionics	Type of Avionics
Type of Cargo	Type of Cargo
Type of Engine	Type of Engine
Type of Flaps	Type of Flaps
Type of Fuel Tank	Type of Fuel Tank
Type of LG	Type of Landing Gear
Type of Payload	Type of Payload
Type of Tail	Type of Tail
Type of Technology	Type of Technology
Type of Wing	Type of Wing
Utilization	Utilization Rate
V	Velocity
V Approach	Approach Speed
V Cruise	Cruise Velocity
V Dive	Dive Velocity
V Eq	Equivalent Airspeed
V Ldg	Velocity at Landing
V Loiter	Loiter Velocity
V Maneuver	Maneuver Speed
V Max	Maximum Velocity
V Max_C5	Maximum Velocity of the C5
V Sound	Velocity of Sound
V Stall	Stall Speed
V Stall neg	Negative Stall Speed
V/Vstall	Velocity Compared to Stall Velocity
VCruise Segment	Velocity per Cruise Segment
Vol Cargo	Volume of Cargo
Vol Fuel	Volume Fuel
Vol Fuel	Volume of Fuel
Vol Fuel Calc_C5	Volume Fuel of the C5 Calculated
Vol Fuel Fuse	Volume of Fuel in the Fuselage
Vol Fuel Max	Maximum Fuel Volume
Vol Fuel Min	Minimum Fuel Volume
Vol Fuel Storage Avail	Volume of Fuel Storage Available

Table 51. List of metric abbreviations and their full name (Cont'd)

Metric Abbreviation	Full Metric Name
Vol Fuel Storage Avail_C5	Volume of Fuel Storage Available in C5
Vol Fuel Wing	Volume of Fuel in the Wing
Vol Fuel_C5	Volume Fuel of the C5
Vol Reserve Fuel	Volume of Reserve Fuel
Vol Trapped Fuel & Oil	Volume of Trapped Fuel and Oil
Volume Avionics	Avionics Equipment Volume
VSP Alts	Vehicle Sketch Pad Alternatives
VSP Components	Vehicle Sketch Pad Components
VTD	Touchdown Speed
VTO	Takeoff Speed
W	Weight
W 3rd Bogie	Weight Carried by 3rd Bogie
w Aft Loading	Width of Aft Loading
W Airframe	Airframe Unit Weight
W Allow	Allowable Weight
W Avionics	Avionics Equipment Weight
W Avionics	Weight of the Avionics
W Calc	Weight Calculated
W cargo	Weight of Cargo
w cargo	Width of Cargo
w cargo bay	Width Cargo Bay
w cargo bay	Width of Cargo Bay
w cargo bay_C5	Width of Cargo Bay in the C5
w Center Body	Width of Center Body
W Components	Weight of Components
W Crew	Weight of Crew
W Crew_C5	Weight of Crew of the C5
W Cruise Segment	Weight per Cruise Segment
W Descent	Weight in Descent
W Empennage per Area	Ratio of Empennage Weight per Area
W Empty	Empty Weight
W Empty Allow	Empty Weight Allowable
W Empty Calc	Empty Weight Calculated
W Empty Est	Empty Weight Estimated
W Empty Manuf	Empty Weight of Manufacturing
W Empty Model	Empty Weight from Model
W Empty TO	Empty Weight at Takeoff
W Empty_C130	Empty Weight of the C130
W Empty_C17	Empty Weight of the C17
W Empty_C5	Empty Weight of the C5
W Empty_Similar AC	Empty Weight of Similar Aircraft

Table 51. List of metric abbreviations and their full name (Cont'd)

Metric Abbreviation	Full Metric Name
W Empty/WTO	Empty Weight Fraction
W Engine	Weight of Engine
W Engine Controls	Weight of Engine Controls
W Engine Starting System	Weight Engine Starting System
W Engine_Similar AC	Weight of Engine of Similar Aircraft
W Fixed Equip	Weight of Fixed Equipment
W Fixed Equip_Similar AC	Weight of Fixed Equipment of Similar Aircraft
W Floor	Weight of Floor
w Flt Deck	Width of Flight Deck
W Fuel	Weight of Fuel
W Fuel Max	Maximum Fuel Weight
W Fuel Max Pay	Weight of Fuel with Maximum Payload
W Fuel Nom	Weight of Fuel in Nominal Case
W Fuel Reserves	Weight of Fuel Reserves
W Fuel Segment	Weight of Fuel of Each Segment
W Fuel Used	Weight of the Fuel Used
w Fuse Max	Maximum Width of the Fuselage
w I-Beam	Width of I-Beam
W Loaded_C5	Loaded Weight of the C5
W Max 0 Fuel	Maximum Weight with No Fuel
W OE	Operating Empty Weight
W Oil System	Weight Oil System
W Pay	Payload Weight
W per in	Weight per Inch
W Segment	Weight by Segment
W Structures	Weight of the Structure
W Structures_Similar AC	Weight of Structures of Similar Aircraft
W Sys_787	Systems Weight of 787
W Wing	Weight of the Wing
W_C17	Weight of the C17
W/S	Wing Loading
W/S Ldg	Wing Loading at Landing
W/S MTOW	Wing Loading at Maximum Takeoff Weight
W/S_C5	Wing Loading of the C5
W/S_Similar AC	Wing Loading of Similar Aircraft
w0	Natural Frequency
w0 Rqmt	Natural Frequency Requirement
WE/WTO	Weight Fraction
WE/WTO_787	Weight Fraction of 787
WE/WTO_Similar AC	Weight Fraction of Similar Aircraft
Weight Climb	Weight of Aircraft in a Climb

Table 51. List of metric abbreviations and their full name (Cont'd)

Metric Abbreviation	Full Metric Name
WF	Weight Fraction
WF Segment	Weight Fraction by Segment
Wing Carry-Through Volume	Wing Carry-Through Volume
Wing Config	Configuration of the Wing
Wing Ground Clearance	Wing Ground Clearance
Wing Ground Clearance Rqmt	Wing Ground Clearance Requirement
WLdg	Weight of the Aircraft at Landing
wPallets	Width of Pallets
WPay	Payload Weight
Wpay Case 1	Payload Weight of Case 1
Wpay Case 2	Payload Weight of Case 2
WPay Max	Maximum Payload Weight
WPay Max Rqmt	Maximum Payload Weight Requirement
WPay Max_C5	Maximum Payload Weight of the C5
WPay Nom Scenario	Payload Weight for Nominal Scenario
WPay Rqmt	Payload Weight Requirement
WPay_C17	Payload Weight of the C17
WPay_C5	Payload Weight of the C5
WTFO	Weight Trapped Fuel and Oil
WTO	Takeoff Weight
WTO Case 1	Takeoff Weight of Case 1
WTO Case 2	Takeoff Weight of Case 2
WTO Guess	Guessed Takeoff Weight
WTO_C5	Takeoff Weight of the C5
WTO/S	Wing Loading at Takeoff
x	Location on the Span
x AC Components	x Location of Aircraft Components
x/c	Location along the Chord
xac	Location of the Aerodynamic Center
xachoriz	Location of the Horizontal Stabilizer Aerodynamic Center
xacwf	Location of the Wing/Fuselage Aerodynamic Center
xcg	Location of the Center of Gravity
y AC Components	y Location of Aircraft Components
Y Composite	Year of Composite Use
Y Ret_C5	Year of C-5 Retirement
Year	Year
Year AC	Year of Aircraft Production
Year Engine Dev	Engine Development Year
YS	Yield Strength
YS Max	Maximum Yield Strength
zDrag	Vertical Distance from Drag to the Center of Gravity

Table 51. List of metric abbreviations and their full name (Cont'd)

Metric Abbreviation	Full Metric Name
zmg	Vertical Distance to the Main Gear
zThrust	Vertical Distance from Thrust to the Center of Gravity

APPENDIX C – DESIGN COMPETITION RFP'S

Request for Proposal begins on the next page (16 pages)

2014-2015 AIAA Foundation Undergraduate Individual Aircraft Design Competition

Uninhabited Long Range Strike Vehicle

I. Rules – General

1. All AIAA Student Members are eligible and encouraged to participate.

2. Students may **NOT** participate on more than one team in any one design competition category. However, a student may participate in multiple design categories.

   For example, a student **MAY** participate in both the Undergraduate Team Aircraft competition and the Undergraduate Team Space Transportation competition; but that student may **NOT** participate on two teams in the Undergraduate Team Space Transportation competition.

3. Students must submit their final report via email to AIAA Student Programs (Rachel Andino, rachela@aiaa.org). It is the team's responsibility to ensure delivery of the final report to AIAA. We recommend utilizing the return receipt option for validation.

4. ***A "Signature" page must be included in the report and indicate all participants, including faculty and project advisors, along with students' AIAA member numbers and signatures***. Designs that are submitted must be the work of the students, but guidance may come from the Faculty/Project Advisor and should be accurately acknowledged.

5. Each proposal should be no more than 100 double-spaced pages (including graphs, drawings, photographs, and appendices) if it were to be printed on 8.5" x 11.0" paper, and the font should be no smaller than 10 pt. Times New Roman. Up to five of the 100 pages may be foldouts (11" x 17" max).

6. Design projects that are used as part of an organized classroom requirement are eligible and encouraged for competition.

7. The prizes shall be: First place-$500; Second place-$250; Third place-$125 (US dollars). Certificates will be presented to the winning design team or individual for display at their university and a certificate will also be presented to each team member and the faculty/project advisor. One representative from the first place design team may be asked to present a summary paper at an AIAA Conference.

   If a presentation is to be made, reasonable airfare and lodging will be defrayed by the AIAA Foundation for the team representative.

8. More than one design may be submitted from students at any one school, but only one design per team may be submitted.

9. If a design group withdraws their project from the competition, the team leader must notify AIAA Headquarters immediately.

10. Team competitions will be groups of not more than ten AIAA Student Members per entry. Individual competitions will consist of only 1 or 2 AIAA Student Member per entry.

II. Copyright

All submissions to the competition shall be the original work of the team members.

Any submission that does not contain a copyright notice shall become the property of AIAA. A team desiring to maintain copyright ownership may so indicate on the signature page but nevertheless, by submitting a proposal, grants an irrevocable license to AIAA to copy, display, publish, and distribute the work and to use it for all of AIAA's current and future print and electronic uses (e.g. "Copyright © 20__ by _____. Published by the American Institute of Aeronautics and Astronautics, Inc., with permission.).

Any submission purporting to limit or deny AIAA licensure (or copyright) will not be eligible for prizes.

III. Schedule and Activity Sequences

Significant activities, dates, and addresses for submission of proposal and related materials are as follows:

A. Letter of Intent — 31 January 2015
B. Proposal delivered to AIAA Headquarters — 8 June 2015
C. Announcement of Winners — August 2015

Groups intending to submit a proposal must submit a Letter of Intent (Item A), with a maximum length of one page to be received with the attached form on or before the date specified above. LOI must be emailed to Rachel Andino (rachela@aiaa.org).

The email containing the finished proposal must be received at the same address on or before the date specified above for the Receipt of Proposal (Item B).

IV. Proposal Requirements

The technical proposal is the most important factor in the award of a contract. It should be specific and complete. While it is realized that all of the technical factors cannot be included in advance, the following should be included and keyed accordingly:

1. Demonstrate a thorough understanding of the Request for Proposal (RFP) requirements.

2. Describe the proposed technical approaches to comply with each of the requirements specified in the RFP, including phasing of tasks. Legibility, clarity, and completeness of the technical approach are primary factors in evaluation of the proposals.

3. Particular emphasis should be directed at identification of critical, technical problem areas. Descriptions, sketches, drawings, systems analysis, method of attack, and discussions of new techniques should be presented in sufficient detail to permit engineering evaluation of the proposal. Exceptions to proposed technical requirements should be identified and explained.

4. Include tradeoff studies performed to arrive at the final design.

5. Provide a description of automated design tools used to develop the design.

V. Basis for Judging

1. *Technical Content (35 points)*
   This concerns the correctness of theory, validity of reasoning used, apparent understanding and grasp of the subject, etc. are all major factors considered and a reasonably accurate evaluation of these factors presented?

2. *Organization and Presentation (20 points)*
   The description of the design as an instrument of communication is a strong factor on judging. Organization of written design, clarity, and inclusion of pertinent information are major factors.

3. *Originality (20 points)*
   The design proposal should avoid standard textbook information, and should show the independence of thinking or a fresh approach to the project. Does the method and treatment of the problem show imagination? Does the method show an adaptation or creation of automated design tools?

4. *Practical Application and Feasibility (25 points)*
   The proposal should present conclusions or recommendations that are feasible and practical, and not merely lead the evaluators into further difficult or insolvable problems.

VI. Request for Proposal

Uninhabited Long Range Strike Vehicle

1.0 Background

Design provisions for the flight crew of combat aircraft place many constraints on the vehicle and its performance. Numerous cost and weight penalties are associated with systems that are necessitated only or largely by the presence of a human pilot including displays, switches, g-seats, g-suits, oxygen, pressurization, and other environmental control systems. The aircraft's maneuver capabilities are limited by the pilot's physiological limits such as g tolerance, susceptibility to disorientation, or even physical endurance. With pilots onboard, all aspects of the aircraft design process are strongly impacted. The aircraft size, shape, and configuration arrangement are affected.

Providing adequate visibility leads to constrained forebodies and large canopies that increase the aircraft's drag signature. The design of the aircraft is strongly influenced by human-related issues such as safety factors, redundancy levels, failure modes, and vulnerability. Most of the useful life of today's combat aircraft is devoted to training and proficiency flying, thus requiring longer design lives than would be needed to meet combat requirements.

Removing the constraints imposed by the pilot could lead to revolutionary design approaches and should allow for dramatic new vehicle concepts. One class of vehicle that is of particular interest is Uninhabited Combat Air Vehicles (UCAV), of which this RFP is an example. The UCAV can be designed specifically for combat rather than primarily for proficiency flying. This would allow the vehicle to be optimized to do a specific mission and would enable it to complete radical new maneuvers impossible or even unimaginable with a pilot in the vehicle. The design approach for UCAVs would focus on designing a vehicle with a shorter operational life and with lower factors of safety and lower levels of redundancy than piloted aircraft. These new design approaches and aircraft concepts should provide dramatic improvements in performance such as reduced observables and drag and increased range, speed, payload, maneuverability, and survivability. These vehicles should be lighter, smaller, and less expensive than current or future piloted aircraft and as a consequence are a possible solution to an overwhelming issue for the military – the affordability of future weapon systems.

2.0 Statement of Objectives (Requirements)

2.1 Design an uninhabited combat aerial vehicle (UCAV) to meet the requirements of the Uninhabited Long-Range Strike (ULRS) mission.

2.2 Attachment 1 provides specific information on the design mission.

2.3 Attachment 2 specifies minimum performance requirements.

3.0 Other Required Capabilities and Characteristics

3.1 UCAV Control System (required): Aircraft will be semi-autonomous and controlled by a person in a ground control station (GCS) linked to the ULRS via satellite. The GCS will be similar to that currently used for the RQ-4 Global Hawk aircraft and decidedly different from the GCS used for the MQ-1 Predator and MQ-9 Reaper. The ULRS GCS will not be equipped for remotely hand-flying the aircraft as is done for MQ-1 and MQ-9. Rather, the operator will interact with ULRS through computer mission planning and monitoring touch screens.

3.2 Maintenance/Servicing (required): The design must allow easy access to and removal of primary elements of all major systems. Minimize requirements for unique support equipment—development of any new support equipment will be included in program cost estimates.

3.3 Structure (required): Design limit load factors are +12 and -8 vertical g's in the clean configuration at maximum gross weight. The structure should withstand a dynamic pressure of 2166 psf (Mach 1.2 at sea level). A factor of safety of 1.3 shall be used on all design ultimate loads. Primary structures should be designed for durability and damage tolerance. Design service life is 10,000 hours.

3.4 Fuel/Fuel Tanks (required): Primary design fuel is standard JP-8 or Jet-A (6.8 lb/gal = 50.87 lb/ft3) jet engine fuel. If external fuel tanks are required (this is not desirable) limit them to conformal fuel tanks that must be retained for the entire mission.

3.5 Stability (required): Unaugmented subsonic longitudinal static margin (S.M.) shall be no greater than 10% and no less than -5%. Maximum c.g. excursion for all loading conditions must not exceed 7% M.A.C. A digital flight control system is mandatory.

3.6 Cost: Costs requirements are broken into per unit production costs (recurring) and non-recurring (NRE) costs. Per unit production costs are defined as the average incremental cost for each aircraft and will include the entire aircraft. Due to learning curve and some production tooling costs, this cost may be affected to a small degree by the number of aircraft bought. NRE will consist of all development and production preparation costs. If unique support equipment is required, the cost of developing this equipment will be included in NRE. NRE costs will be considered fixed given no delays in the planned development program. When able, report both Development and Production NRE costs. Also, be prepared to report flyaway costs for a 200 aircraft buy. For initial estimates plan on 10 flight test aircraft which may be included in the 200 aircraft buy.

3.6.1 Total NRE costs will not exceed $10 billion in constant 2015 dollars

3.6.2 Per unit cost will not exceed $200 million in constant 2014 dollars

3.6.3 All practical measures including reducing operations cost will be taken to minimize total life cycle costs.

4.0 Measures Of Merit

Designs will be evaluated against design mission performance, other performance requirements, cost and the Measures of Merit described below. The following measures of merit will be reported:

4.1 Weight summary, gross takeoff weight, empty weight, mission fuel burn, wing loading (W_{TO} /S), thrust-to-weight ratio (T_{SL}/ W_{TO}), mission fuel fraction (W_f /W_{TO}) including external tanks, if used, and weight statements are required.

4.2 Aircraft geometry and systems integration (wing and control surface area, fuselage length, width/diameter, size and volume, frontal cross sectional area distribution, wetted area, inlet and diffuser, landing gear, sensor and avionics locations, crew station, etc.)

4.3 Mission duration, radius or range, fuel burn by mission segment for design mission.

4.4 Take-off and landing distance at max gross weight including standard day and icy runway balanced field length at sea level. For single-engine designs runway length requirements may be approximated by adding take-off and landing distance together. For multi-engine designs actual balanced field length should be considered.

4.5 Performance at combat weight (50% internal fuel) for ULRS design mission loadings.

4.5.1 Maximum Mach Number at 50,000 ft above mean sea level (MSL)

4.5.2 1-g Maximum Thrust Specific Excess Power Envelope

4.5.3 Time to accelerate from M = 0.93 to M = 2.0 at 50,000 ft MSL

4.5.4 Energy Maneuverability Diagram at 50,000 ft MSL

4.5.5 L/D vs Mach at 50,000 ft

4.6 NRE, per unit production cost, per unit flyaway cost, operations costs and total life cycle costs. Show cost trades for aircraft buys of 100 to 700 units.

4.7 A pictorial of a model of the aircraft is required. This may be a CAD model or photographs of a physical model.

4.8 Document a) concept selection trades and b) concept development trades.

4.9 Develop and present the alternative concepts considered leading to the downselect of your preferred concept. The methods and rationale used for the downselect shall be presented. At a minimum a qualitative assessment of strengths and weaknesses of the alternatives shall be given, discussing merits, leading to a justification as to why the preferred concept was the best proposal response. Quantitative justification of why the selected proposal is the best at meeting the proposal measures of merit(s) will strengthen the proposal.

4.10 Include the major trade studies conducted justifying the optimization, sizing, architectural arrangement and integration of the specifically selected proposal concept. Quantitative data shall be presented showing why your concept 'works' and is the preferred design compromise that best achieves the RFP requirements and objectives.
Note that issues of observability are important considerations for aircraft of this type; however, as the individual undergraduate aircraft design topic, students responding to this opportunity do not need to conduct analyses or studies of observability. Design concepts and studies that do use textbook-like approaches to address observability are welcome but these studies should not replace the focus on airframe design and performance as described above.

Attachment 1
High Altitude Supersonic Strike Mission

Required configuration: (4) 1,000 lb JDAM

Phase	Description
1	Fuel allowance for start (100 lb/engine), warm-up/taxi (50 lb/min/engine – plan on 30 minutes ground time), Mil power run up (200 lb/engine)
2	Take-off and acceleration allowance (computed at sea level. 59º F)
	a. Fuel to accelerate to climb speed at take-off thrust (no distance credit)
3	Climb from sea level to optimum supercruise altitude (Min fuel burn. Distance credit allowed.)
4	Supercruise out 800 nm total (including previous leg) at M = 1.5 and optimum altitude. Final cruise altitude must be above 50,000 ft.
5	Dash out 200 nm at M = 2.0 at or above 50,000 ft.
6	Zoom to less than M = 0.93. Distance to zoom and ballistic range of weapon released at this altitude and Mach may be included in the 200 nm total range of the previous leg.
7	Weapons delivery: Fuel required to perform a single 180 degree turn at 50,000 ft or above and at least 0.85 Mach. If a descending turn is selected then remain above 50,000 ft for the entire maneuver. Weapons delivery must be performed no faster than 0.93 Mach due to weapons limits.
8	Accelerate to M = 2.0. Remain above 50,000 ft.
9	Dash back 200 nm (including previous leg) at M = 2.0 at or above 50,000 ft.
10	Descend / climb to best cruise Mach and best cruise altitude (BCM/BCA).
11	Subsonic cruise back 800 nm at BCM/BCA.
12	Descend to sea level (No distance credit allowed).
13	Reserves: fuel for either 30 minutes or 10% of design mission time at 10,000 feet and speed for maximum endurance whichever is greater.

Note: Base all performance calculations on standard day conditions with no wind.

Attachment 2

ULRS Minimum Performance Requirements

Criteria	Requirement	Actual
Cruise Ceiling	**60,000 ft**	
Runway Length	**10,000 ft**	
Payload (expendable)	**4,100 lb**	
Range (unrefueled)	**2,000 nm at M = 1.6**	
Cruise Mach	**1.5**	
Dash Mach	**2.0**	
Time to Accelerate for M = 0.93 to M = 2.0 at 50,000 ft	**2 minutes maximum**	
NRE	**$10 billion**	
Flyaway Cost	**$200 Million for 200-aircraft buy. Show cost trades for 100 to 700 aircraft**	

Intent Form

AIAA
Undergraduate Individual Aircraft Design Competition
Request for Proposal: **Uninhabited Long Range Strike Vehicle**

Title of Design Proposal: ____

Name of School: ____

Designer's Name	**AIAA Member #**	**Graduation Date**	**Degree**
______________________ Team Leader	______________	______________	_________________

____
Team Leader E-mail

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In order to be eligible for the 2014/2015 AIAA Foundation Undergraduate Team Space Transportation Design Competition, you must complete this form and return it to AIAA Student Programs ***before 31 Jan 2015***, at AIAA Headquarters to satisfy Section III, "Schedule and Activity Sequences" of the competition. For any nonmember listed above, a student member application and member dues payment should also be included with this form.

____
Signature of Faculty Advisor   Signature of Project Advisor   Date

____
Faculty Advisor – Printed   Project Advisor – Printed   Date

____
Faculty Advisor – Email   Project Advisor – Email

Please include a short abstract of your proposal response on a separate sheet.

2014-2015 AIAA Foundation Undergraduate Team Aircraft Design Competition

Next Generation Strategic Airlift Military Transport

I. Rules – General

1. All AIAA Student Members are eligible and encouraged to participate.

2. Students may **NOT** participate on more than one team in any one design competition category. However, a student may participate in multiple design categories.

   For example, a student **MAY** participate in both the Undergraduate Team Aircraft competition and the Undergraduate Team Space Transportation competition; but that student may **NOT** participate on two teams in the Undergraduate Team Space Transportation competition.

3. Students must submit their final report via email to AIAA Student Programs (Rachel Andino, rachela@aiaa.org). It is the team's responsibility to ensure delivery of the final report to AIAA. We recommend utilizing the return receipt option for validation.

4. ***A "Signature" page must be included in the report and indicate all participants, including faculty and project advisors, along with students' AIAA member numbers and signatures***. Designs that are submitted must be the work of the students, but guidance may come from the Faculty/Project Advisor and should be accurately acknowledged.

5. Each proposal should be no more than 100 double-spaced pages (including graphs, drawings, photographs, and appendices) if it were to be printed on 8.5" x 11.0" paper, and the font should be no smaller than 10 pt. Times New Roman. Up to five of the 100 pages may be foldouts (11" x 17" max).

6. Design projects that are used as part of an organized classroom requirement are eligible and encouraged for competition.

7. The prizes shall be: First place-$500; Second place-$250; Third place-$125 (US dollars). Certificates will be presented to the winning design team or individual for display at their university and a certificate will also be presented to each team member and the faculty/project advisor. One representative from the first place design team may be asked to present a summary paper at an AIAA Conference.

   If a presentation is to be made, reasonable airfare and lodging will be defrayed by the AIAA Foundation for the team representative.

8. More than one design may be submitted from students at any one school, but only one design per team may be submitted.

9. If a design group withdraws their project from the competition, the team leader must notify AIAA Headquarters immediately.

10. Team competitions will be groups of not more than ten AIAA Student Members per entry. Individual competitions will consist of only 1 or 2 AIAA Student Member per entry.

II. Copyright

All submissions to the competition shall be the original work of the team members.

Any submission that does not contain a copyright notice shall become the property of AIAA. A team desiring to maintain copyright ownership may so indicate on the signature page but nevertheless, by submitting a proposal, grants an irrevocable license to AIAA to copy, display, publish, and distribute the work and to use it for all of AIAA's current and future print and electronic uses (e.g. "Copyright © 20__ by _____. Published by the American Institute of Aeronautics and Astronautics, Inc., with permission.).

Any submission purporting to limit or deny AIAA licensure (or copyright) will not be eligible for prizes.

III. Schedule and Activity Sequences

Significant activities, dates, and addresses for submission of proposal and related materials are as follows:

A. Letter of Intent — 31 January 2015
B. Proposal delivered to AIAA Headquarters — 8 June 2015
C. Announcement of Winners — August 2015

Groups intending to submit a proposal must submit a Letter of Intent (Item A), with a maximum length of one page to be received with the attached form on or before the date specified above. LOI must be emailed to Rachel Andino (rachela@aiaa.org).

The email containing the finished proposal must be received at the same address on or before the date specified above for the Receipt of Proposal (Item B).

IV. Proposal Requirements

The technical proposal is the most important factor in the award of a contract. It should be specific and complete. While it is realized that all of the technical factors cannot be included in advance, the following should be included and keyed accordingly:

1. Demonstrate a thorough understanding of the Request for Proposal (RFP) requirements.

2. Describe the proposed technical approaches to comply with each of the requirements specified in the RFP, including phasing of tasks. Legibility, clarity, and completeness of the technical approach are primary factors in evaluation of the proposals.

3. Particular emphasis should be directed at identification of critical, technical problem areas. Descriptions, sketches, drawings, systems analysis, method of attack, and discussions of new techniques should be presented in sufficient detail to permit engineering evaluation of the proposal. Exceptions to proposed technical requirements should be identified and explained.

4. Include tradeoff studies performed to arrive at the final design.

5. Provide a description of automated design tools used to develop the design.

V. Basis for Judging

1. *Technical Content (35 points)*
   This concerns the correctness of theory, validity of reasoning used, apparent understanding and grasp of the subject, etc. are all major factors considered and a reasonably accurate evaluation of these factors presented?

2. *Organization and Presentation (20 points)*
   The description of the design as an instrument of communication is a strong factor on judging. Organization of written design, clarity, and inclusion of pertinent information are major factors.

3. *Originality (20 points)*
   The design proposal should avoid standard textbook information, and should show the independence of thinking or a fresh approach to the project. Does the method and treatment of the problem show imagination? Does the method show an adaptation or creation of automated design tools?

4. *Practical Application and Feasibility (25 points)*
   The proposal should present conclusions or recommendations that are feasible and practical, and not merely lead the evaluators into further difficult or insolvable problems.

VI. Request for Proposal

Next Generation Strategic Airlift Military Transport

1. Opportunity Description

The strategic airlift capability of the armed forces is undergoing considerable modernization to extend the life and augment the overall performance of the current fleet. Just as this modernization has resulted in considerable mission performance improvements over the previous generation of aircraft, it is expected that the next generation will provide major improvements over the present one. This RFP is for the design of a next generation strategic airlift military transport with an assumed 2030 entry into service (EIS).

2. Mission Requirements

Mission Performance Requirements:

- 6,300 nm unrefueled range with a wartime planned load of 120,000 lb
- Maximum payload weight shall be no less than of 300,000 lb
- Cruise Mach number no less than 0.60
- Time to top of climb / climb to initial cruise altitude no more than 20 min with 205,000 lb
- Takeoff field length with maximum payload, and landing field length with maximum landing weight, no greater than 9,000 ft
- Takeoff, landing and climb requirements must be met at sea level in a ISA + 30 C day. Takeoff, and landing performance should also be shown at ISA+10 C at 10,000' above MSL.
- The aircraft shall be able to perform a takeoff, climb to pattern altitude, conduct pattern flight, and return to base with one or more engines out immediately after decision speed. Aircraft with an even number N of engines shall meet this requirement with any N/2 engine inoperative; if N is odd then assume N/2 +1 engines inoperative. Indicate the maximum allowable increase in temperature and altitude over ISA sea level for

which engine(s) out takeoff, as described here, can be met

- The aircraft shall be able to perform a tactical approach for arrivals to bases embedded in combat environments (see primary design objectives)
- Internal cargo volume, and corresponding cargo weight capacity, shall be no less than 44 463L master pallets, or one M104 Wolverine Heavy Assault Bridge.

Other features and considerations

- The aircraft must be designed for minimal turn-around time, including: load and off load time, total cargo transfer time, servicing and refueling time.
- Loading and unloading access must be demonstrated, with proper access doors, ramps, and clearances, for anticipated cargo units

Primary Design Objectives

- Minimize fuel consumption for all missions
- Maximize range for maximum payload
- Minimize operating and fly away cost
- Minimize time and ground track distance below 10,000 ft for optional tactical approach and landing

Secondary Design Objectives

- Maximize cargo capacity in terms of number of units, without mixing, of the following (with consideration for weight and volume): M1A Abrams main battle tanks, M2/M3 Bradley Infantry Vehicles, Apache helicopters.

Notes and assumptions:

- Unless otherwise noted, assume standard atmosphere, and sea level for takeoff and landing
- Assume fuel reserves for a 200 nm radius (at optimal altitude for reserve cruise)
- No cruise altitude or Mach number is specified. Only level cruise segments may be considered, no cruise-climb is allowed. Cruise may be broken down to no more than 3 segments with altitude changes. Selection of all altitudes and timing of altitude changes within the cruise leg must be justified with proper analysis.
- Climb speed shall not exceed 250 kts below 10,000 ft
- Assume production of 120 units
- Assume an EIS by 2030 for technology and concept assumptions

Proposal and Design Data Requirements

The technical proposal shall present the design of the aircraft clearly and concisely; the proposal shall cover all relevant aspects, features, and disciplines. Pertinent analyses and studies supporting design choices shall appear in sufficient detail.

A full description of the aircraft is expected along with performance capabilities and operational limits. These include, at a minimum:

1. A description of the design mission defined for the proposed concept for use in calculations of mission performance as per design objectives. This includes the selection of cruise altitude(s) and Mach number(s) supported by pertinent trade analyses and discussion.
2. Aircraft performance descriptions for key mission segments and performance flight envelope

3. Takeoff and landing performance, takeoff performance for required engine out conditions including maximum increase of altitude and temperature over SL ISA, climb performance, tactical approach performance
4. Payload range chart(s)
5. Aircraft weight statement, aircraft center-of-gravity envelope reflecting relevant payloads and fuel allocation.
6. Materials selection for main structural groups and general structural design, including layout of primary airframe structure.
7. A V-n diagram for the aircraft with identification of necessary aircraft velocities and design load factors.
8. Complete geometric description, including clearances, control surfaces, and internal arrangement of the aircraft illustrating sufficient volume for all necessary components and systems. Scaled three-views and 3-D model imagery of appropriate quality are expected. In addition the following shall be procured:
    a. Diagrams and/or estimates showing that internal volume requirements are met, including as a minimum the internal arrangement of the two required cargo options (44 463L master pallets or M104 Wolverine Heavy Assault Bridge). Internal arrangement of other units described in the secondary objectives is optional.
    b. Diagrams of representative loading/unloading of 463L master pallets and M104 Wolverine Heavy Assault Bridge units, demonstrating feasibility of access into and out of the aircraft, with consideration for minimal cargo transfer time design requirements
9. Important aerodynamic characteristics and aerodynamic performance for key mission segments and requirements
10. Propulsion system description and characterization including performance, dimensions, and weights. The selection of a propulsion system concept, sizing, and airframe integration must be supported by appropriate analysis, trade studies, and discussion
11. Summary of basic stability and control characteristics; this should include, but is not limited to static margin, pitch, roll and yaw derivatives
12. Summary of cost estimate analysis, with clear identification of main cost groups and drivers, assumptions, and design choices aimed at the reduction of operating and fly-away costs

The proposal response will include trade documentation on the two major aspects of the design development, a) the concept selection trades, and b), the concept development trades.

A. The students are to develop and present the alternative concepts considered leading to the downselect of their preferred concept. The methods and rationale used for the downselect shall be presented. At a minimum a qualitative assessment of strengths and weaknesses of the alternatives shall be given, discussing merits, leading to a justification as to why the preferred concept was the best proposal response. Quantitative justification of why the selected proposal is the best at meeting the proposal measures of merit(s) will strengthen the proposal.

B. In addition, the submittal shall include the major trade studies conducted justifying the optimization, sizing, architectural arrangement and integration of the specifically selected proposal concept. Quantitative data shall be presented showing why their concept 'works' and is the preferred design compromise that best achieves the RFP requirements and objectives.

Specific analysis and trade studies of interest sought in proposals include:

1. Mission performance and sizing for the definition of a mission profile, particularly cruise altitude(s) and Mach number(s)
2. Overall aircraft concept selection (airframe and propulsion system) vs. design requirements objectives
3. Consideration for two-, three-, and other multi-engine options vs. the conventional four-engine configuration with regards to design requirements and objectives

All concept and technology assumptions must be reasonable and justified for the EIS year.

Intent Form

AIAA
Undergraduate Team Aircraft Design Competition
Request for Proposal: **Next Generation Strategic Airlift Military Transport**

Title of Design Proposal: ____

Name of School: ____

Designer's Name	**AIAA Member #**	**Graduation Date**	**Degree**
______________________ Team Leader	______________	______________	_________________

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Team Leader E-mail

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In order to be eligible for the 2014/2015 AIAA Foundation Undergraduate Team Space Transportation Design Competition, you must complete this form and return it to AIAA Student Programs ***before 31 Jan 2015***, at AIAA Headquarters to satisfy Section III, "Schedule and Activity Sequences" of the competition. For any nonmember listed above, a student member application and member dues payment should also be included with this form.

____
Signature of Faculty Advisor		Signature of Project Advisor		Date

____
Faculty Advisor – Printed		Project Advisor – Printed		Date

____
Faculty Advisor – Email		Project Advisor – Email

Please include a short abstract of your proposal response on a separate sheet.

APPENDIX D – IRB FORMS

The IRB documents begin on the next page (6 pages)

CONSENT DOCUMENT FOR ENROLLING ADULT PARTICIPANTS IN A RESEARCH STUDY

Georgia Institute of Technology

Investigators: Dr. Alexandra Coso, Dr. Amy Pritchett, and Elizabeth S. Fleming, School of Aerospace Engineering

Protocol and Consent Title: Incorporating Integrated Decision-Making and Cooperative Design into Fixed Wing Design Education: An Exploratory Study (Main 08/01/14v1)

You are being asked to be a volunteer in a research study.

Purpose:

The purpose of this study is to explore students' understanding of and perceptions about how a cooperative approach to design impacts the engineering design process.

Exclusion/Inclusion Criteria:

Only those individuals who are the instructors within the Fixed Wing Design course at Georgia Tech in the fall 2014 and/or spring 2015 semester are eligible to participate.

Procedures:

If you decide to take part in this study, you give the researcher permission to observe the course lectures and lab sessions and record notes. The researcher will also ask you questions about the progress of individual students, student teams, and the class as a whole. Notes will be recorded related to the processes being used by the different groups and the ways cooperative design is being considered. (*Note*: Permission will also need to be attained from the students to inquire about their progress within the course as per FERPA regulations). These conversations will occur at mutually agreeable times.

Risks or Discomforts:

The risks involved with participation in this study are no greater than those involved in daily activities such as teaching your courses or attending meetings.

Benefits:

By participating in this study, you can provide valuable insights for improving aerospace engineering design curricula.

Compensation to You:

No compensation is provided for your participation.

Confidentiality:

The information that you give in this study will be handled confidentially. Your name will not be used in any report (pseudonyms will be used). Data collected will be kept in password-protected files and only study staff at Georgia Tech will be allowed to look at them. To make sure that this research is being carried out in the proper way, the Georgia Institute of Technology IRB and the Office of Human Subject Research Protection may review study records.

Costs to You:

There are no costs to you, other than your time, for being in this study.

Participant Rights:

- Your participation in this study is voluntary. You do not have to be in this study if you don't want to be.
- You have the right to change your mind and leave the study at any time without giving any reason and without penalty.
- Any new information that may make you change your mind about being in this study will be given to you.
- You will be given a copy of this consent form to keep.
- You do not waive any of your legal rights by signing this consent form.

Questions about the Study:

If you have any questions about the study or would like to withdraw from the study, please email Elizabeth Fleming at efleming@gatech.edu at any time.

Questions about Your Rights as a Research Participant:

If you have any questions about your rights as a research participant, you may contact
Ms. Melanie Clark, Georgia Institute of Technology
Office of Research Integrity Assurance, at (404) 894-6942.
or
Ms. Kelly Winn, Georgia Institute of Technology
Office of Research Integrity Assurance, at (404) 385- 2175.

If you sign below, it means that you have read (or have had read to you) the information given in this consent form, and you would like to be a volunteer in this study.

____

Participant Name (printed)

____ ____________

Participant Signature Date

____ ____________

Signature of Person Obtaining Consent Date

APPROVED *Consent Form Approved by Georgia Tech IRB: August 19, 2014 - Indefinite*

CONSENT DOCUMENT FOR ENROLLING ADULT PARTICIPANTS IN A RESEARCH STUDY

Georgia Institute of Technology

Investigators: Dr. Alexandra Coso, Dr. Amy Pritchett, and Elizabeth S. Fleming, School of Aerospace Engineering

Protocol and Consent Title: Incorporating Integrated Decision-Making and Cooperative Design into Fixed Wing Design Education: An Exploratory Study (Main 06/01/14v1)

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Purpose:
The purpose of this study is to explore students' understanding of and perceptions about how a cooperative approach to design impacts the engineering design process.

Exclusion/Inclusion Criteria:
Only those individuals who are students within the Fixed Wing Design course at Georgia Tech in the fall 2014 and/or spring 2015 semesters are eligible to participate.

Procedures:
As part of your senior design course, you will be asked to complete in-class evaluations related to cooperative design. If you decide to take part in this study, you give the researcher permission to use your responses in her study and also to observe your participation in lectures and lab sessions and record notes about your experiences related to this topic. The researchers will also examine your course submissions, related to requirements, stakeholders, and design, to supplement the observations. Finally, the researcher may interview your instructors during the semester to inquire about your progress within the course.

Please remember while you must complete the evaluations and attend the lectures and lab sessions for the course, your participation in the study is completely voluntary and will not affect your final grade.

Risks or Discomforts:
The risks involved with participation in this study are no greater than those involved in daily activities such as attending class or participating in in-class activities.

Benefits:
By participating in this study, you can provide valuable insights for improving aerospace engineering design curricula.

Compensation to You:
No compensation is provided for your participation.

APPROVED *Consent Form Approved by Georgia Tech IRB: August 19, 2014 - Indefinite*

Confidentiality:
The information that you give in this study will be handled confidentially. Your name will not be used in any report (pseudonyms will be used). Data collected will be kept in password-protected files and only study staff at Georgia Tech will be allowed to look at them. To make sure that this research is being carried out in the proper way, the Georgia Institute of Technology IRB and the Office of Human Subject Research Protection may review study records.

Costs to You:
There are no costs to you, other than your time, for being in this study.

Participant Rights:

- Your participation in this study is voluntary. You do not have to be in this study if you don't want to be.
- You have the right to change your mind and leave the study at any time without giving any reason and without penalty.
- Any new information that may make you change your mind about being in this study will be given to you.
- You will be given a copy of this consent form to keep.
- You do not waive any of your legal rights by signing this consent form.

Questions about the Study:
If you have any questions about the study or would like to withdraw from the study, please email Elizabeth Fleming at efleming@gatech.edu at any time.

Questions about Your Rights as a Research Participant:
If you have any questions about your rights as a research participant, you may contact
Ms. Melanie Clark, Georgia Institute of Technology
Office of Research Integrity Assurance, at (404) 894-6942.
or
Ms. Kelly Winn, Georgia Institute of Technology
Office of Research Integrity Assurance, at (404) 385- 2175.

If you sign below, it means that you have read (or have had read to you) the information given in this consent form, and you would like to be a volunteer in this study.

____
Participant Name (printed)

____ ____________
Participant Signature Date

____ ____________
Signature of Person Obtaining Consent Date

APPROVED *Consent Form Approved by Georgia Tech IRB: August 19, 2014 - Indefinite*

Georgia Tech | **Office of Research Integrity Assurance**

Protocol: H14280
Funding Agency: NSF Graduate
Review Type: Exempt, category 1
Title: Incorporating Integrated Decision-Making and Cooperative Design into Fixed Wing Design Education: An Exploratory Study
Number of Subjects: 90
Number Enrolled: n/a

19 August, 2014

Alexandra Emelina Coso
GT Aero Eng
0383

Dear Dr. Coso,

The GT Institutional Review Board (IRB) has carefully considered the referenced ***proposal*** for protocol *#H14280* above. Your approval is effective ***19 August, 2014***. However, the proposed procedures have been determined exempt from further review by the Georgia Tech Institutional Review Board.

This minimal risk research study qualifies for exemption status per the federal regulations at 45 CFR 46.101b.1.

Thank you for allowing us the opportunity to review your plans. If any complaints or other evidence of risk should occur, or if there is a **change in the plans, processes, or personnel,** the IRB must be notified via an amendment.

If you have any questions concerning this approval or regulations governing human subject activities, please feel free to contact Dr. Dennis Folds, IRB Chair, at 404/407-7262, or me at 404 / 385-2175.

Sincerely,

Kelly Winn Date: 2014.08.19
11:02:41 -04'00'

Kelly Winn, CIP
Research Associate
Georgia Institute of **Tech**nology
Office of **R**esearch **I**ntegrity **A**ssurance

cc: Dr. Dennis Folds, IRB Chair
OSP

Georgia Tech
Research Integrity Assurance

Protocol Number: H14280
Funding Agency: NSF
Review Type: Exempt, Category 1
Title: Incorporating Integrated Decision-Making and Cooperative Design into Fixed Wing Design Education: An Exploratory Study
Number of Subjects: 60-90

January 7, 2015

Alexandra Coso
CETL
0383

Dear Dr. Coso:

The Institutional Review Board (IRB) has carefully considered **amendment #2** for protocol ***#H14280*** referenced above. Your approval is effective as of **January 7, 2015**. The proposed procedures are exempt from further review by the Georgia Tech Institutional Review Board.

Project qualified for exemption status under 45 CFR 46 101b. 1.

Thank you for allowing us the opportunity to review your plans. If any complaints or other evidence of risk should occur, or if there is a significant change in the plans, the IRB must be notified.

If you have any questions concerning this approval or regulations governing human subject activities, please feel free to contact Dennis Folds, IRB Chair, at 404/407-7262, or me at 404 / 894-6944.

Sincerely,

Martha E. C. Patterson
Digitally signed by Martha E. C. Patterson
Date: 2015.01.07 12:37:38 -05'00'

Martha E. C. Patterson, CIP
Compliance Officer
Georgia Tech Office of Research Integrity Assurance

cc: Dr. Dennis Folds, IRB Chair

APPENDIX E – TEAM 1'S DETAILED DATA FROM OBSERVATIONS

Transcripts for Team 1's midterm and final design presentations were analyzed using a qualitative analysis. The results of this analysis are outlined in Table 52 (midterm presentation) and

Table 53 (final presentation). The evidence for identifying the tasks is presented in Table 54 (midterm presentation) and

Table 55 (final presentation). Table 56 compares the midterm and final presentation task breakdowns. Table 57 lists the metrics that were referenced by Team 1 and classifies if the metric was mentioned in the midterm or final presentation. Table 58 is a list of all the metrics that were repeated across and within disciplines. Finally, evidence of Team 1's decisions are in Table 59 (midterm presentation) and Table 60 (final presentation).

Table 52. Team 1's detailed design process in the midterm presentation

High-level Task	Lower-level Task	Decision	Metrics
Define Requirements and Outline Mission	Outline aircraft requirements	No decision, outlining the project	EIS
			#AC
			RNom
			WPay Rqmt
			WPay Max Rqmt
			M Cruise Rqmt
			Time to top climb
			TO Ldg FL
			FL Rqmt
	Outline Mission Profile	Mission Profile, M, R, h, TOFL	M
			R
			h
			TOFL
			h Segment
			R Cruise
	Perform Trade Study to Select Mach Number	Mach Number (Modeled)	R Cruise
			SR
			M

Table 52. Team 1's detailed design process in the midterm presentation (Cont'd)

High-level Task	Lower-level Task	Decision	Metrics
			M

Table 52. Team 1's detailed design process in the midterm presentation (Cont'd)

High-level Task	Lower-level Task	Decision	Metrics
	Perform Trade Study to Select Altitude	Max altitude (Modeled)	M_Similar AC
			h Segment
			W Cruise Segment
			hmax
			Altitude_Similar AC
Choose Configuration	Examine stakeholders	Rate importance of stakeholders (Assumed)	Stakeholders
			Stakeholder Wants
	Analyze Figures of Merit		Cost
			Storage
			Eff Fuel Burn
			FOM Weight
	Create a VSP model	Configuration (Selected)	Config Components
			Config Alt
			FOM Weight
Initial Weight Estimation	Historical Regression of Weight	W_empty, W_gross, B Slope, A Intercept	W Empty_Similar AC
			MTOW_Similar AC
			A Intercept
			B Slope
			Data_C5
	Select Technologies to Incorporate into Design	Aircraft Technologies	DD Cruise
			DW due to Tech
			DEff Fuel Burn
			Dlift due to Tech
			Ddrag due to Tech
			HBPR
			TRL
			DW due to Tech
			Cost Maintenance
	Calculate Class I Weight Breakdown	Eta, W	DW due to Tech
			WF Segment
			W Components
			DW due to Composites by Component
			W
			eta
	Calculate Fuel Used in Mission	Update Aircraft Weight	FF Segment
			h

Table 52. Team 1’s detailed design process in the midterm presentation (Cont’d)

High-level Task	Lower-level Task	Decision	Metrics
			V
			TSFC
			R
			ROC
	Update Weights		W Crew
			Wpay Max
			Vol Reserve Fuel
			MTOW
			W Gross
	Estimate Drag polar	C Fuse, CD, CL	CLMax
			c Coef
			d Coef
			C Fuse
			eta
			AR Wing
			W/S
			CL
			CD
	Constraint Sizing	W/S, T/W, W_To, Wing Area	
			CLMax TO
			CLMax Ldg
			TOFL
			Ldg Beta
			ROC Segment
			h Segment
			WTO/S
			T/W
			Swing
			Thrust
			Wto/S_Similar AC
			Swing_Similar AC
			WTO/Tsl_Similar AC
			Thrust_Similar AC
	Baseline Analysis	W Empty	
			TSFC_C5
			h_C5
			R_C5

Table 52. Team 1's detailed design process in the midterm presentation (Cont'd)

High-level Task	Lower-level Task	Decision	Metrics
			W Empty_C5
			MTOW_C5
			Vol Fuel_C5
			DWeight Calc
Determine Initial Configuration and Layout of Aircraft	Design the Fuselage	Fuselage size	Cargo
			Dim Cargo
			d fuse_Similar AC
			l fuse
			d fuse
			t Fuse
			h Fuse Max
			w Fuse Max
			l TC
			FCA
			lf/df
			TCA
			Cargo Rqmt
	Design the Wing Configuration	t/c, High-lift devices, Aneh Wing, ct/cr, Sweep c/4	Swing
			AR Wing
			Sweep c/4
			ct/cr
			Airfoil Type
			High L Dev
			Aneh Wing
			Aneh Wing_Similar AC
			M DD
			CL
			t/c
	Select Airfoil and Perform CFD Analysis	Select Airfoil	Airfoil Type
			Cl_Similar Airfoil
			Cd_Similar Airfoil
			Cl
			Cd
			t/c
			W wing
			Temp
			%Laminar Flow

Table 52. Team 1's detailed design process in the midterm presentation (Cont'd)

High-level Task	Lower-level Task	Decision	Metrics
			M
			i
			CLMax
	Select High-Lift Systems	High lift devices	CLMax_Var AC
			CLMax Ldg
	Design the Empennage	Tail size	SWing_Similar AC
			c Geom_Similar AC
			STail_Similar AC
			Ratio Ctl Surface_Similar AC
			Distance Btwn Tail Wing
			Stail
			t/c Horiz Tail
Perform Weight & Balance			
	Find Aircraft Center of Gravity	Placement of Aircraft Components	CG Components
			x AC Components
			CG Overall
	Select Cargo Loading Configuration	Loading configuration	Cargo Rqmt
			MTOW
			#Pallets
			Size Pallets
			Layout_Similar AC
			CG Range
			CG Overall
Analyze Performance			
	Payload Range Diagram		R max
			Vol Fuel Max
			R Min
			WPay
			Cargo
			R
	V-n diagram		V Manuever
			V Dive
			n
	Analyze Propulsion System	Select Engine	T Engine
			#Engines
			TR

Table 52. Team 1's detailed design process in the midterm presentation (Cont'd)

High-level Task	Lower-level Task	Decision	Metrics
			Wpay
			W Engine
		Select APU	Running Cost
			Env Factors
	Calculate stability derivatives		Airfoil Type
			Dim Airfoil
			Aneh Wing
			CG Overall
			A Mat
			B Mat
			Eigenvalues
			Eigenvectors
			SP
			LP
			Phugoid

Table 53. Team 1's detailed design process in the final presentation

High-level task	Detailed-task	Decision	Metric
Define Requirements and Outline Mission	Outline aircraft requirements		EIS
			#AC
			RNom
			WPay Rqmt
			WPay Max Rqmt
			M Cruise Rqmt
			Time to top climb
			TO Ldg FL
			FL Rqmt
			Cargo Rqmt
			Fuel Obj
			R Obj
			Cost Obj
			Cost Benefits
			Structural Benefits
			Technology Improvements
			hmax
			vmax
			Rmax
Select aircraft configuration	Identify Stakeholders and needs	Stakeholders and their importance	Stakeholders
			Stakeholder Wants
			Stakeholder Weight
			FOM
	Perform Preliminary Configuration Selection	Configuration	VSP Components
			VSP Alts
Outline Mission	Outline Mission Profile	Mission Profile, TOFL, h, ROC, R	Mission Profile
			TOFL
			h Segment
			ROC Segment
			R Segment
			Range Reserve
			R Descent
			h Tactical Appr
			LFL
	Sensitivity Study: Specific Range vs Mach Number	Mach	SR
			M Cruise_Similar AC
			M Cruise

Table 53. Team 1's detailed design process in the final presentation **(Cont'd)**

High-level task	Detailed-task	Decision	Metric
	Sensitivity Study: Specific Range vs Altitude	Altitude	SR
			W Segment
			M Cruise
			h Segment
			h max_Similar AC
			M Cruise_Similar AC
			M Cruise Max_Similar AC
Initial Aircraft Sizing			
	Historical Weight Regression	Empty weight, B Slope, A Intercept	W Empty_Similar AC
			MTOW_Similar AC
			W Empty Est
			MTOW Est
			B Slope
			A Intercept
	Select Technologies	Technologies	Erg Perf
			Drag
			Eff Fuel Burn
			SFC
			DWTO
			Noise
			DW
			Eff Fuel Burn
			DCost Maintenance
			DCost Operation
			DDrag
			Eff Fuel Burn
			DW due to Tech
			DCost due to Tech
			DComplexity
			Engine Lifespan
			TRL
	First Weight Estimate	Eta	W Structures_Similar AC
			W Engine_Similar AC
			W Fixed Equip_Similar AC

Table 53. Team 1's detailed design process in the final presentation **(Cont'd)**

High-level task	Detailed-task	Decision	Metric
			MTOW_Similar AC
			eta
			DW due to Tech
	Create Weight Sizing Tool	W Empty	M Cruise
			h segment
			FF Segment
			R
			ROC
			SFC
			eta
			A Intercept
			B Slope
			W Crew
			WPay Max Rqmt
			Vol Reserve Fuel
			Vol Trapped Fuel & Oil
			W Empty Calculated
			W Empty Model
			DWeight Calc
	Class I Drag Polar	CD0	c Coef
			d Coef
			e
			K
			cf
			CD0 Class I
	Class II Drag Polar	Drag Component, CD0	Drag Component
			CD0 Class II
			h Segment
			CD0 Wing
			CD0 Fuse
			CD0 Nacelle
			CD0 Vert Tail
			CD0 Horiz Tail
			CD0 Class I
	Constraint Sizing	T/W W/S	CLMax TO
			CLMax Ldg

Table 53. Team 1’s detailed design process in the final presentation **(Cont’d)**

High-level task	**Detailed-task**	**Decision**	**Metric**
		Wing Area Thrust Required at Takeoff	TOFL
			Ldg Beta
			ROC Segment
			Mach <10K
			Mach >10K
			W/S
			SWing
			T/W
			TR
			W/S_Similar AC
			SWing_Similar AC
			T/W_Similar AC
			TR_Similar AC
	Baseline Weight Tools		W Empty_C5
			MTOW_C5
			Vol Fuel_C5
			W Empty_C5
			MTOW Calc_C5
			Vol Fuel Calc_C5
			DWeight Calc
Determine Initial Configuration and Layout of Aircraft	Size Fuselage	Fuselage size: Length, height	lf/df
			lf/df Range
			l fuse
			TCA Range
			TCA
			d fuse
			t Fuse
			h Fuse Max
			w Fuse Max
			l TC
			FCA
		Size Cargo Bay Cargo Bay Access Doors Cargo Loading/Unloading Mechanism	Cargo
			Dim Cargo
			Cargo Access_Similar AC
			Type of LG

Table 53. Team 1's detailed design process in the final presentation **(Cont'd)**

High-level task	Detailed-task	Decision	Metric
	Wing Configuration	Wing parameters: Sweep at c/4, Taper Ratio, Anhedral angle, span	SWing
			Dim Hangar
			bWing
			AR Wing
			Sweepc/4_Similar AC
			ct/cr_Similar AC
			Aneh Wing_Similar AC
			Wing Tip Types
			Sweepc/4
			ct/cr
			Aneh Wing
	Airfoil Selection	Airfoil at root, airfoil at tip	Airfoil Types
			Cl CAST102
			Cd CAST102
			Cl SC(2)0714
			Cd SC(2)0714
			Cl BAC1
			Cd BAC1
			NACA2412 Exp
			t/c
			CLMax Rqmt
			i
			CLMax Calc
	Select High-lift Devices	High lift devices	High L Dev
			CLMax Ldg Rqmt
			CLMax Ldg_Similar AC
			Dim Flaps_A340
	Preliminary Sizing of Empennage	Empennage characteristics: horizontal tail area, vertical tail area, tail placement	Tail Vol Ratio_Similar AC
			SWing_Similar AC
			cWing_Similar AC
			STail_Similar AC
			Ratio Ctl Surface_Similar AC
			Tail Vol Ratio
			Location of Empennage
			Dim Horiz Tail
			Dim Vert Tail

Table 53. Team 1's detailed design process in the final presentation **(Cont'd)**

High-level task	Detailed-task	Decision	Metric
			Dim Elevator
			Dim Rudder
			h fuse
			l fuse
			bWing
	Calculate Weight and Balance	Component/payload placement, x AC components, y AC components, Loading Options	x AC Components
			y AC Components
			CG Range
			CG Range_Roskam
			CG Overall
			Wpay Max Rqmt
			Cargo Access
			Wpay
			Aft CG
			Fwd CG
			CG Range
			CG Range_Roskam
			MTOW
			x AC Components
			y AC Components
	Design Landing Gear	Landing gear placement	Aft CG
			Fwd CG
			Wempty
			Tip-Over Criteria Long Rqmt
			TCA
			Tail Ground Clearance Rqmt
			Wing Ground Clearance Rqmt
			Tip-Over Criteria Lateral Rqmt
			Tip-Over Criteria Long
			Tail Ground Clearance
			Wing Ground Clearance
			Tip-Over Criteria Lateral
			CL
			AoA
			Pn

Table 53. Team 1's detailed design process in the final presentation **(Cont'd)**

High-level task	Detailed-task	Decision	Metric
	Select Landing Gear Tires	Landing gear tires, #Tires, #Bogies, #Struts LG	Pm
			Tires Rated Velocity
			Tires Rated Load
			Dim Tires
			Tires Tread
			#Tires
			#Bogies
			#Struts LG
			Pn Total
			Pm Total
			Pn Req
			Pm Req
	Design Landing Gear Retraction Method	Retraction mechanism	Steering Rqmt
			Maintenance Complexity
			Type of LG_Similar AC
			Steerable Angle_Similar AC
Conduct a performance analysis	Select engine	Engine, T Max, W Engine, d Engine Fan, l Engine	T Engine
			#Engines
			TR
			EIS
			T Max
			W Engine
			d Engine Fan
			l Engine
			V
			Time
			AoA
			Gamma
			Climb Rqmt
			TOFL Emergency
			TOFL
	Construct Payload/Range Diagram		DWPay
			Wpay Max Rqmt
			Vol Fuel
			R
			Wpay

Table 53. Team 1's detailed design process in the final presentation **(Cont'd)**

High-level task	Detailed-task	Decision	Metric
			R Rqmt
			R_C5
			WPay_C5
	Construct Vn Diagram		n
			V Eq
			LLF
			V Manuever
	Calculate stability and control		Stability Deriv
			A Mat
			B Mat
			Structural Capability Req
			Cruise Seg Cond
			MAC
			h
			M
			Trim Angle
			Damping Ratio Rqmt
			w0 Rqmt
			TC Rqmt
			TD Rqmt
			Stability Deriv
			Eigenvalues
			Damping Ratio
			w0
			TC
			TD
			TD Phugoid
			Complexity
			Cost
	Choose subsystems	electrohydraulic actuators, Autotransformer rectifier units, battery, Ram Air Turbine, Electromechanical servo actuators, Electric APU,	P Avail
			Eff Fuel Burn
			Cost Production
			Cost Maintenance
			#APU Gen
			#Engine Gen
			#APU Gen

Table 53. Team 1's detailed design process in the final presentation **(Cont'd)**

High-level task	Detailed-task	Decision	Metric
		Integrated Modular Avionics (IMA), Network Systems Server (NSS), Air Data and Inertial Reference System (ADIRS), GPS, Radios, Fuel System	Electrical System Components
			P
			h
			P
			Avionics_Similar AC
			Avionics Components
			#Engine Gen
			Env Ctl System Components
			Fuel System Components
	Analyze Structure & Manufacturing	Materials # fuselage sections lightning strike protection Structure types Assembly process	Materials_Similar AC
			Materials
			Manufacturing Components
			Structures Components
			#Fuselage Sections
		Location of manufacturing	Location of Manufacturing
	Perform Cost analysis		Cost Total
			Cost R&D
			Cost O&S
			Cost Maintenance Labor
			W Empty
			MTOW
			V Max
			#AC
			#AC Dev
			Cost Engines per lb
			Cost Avionics per lb
			Conversion Rate of $
			Cost Dev
			Cost Flt Test
			Cost Manuf & Materials
			Cost Engine
			Cost Avionics
			Cost Tooling
			Cost Technician
			Cost Engr

Table 53. Team 1's detailed design process in the final presentation **(Cont'd)**

High-level task	Detailed-task	Decision	Metric
			Cost Qual Ctl
			Cost Manuf
			Cost Procurement
			Cost per AC_C5
	Calculate Operation & Support Cost of Aircraft		Cost Fuel
			Cost Crew
			Cost Maintenance
			Cost O&S
	Finalize 3-D Model & Three View		

Table 54. Task breakdown of Team 1's midterm design review

High-level Task	Lower-level Task	Evidence
(1) Define Requirements and Outline Mission	(1.01) Outline aircraft requirements	
	(1.02) Outline Mission Profile	"The first thing that we needed to figure out is our mission profile, which we got pretty much from our RFP and a bunch of assumptions that we made," Rocco
	(1.03) Perform Trade Study to Select Mach Number	"Mach number was selected based on specific trade study that we did, which is Mach versus the specific range, " Rocco
	(1.04) Perform Trade Study to Select Altitude	"And then, we took that Mach number, we did another trade study for altitudes." Damien
(2) Choose Configuration	(2.01) Examine stakeholders	"So, before our design process began, we learned last semester to take into account our stakeholders. So, for us, our stakeholders - who are the important stakeholders?" Rocco
	(2.02) Analyze Figures of Merit	"So the next slide - how do we rate this? So, the figures of merit process, which we were talking about last semester, some of the things, again, they are rated pretty high," Damien
	(2.03) Create a VSP model	"Okay, so, before I go on, we created several VSP models for all the different configurations," Damien
(3) Initial Weight Estimation		"So, once we had the configuration process done, we started actually sizing our aircraft," Rocco
	(3.01) Historical Regression of Weight	"So, the first step we had to do was weight regression, in order to re-estimate our empty weight and our gross weight," Rocco
	(3.02) Select Technologies to Incorporate into Design	"For aircraft technologies, since our aircraft is coming in 2030, we used several technology features to incorporate into our aircraft," Spencer
	(3.03) Calculate Class I Weight Breakdown	"So using these technologies, we used them to estimate the weight reduction or a specific component of the plane...Anyways, so we did this class one weight breakdown, where we get these weights, and then, since we have every single component, and we looked at our technologies, we were able to estimate exactly how much weight reduction we're going to get for each component," Rocco
	(3.04) Calculate Fuel Used in Mission	"So we used all this data that we estimated for the mission profile, and from technologies that we chose. And we were able to calculate how much fuel is going to be used per mission segment," Rocco
	(3.05) Update Weights	
	(3.06) Estimate Drag polar	"So, for the drag polar, first to estimate the drag polar to get the CL max," Spencer

Table 54. Task breakdown of Team 1's midterm design review (Cont'd)

High-level Task	Lower-level Task	Evidence
	(3.07) Constraint Sizing	"All right, so after weight sizing, we developed our tool for constraint sizing and we were able to create constraint lines for each segment in our mission profile," Damien
	(3.08) Baseline Analysis	"So, after doing all of this, how do we know our numbers are right? How do we know we can trust our tools? So, after we did all the calculations, we grabbed a spreadsheet, and I mentioned before, when I was talking about the eta factor, we took the C5A, which is an aircraft - once again, it is not being a part of the weight regression. And we put it in our spreadsheet, we found a lot of information online, enough to build estimated mission profile, or sizing mission," Rocco
(4) Determine Initial Configuration and Layout of Aircraft		"The aircraft design now," Spencer
	(4.01) Design the Fuselage	"So, the first step was designing the fuselage, because it was the main part of the aircraft, with most of cargo," Spencer
	(4.02) Design the Wing Configuration	"And now we're going to design the wing configuration, and so, as seen earlier from constraints sizing, we determined our wing area and wing span aspect ratio," Spencer
	(4.03) Select Airfoil and Perform CFD Analysis	"And now, for airfoil selection, we, as I said earlier, we chose the BAC 1 airfoil at the tip, and SCE 0712 for the root And we used different tools to analyze the airfoil and one of them was CFD," Spencer
	(4.04) Select High-Lift Systems	"And for the high lift systems, we found a paper that had different aircraft plotted like against the Cl max," Spencer
	(4.07) Design the Empennage	"As a part of this same process, we also designed the tail," Rocco
(5) Perform Weight & Balance		"So now we have the interesting weight balance," Rocco
	(5.01) Select Cargo Loading Configuration	"So, as you will see in our next slide, our loading options. So this is what matters. This is where it drives our excursion diagrams," Rocco
(6) Analyze Performance		"Our next is performance analysis," Spencer
	(6.01) V-n diagram	"So we constructed a V-n diagram for our aircraft, because like different flight conditions, like maneuvering and those types of condition, the structural component of the aircraft should withstand those flight conditions," Spencer
	(6.02) Analyze Propulsion System	"And for propulsion system, as we talked about earlier, using the GENX engines, and we're using two engines, we decided to use that because each engine produces 76000 pounds of thrust, and combined we get 152,000 pounds of thrust," Spencer
	(6.03) Calculate stability derivatives	"Finally we started working on our stability derivatives," Rocco

Table 55. Task breakdown of Team 1’s final design review

High-level task	Detailed-task	Evidence
(1) Define Requirements and Outline Mission	(1.01) Outline aircraft requirements	"Here’s a quick summary of our RFP. I’m not going to go into detail about every single point, but I’m just going to mention some of the key factors that we were paying close attention to while we were designing the aircraft," Rocco
(2) Select aircraft configuration	(2.01) Identify Stakeholders and needs	"So, as we started the design process, we decided on our different stakeholders," Rocco
	(2.02) Perform Preliminary Configuration Selection	"Once we knew a lot about the RFP, and we knew a lot about our stakeholders and what was important to us and our figures of merit, we started coming up with different ideas, different sketches of our configuration selection with the different wings, different fuselages, different engine locations, and different tails," Rocco
(3) Outline Mission		<Slide Divider>
	(3.01) Outline Mission Profile	So, now that we know what our aircraft. is going to look like, and we’ve put a little bit of thought processes into the RFP, we started looking into the mission profile.
	(3.02) Sensitivity Study: Specific Range vs Mach Number	"Now, looking at our mission profile, you may think that some of these altitudes may seem kind of random, some these velocities may seem kind of randomly picked out of a hat, but no, they were actually calculated using different criteria," Rocco
	(3.03) Sensitivity Study: Specific Range vs Altitude	"Then, the chart to your right is a specific range versus altitude for different weights that we estimated our aircraft would have in specific cruise segments," Rocco
(4) Initial Aircraft Sizing		"Then we’re starting the weight sizing process," Rocco
	(4.01) Historical Weight Regression	"We took about twenty different aircraft and we input them into this Excel sheet by looking at their empty weight and maximum takeoff gross weight, and from this data we were able to outline a trend," Rocco
	(4.02) Select Technologies	"So, we did some research to find out the kinds of technologies that could be applied to this aircraft type, and we were able to settle at these five specific ones that actually would be implemented in the aircraft," Astrid
	(4.03) First Weight Estimate	"We used twenty aircraft from the weight regression process and broke down their aircraft into several different components with the three major groups being: the

High-level task	Detailed-task	Evidence
		structural components, the power plans, and the fixed equipment, and we just calculated the weight that could be applied to these three different groupings," Astrid

Table 55. Task breakdown of Team 1's final design review **(Cont'd)**

High-level task	Detailed-task	Evidence
	(4.04) Create Weight Sizing Tool	"So, now we went on to create our sizing tool. We did this using excel spreadsheet method and we created first a weight-sizing tool which basically takes in the mission profile," Astrid
	(4.05) Class I Drag Polar	"We also used a spreadsheet method as well to do our drag polar analysis," Astrid
	(4.06) Class II Drag Polar	"Later on in the process, we also did a more in-depth Class II drag polar analysis," Astrid
	(4.07) Constraint Sizing	"Then we went on to create a constraint diagram,"
	(4.08) Baseline Weight Tools	"So, once we had our tools all set up and done, and we had our numbers working, we had to make sure they were actually giving us accurate numbers," Astrid
(5) Determine Initial Configuration and Layout of Aircraft		Slide Divider
	(5.01) Size Fuselage	"So, now that we have the aircraft size, it was important to design the aircraft. The first thing we designed was the fuselage again using Roskam process for the several specifications that he outlined for military transport, specifically here we're looking at the fineness ratio," Damien
	(5.02) Wing Configuration	"The next thing to design was our wing configuration. Sorry, our wing," Damien
	(5.03) Airfoil Selection	"So, the way we selected our airfoils was doing a CFD analysis," Damien
	(5.04) Select High-lift Devices	"The next thing we did was look at some high-lift devices for aircraft," Damien
	(5.05) Preliminary Sizing of Empennage	"The next thing we looked at was designing the empennage," Damien
	(5.06) Calculate Weight and Balance	"The next thing we looked at was weight and balance and the loading options," Damien

Table 55. Task breakdown of Team 1's final design review **(Cont'd)**

High-level task	**Detailed-task**	**Evidence**
	(5.07) Design Landing Gear	"Then, we went ahead and designed the landing gear...As far as landing gear, we also went ahead and selected the tires...Then, the next thing we designed was a retraction mechanism," Damien
	(5.08) Select Landing Gear Tires	"As far as landing gear, we also went ahead and selected the tires," Damien
	(5.09) Design Landing Gear Retraction Method	"Then, the next thing we designed was a retraction mechanism," Damien
(6) Conduct a performance analysis		"I went on to analyze the performance capabilities of our aircraft," Astrid
	(6.01) Select engine	"We selected the propulsion system," Astrid
	(6.02) Construct Payload/Range Diagram	"Then we also constructed a payload versus range diagram," Astrid
	(6.03) Construct Vn Diagram	"Then, we constructed a Vn diagram," Astrid
	(6.04) Calculate stability and control	"So, that brings us into stability and control. The way we handled stability and control was that we used the mechanics of textbook, which taught us how to build an A and B matrix that would allow us to analyze the different stability moments of our aircraft," Rocco
	(6.05) Choose subsystems	"Alright, I'm going to spend some time discussing the different subsystems that we have on the flying Farasi," Mauro
	(6.06) Analyze Structure & Manufacturing	"After that, we also looked at structure and manufacturing for the flying Farasi," Mauro
	(6.07) Perform Cost analysis	So, with all the design process done, the last thing that was remaining was the cost analysis for our aircraft. Now, cost analysis wasn't as simple as just determining how much it would cost to build one airplane. It was basically determining the life cycle cost of the entire program, and that includes things like development costs, so how much it would cost to develop and research, and also test-flying the airplanes...It includes the procurement cost, which is the cost to build one airplane, including the manufacturing and the materials. And, finally, the operation and support cost, which is

Table 55. Task breakdown of Team 1's final design review **(Cont'd)**

High-level task	Detailed-task	Evidence
		the fuel and maintenance for operating the airplane over a certain period of time," Mauro
	(6.08) Calculate Operation & Support Cost of Aircraft	"After that was figuring out the operation and support cost," Mauro
	(6.09) Finalize 3-D Model & Three View	"So, we actually had some time to do some renderings over aircraft, so we're going to show you," Damien

Table 56. Differences in Team 1's midterm and final presentation task breakdowns. gray shading denotes new tasks that were discussed in the final presentation but not in the midterm.

High-Level Task	Lower-level Task	High-Level task	Detailed-task
Define Requirements & Outline Mission	Outline aircraft requirements	Define Requirements	Outline aircraft requirements
	Outline Mission Profile	Select aircraft configuration	Analyze Stakeholders
	Perform Trade Study Mach Number		Perform Preliminary Configuration Selection
	Perform Trade Study Altitude	Outline Mission	
Choose Configuration	Examine stakeholders		Outline Mission Profile
	Analyze Figures of Merit		Sensitivity Study: Mach Number
	Create a VSP model		Sensitivity Study: Altitude
Initial Weight Estimation	Historical Regression of Weight	Initial Aircraft Sizing	Historical Weight Regression
	Select Technologies to Incorporate into Design		Select Technologies
	Calculate Class I Weight		First Weight Estimate
	Calculate Fuel Used in Mission		Create Weight Sizing Tool
	Update Weights		
	Estimate Drag polar		Class I Drag Polar
			Class II Drag Polar
	Constraint Sizing		Constraint Sizing
	Baseline Analysis		Baseline Weight Tools
Determine Initial Configuration and Layout of Aircraft	Design the Fuselage	Determine Initial Configuration and Layout of Aircraft	Size Fuselage
	Design the Wing Configuration		Wing Configuration
	Select Airfoil and Perform CFD Analysis		Airfoil Selection
	Select High-Lift Systems		Select High-lift Devices
	Design the Empennage		Preliminary Sizing of Empennage
Perform Weight & Balance	Select Cargo Loading Configuration		Calculate Weight and Balance
			Design Landing Gear
			Select Landing Gear Tires
			Design Landing Gear Retraction Method
Analyze Performance	V-n diagram	Conduct a performance analysis	Select engine
	Analyze Propulsion System		Construct Payload/Range Diagram
	Calculate stability derivatives		Construct Vn Diagram
			Calculate stability and control
			Choose subsystems
			Analyze Structure & Manufacturing
			Perform Cost analysis
			Calculate Operation & Support Cost of Aircraft
			Finalize 3-D Model & Three View

Table 57. Metrics referenced by Team 1 in the midterm and final presentations

Metric Abbreviation	Midterm	Final
#AC	X	X
#Engines	X	X
A Intercept	X	X
A Mat	X	X
Aneh Wing	X	X
Aneh Wing_Similar AC	X	X
AR Wing	X	X
B Mat	X	X
B Slope	X	X
c Coef	X	X
Cargo	X	X
Cargo Rqmt	X	X
CG Overall	X	X
CG Range	X	X
CL	X	X
CLMax Ldg	X	X
CLMax TO	X	X
Cost	X	X
Cost Maintenance	X	X
ct/cr	X	X
d Coef	X	X
Dim Cargo	X	X
DW due to Tech	X	X
DWeight Calc	X	X
Eff Fuel Burn	X	X
Eigenvalues	X	X
EIS	X	X
eta	X	X
FF Segment	X	X
h	X	X
h Segment	X	X
High L Dev	X	X
hmax	X	X
i	X	X
l fuse	X	X
lf/df	X	X
M	X	X
M Cruise Rqmt	X	X
MTOW	X	X
MTOW_C5	X	X
MTOW_Similar AC	X	X
R	X	X
R_C5	X	X
RNom	X	X
ROC	X	X
ROC Segment	X	X
SR	X	X
Stakeholder Wants	X	X
Stakeholders	X	X
SWing	X	X

Table 57. Metrics referenced by Team 1 in the midterm and final presentations (Cont'd)

Metric Abbreviation	Midterm	Final
SWing_Similar AC	X	X
T Engine	X	X
t/c	X	X
T/W	X	X
TCA	X	X
TO Ldg FL	X	X
TOFL	X	X
TR	X	X
V	X	X
Vol Fuel_C5	X	X
Vol Reserve Fuel	X	X
W Crew	X	X
W Empty_C5	X	X
W Empty_Similar AC	X	X
W Engine	X	X
W/S	X	X
Wpay	X	X
WPay Max Rqmt	X	X
WPay Rqmt	X	X
d fuse	X	S
FL Rqmt	X	S
h Fuse Max	X	S
l TC	X	S
Ldg Beta	X	S
Ratio Ctl Surface_Similar AC	X	S
STail_Similar AC	X	S
t Fuse	X	S
TRL	X	S
w Fuse Max	X	S
x AC Components	X	S
n	S	X
V Manuever	S	X
FCA	S	S
Time to top climb	S	S
Swing_Similar AC	X	
#Pallets	X	
%Laminar Flow	X	
Airfoil Type	X	
Altitude_Similar AC	X	
C Fuse	X	
c Geom_Similar AC	X	
CD	X	
Cd_Similar Airfoil	X	
CG Components	X	
Cl_Similar Airfoil	X	
CLMax	X	
CLMax_Var AC	X	
Config Alt	X	

Table 57. Metrics referenced by Team 1 in the midterm and final presentations (Cont'd)

Metric Abbreviation	Midterm	Final
Config Components	X	
d fuse_Similar AC	X	
Data_C5	X	
DD Cruise	X	
Ddrag due to Tech	X	
DEff Fuel Burn	X	
Dim Airfoil	X	
Distance Btwn Tail Wing	X	
Dlift due to Tech	X	
DW due to Composites by Component	X	
Eigenvectors	X	
Env Factors	X	
FOM Weight	X	
h_C5	X	
HBPR	X	
Layout_Similar AC	X	
LP	X	
M DD	X	
M_Similar AC	X	
Phugoid	X	
R Cruise	X	
R max	X	
R Min	X	
Running Cost	X	
Size Pallets	X	
SP	X	
Stail	X	
Storage	X	
Swing	X	
t/c Horiz Tail	X	
Temp	X	
Thrust_Similar AC	X	
TSFC	X	
TSFC_C5	X	
Vol Fuel Max	X	
W	X	
W Components	X	
W Cruise Segment	X	
W Gross	X	
W wing	X	
WF Segment	X	
Wpay Max	X	
WTO/S	X	
Wto/S_Similar AC	X	
WTO/Tsl_Similar AC	X	
Sweep c/4	S	
Thrust	S	
V Dive	S	
#APU Gen		X
#Bogies		X

Table 57. Metrics referenced by Team 1 in the midterm and final presentations (Cont'd)

Metric Abbreviation	**Midterm**	**Final**
#Engine Gen		X
#Fuselage Sections		X
#Struts LG		X
#Tires		X
Aft CG		X
Airfoil Types		X
AoA		X
Avionics Components		X
Avionics_Similar AC		X
bWing		X
Cargo Access		X
Cargo Access_Similar AC		X
CD0 Class I		X
CD0 Class II		X
CD0 Wing		X
cf		X
CG Range_Roskam		X
Climb Rqmt		X
CLMax Calc		X
CLMax Ldg Rqmt		X
CLMax Rqmt		X
Complexity		X
Conversion Rate of $		X
Cost Avionics		X
Cost Avionics per lb		X
Cost Benefits		X
Cost Crew		X
Cost Dev		X
Cost Engine		X
Cost Engines per lb		X
Cost Fuel		X
Cost Maintenance Labor		X
Cost Manuf		X
Cost Manuf & Materials		X
Cost O&S		X
Cost Obj		X
Cost per AC_C5		X
Cost Procurement		X
Cost Production		X
Cost R&D		X
Cost Technician		X
Cost Total		X
Cruise Seg Cond		X
ct/cr_Similar AC		X
d Engine Fan		X
Damping Ratio		X
Damping Ratio Rqmt		X
DComplexity		X
DCost due to Tech		X
DCost Maintenance		X

Table 57. Metrics referenced by Team 1 in the midterm and final presentations (Cont'd)

Metric Abbreviation	Midterm	Final
DCost Operation		X
DDrag		X
Dim Elevator		X
Dim Flaps_A340		X
Dim Hangar		X
Dim Horiz Tail		X
Dim Rudder		X
Dim Vert Tail		X
Drag		X
Drag Component		X
DW		X
DWPay		X
DWTO		X
e		X
Electrical System Components		X
Env Ctl System Components		X
Erg Perf		X
FOM		X
Fuel Obj		X
Fuel System Components		X
Fwd CG		X
h		X
h fuse		X
h Tactical Appr		X
K		X
l Engine		X
lf/df Range		X
LFL		X
LLF		X
Location of Empennage		X
Location of Manufacturing		X
M Cruise		X
M Cruise Max_Similar AC		X
M Cruise_Similar AC		X
Maintenance Complexity		X
Manufacturing Components		X
Materials		X
Materials_Similar AC		X
Mission Profile		X
MTOW Calc_C5		X
MTOW Est		X
NACA2412 Exp		X
P		X
P Avail		X
Pm		X
Pn		X
R Descent		X
R Obj		X
R Rqmt		X
R Segment		X

Table 57. Metrics referenced by Team 1 in the midterm and final presentations (Cont'd)

Metric Abbreviation	Midterm	Final
Range Reserve		X
Rmax		X
SFC		X
Stability Deriv		X
Stakeholder Weight		X
Steerable Angle_Similar AC		X
Steering Rqmt		X
Structural Benefits		X
Structural Capability Req		X
Structures Components		X
T Max		X
T/W_Similar AC		X
Tail Ground Clearance		X
Tail Ground Clearance Rqmt		X
Tail Vol Ratio		X
Tail Vol Ratio_Similar AC		X
TC		X
TC Rqmt		X
TCA Range		X
TD		X
TD Phugoid		X
TD Rqmt		X
Technology Improvements		X
Tip-Over Criteria Lateral		X
Tip-Over Criteria Lateral Rqmt		X
Tires Rated Load		X
Tires Rated Velocity		X
TOFL Emergency		X
TR_Similar AC		X
Trim Angle		X
Type of LG		X
Type of LG_Similar AC		X
V Eq		X
vmax		X
Vol Fuel		X
Vol Fuel Calc_C5		X
Vol Trapped Fuel & Oil		X
VSP Alts		X
VSP Components		X
W Empty Calculated		X
W Empty Est		X
W Empty Model		X
W Engine_Similar AC		X
W Fixed Equip_Similar AC		X
W Segment		X
W Structures_Similar AC		X
W/S_Similar AC		X
w0		X
w0 Rqmt		X
Wempty		X

Table 57. Metrics referenced by Team 1 in the midterm and final presentations (Cont'd)

Metric Abbreviation	Midterm	Final
Wing Tip Types		X
WPay_C5		X
#AC Dev		S
Cd BAC1		S
Cd CAST102		S
Cd SC(2)0714		S
CD0 Fuse		S
CD0 Horiz Tail		S
CD0 Nacelle		S
CD0 Vert Tail		S
Cl BAC1		S
Cl CAST102		S
Cl SC(2)0714		S
CLMax Ldg_Similar AC		S
Cost Engr		S
Cost Flt Test		S
Cost Qual Ctl		S
Cost Tooling		S
cWing_Similar AC		S
Dim Tires		S
Engine Lifespan		S
Gamma		S
h max_Similar AC		S
MAC		S
Mach <10K		S
Mach >10K		S
Noise		S
Pm Req		S
Pm Total		S
Pn Req		S
Pn Total		S
Sweepc/4		S
Sweepc/4_Similar AC		S
Time		S
Tip-Over Criteria Long		S
Tip-Over Criteria Long Rqmt		S
Tires Tread		S
V Max		S
W Empty		S
Wing Ground Clearance		S
Wing Ground Clearance Rqmt		S
Wpay		S
y AC Components		S

Table 58. Team 1 metrics that are repeated across and within disciplines

New Metric	**Number of Cross-Discipline Integrations**	**Mission/ Requirements Outline**	**Weight Calculation**	**Performance Estimation**	**Configuration**	**Aerodynamics**	**Structures**	**Stability**	**Cost**	**Subsystems**	**Technologies**	**Propulsion**	**Landing Gear**	**Fuselage**	**Empennage**	**Within-Task Elements**
Weight (Empty, Components, Technology, Payload, Takeoff, Requirement)	5	X	X	X	X			X				X				X
h	4	X	X	X		X				X						X
Cost (O&S, Maintenance)	3	X							X	X	X					X
M	3	X	X	X				X								
CL (CL, CLMax, CL Landing)	3			X		X							X			X
CG Overall	3				X			X					X			X
SFC	3		X	X							X					
SWing	3			X		X									X	
R	2	X	X	X												X
Cargo	2	X		X										X		
Eff Fuel Burn	2	X								X	X					
TOFL	2	X		X								X				
eta	2		X			X										
FF Segment	2		X	X												
Aneh Wing	2					X		X								
AoA	2											X	X			

Table 58. Team 1 metrics that are repeated across and within disciplines (Cont'd)

New Metric	**Number of Cross-Discipline**	**Mission/ Requirements**	**Weight Calculation**	**Performance Estimation**	**Configuration**	**Aerodynamics**	**Structures**	**Stability**	**Cost**	**Subsystems**	**Technologies**	**Propulsion**	**Landing Gear**	**Fuselage**	**Empennage**	**Within-Task Elements**
TR	2			X								X				
V	2			X								X				
W/S	2			X		X										
l fuse	2													X	X	
bWing	2					X									X	
FOM Weight	1	X														X
ROC Segment	1	X		X												X
EIS	1	X										X				X
#AC	1	X							X							X
Airfoil Type	1					X										X
AR Wing	1					X										X
CD	1					X										X
High L Dev	1					X										X
t/c	1					X										X
Vol Fuel	1		X													X

Table 59. List of decisions and Team 1's reasoning for the decision in the midterm presentation

High-level Task	Lower-level Task	Decision	Decision Quote
Define Requirements and Outline Mission	Outline aircraft requirements	No decision, outlining the project	
	Outline Mission Profile	Mission Profile, M, R, h, TOFL	"The first thing that we needed to figure out is our mission profile, which we got pretty much from our RFP and a bunch of assumptions that we made," Rocco
	Perform Trade Study to Select Mach Number	M	"Mach number was selected based on specific trade study that we did, which is Mach versus the specific range," Rocco
	Perform Trade Study to Select Altitude	h Max	"And we held a constant for .78 Mach number at three average cruise weights, and we've got three distinct curves, each corresponding to our cruises. And so the first one is at 26,000 feet, our second one is at 30,000 feet, and then, the last one is at 36,500 feet. And to kind of put it in perspective what these numbers make sense, we put a list of similar aircrafts C17, C5, and the Antonov 225. The Mach number you can see ranges somewhere, it falls into that category, as well as the max cruise altitude," Damien
Choose Configuration	Examine stakeholders	Rate importance of stakeholders	"We've taken into consideration all these configurations, for all these different components that we have. We take our figures of merit. We weight each one of these different configurations, different alternatives for components, and then the total weight that we get, we select over all configuration for aircraft," Rocco
	Analyze Figures of Merit		
	Create a VSP model	Configuration	
Initial Weight Estimation	Historical Regression of Weight	W, B Slope, A Intercept	"Regression, which will give us basically a slope of intercept coefficient, which will allow us then to gather maximum takeoff cross-wing estimation, put her into the regression, and output, and then into the wing," Rocco

Table 59. List of decisions and Team 1's reasoning for the decision in the midterm presentation (Cont'd)

High-level Task	Lower-level Task	Decision	Decision Quote
	Select Technologies to Incorporate into Design	Aircraft Technologies	"So, first one is hybrid laminar flow. What it does is that it basically ejects the actuator, which improves the laminar flow over the surface of the wing, especially towards the trailing edge. And that produces like a reduction in cruise drag up to 10 percent, a reduction the takeoff weight of 3 percent. And it also increases the fuel efficiency. And the next technology feature is the raked wing tips. It's basically a tip of the wing has higher angle of speed, and it reduces the lift in the strike. And also it also improves the fuel efficiency and decreases the drag. And the next one, for our propulsion, we used the GENX engines. And they are already in current production and they are used on many modern aircrafts. They have high bypass ratio, and also they increase fuel efficiency as they are made of composite materials. And also, the TRL was very high for most of these, because they are already being researched and developed currently, and implemented on aircraft. And lastly, we're using advanced composites and electro-mechanical actuators. So, electro-mechanical actuators are basically used to place the hydraulics systems, so we don't have to incorporate the hydraulic system which has time maintenance, and fuel leaks and things like that. So that reduces the entire weight of the aircraft, and also has less maintenance cost. So, overall, like all the drawbacks of the technology is they are really expensive, but at the same time they compensate for the weight and the efficiency," Spencer
	Calculate Class I Weight Breakdown	Eta, W	"And by doing that, we then calculated the end weight of our aircraft. We then did the end weight versus the original weight. And we were able to exactly that we were able to use an eta factor of .85. And here you can see a difference between the class one and class one with the eta factor," Rocco
	Calculate Fuel Used in Mission	Update Aircraft Weight	"And we were able to calculate how much fuel is going to be used per mission segment. Other things that also came into consideration, into the RFP, was the true weights...Once we did all this, those were put into a spreadsheet, and we were able to estimate the maximum takeoff and gross weight, and we calculated empty weight, which we then compared it to the numbers that we'd gotten from the regression, and we found that there was a difference of less than .01 percent. So we were very satisfied with these numbers," Rocco
	Update Weights		

Table 59. List of decisions and Team 1’s reasoning for the decision in the midterm presentation (Cont’d)

High-level Task	Lower-level Task	Decision	Decision Quote
	Estimate Drag polar	C Fuse, CD, CL	"And in the CF was coefficient of the fuselage. And that was determined to be .0043; we reduced it from .0047, because we incorporated our technology factors that reduced the drag cost by the fuselage ratio. And the aspect ratio was derived from the constraints sizing. We determined that using that wing loading, and then we got the reduced drag, like that way similarly, and then we came up with the plot for the CL, and then CD for our Drag Polar," Spencer
	Constraint Sizing	W/S, T/W, WTO, Swing	"So, you see from the constraint diagram, we have a design selection for aircraft of 132 000 square feet for our wing loading and 0.24 thrust loading and these are just again to compare with similar aircrafts; listed are the C5, C17, and Antonov 225. Antonov is a little bit big, but it's just to give us a rough estimate of where we stand with our vehicle," Damien
	Baseline Analysis	Wempty	"And when we input these numbers into our spreadsheet, including the TSFC values for its engines, and the altitude at which it normally flies, ranges, so on, we calculated the empty weight, maximum takeoff weight, and fuel carried. And we compared it with the calculated from our spreadsheet to the actual. And we saw there was only a difference of about 2 percent, which we thought was pretty good. This gave us a lot of confidence that our tools and our numbers were working properly," Rocco
Determine Initial Configuration and Layout of Aircraft	Design the Fuselage	Fuselage size	"So, using that, we used Roskam design techniques to determine if our fuselage falls into one of their aircrafts, like types, so we picked the military transport, and the total of our aircraft came to be 215 feet, and the maximum diameter was approximately 28 feet. And we checked the fineness ratio, tail, length, and angle, and if it fits into the Roskam’s recommended values," Spencer
	Design the Wing Configuration	t/c, High-lift devices, Aneh Wing, ct/cr, Sweep c/4	"And for the root we picked the SC(2) 0714 airfoil, and for the tip we picked the BAC 1, of which I'll talk about in detail after. And for the high lift devices we picked the double-slotted flaps, and then we picked an anhedral airfoil, with the angle of 4.5, based on similar aircrafts," Spencer
			"And thickness to cord ratio would, we found on paper that estimated using the mach drag divergence number, and Cl and then a few coefficients to determine the thickness to cord ratio, and using that, we found that thickness to core ratio to be .109. And we're using like a tapered wing, because it provides a better lift distribution. And it also reduces the weight of the wing, and also provides better structure," Spencer

Table 59. List of decisions and Team 1's reasoning for the decision in the midterm presentation (Cont'd)

High-level Task	Lower-level Task	Decision	Decision Quote
	Select Airfoil and Perform CFD Analysis	Airfoil	"As I said earlier, we chose the BAC 1 airfoil at the tip, and SCE 0712 for the root. To do that, we actually picked different super-critical airfoils, and we ran them in CFD," Spencer
	Select High-Lift Systems	High lift devices	"And for the high lift systems, we found a paper that had different aircraft plotted like against the Cl max," Spencer
	Design the Empennage	Tail size	"You will see that the H tail is actually lifted up a little bit from the fuselage, and this was done just so that the wings and the tail would not be in the same plane," Rocco
			"And we were able to back solve for the tail area. We also averaged out the ratios for the elevator through root cord and the elevator for tip cord, to estimate our control surfaces. And we followed the similar process for our vertical tails," Rocco
Perform Weight & Balance	Find Aircraft Center of Gravity	Placement of Aircraft Components	"First of all, I had to move the wing a little forward, which moved the fuel tank and the engine with it," Damien
	Select Cargo Loading Configuration	Loading configuration	<Overviews process and location for multiple loading scenarios>
Analyze Performance	Payload Range Diagram		
	V-n diagram		
	Analyze Propulsion System	Engine	"And for propulsion system, as we talked about earlier, using the GENX engines, and we're using two engines, we decided to use that because each engine produces 76000 pounds of thrust, and combined we get 152 000 pounds of thrust," Spencer
		Select APU	"And for the APU, we're using like a next generation APU as well. It's the Hamilton Sunstrand 5000 APU," Spencer
	Calculate stability derivatives		

Table 60. List of decisions and Team 1's reasoning for the decision in the final presentation

High-level task	Detailed-task	Decision	Decisions Evidence
Define Requirements and Outline Mission	Outline aircraft requirements		
Select aircraft configuration	Identify Stakeholders and needs	Stakeholders and their importance	"Just like before, we determined that the cost, the storage, the maintenance—these were some of the key players on our design," Rocco
	Perform Preliminary Configuration Selection	Configuration	"We looked at our V-tail, our traditional tail, and then our H-tail, and with the scoring system, kind of like the one we just went over, we were able to determine which works best for our aircraft," Rocco
Outline Mission	Outline Mission Profile	Mission Profile, TOFL, h, ROC, R	"We looked at the RFP and we designed a mission profile so that it would fit all the requirements," Rocco
	Sensitivity Study: Specific Range vs Mach Number	Mach	"What we did was started looking at our specific range due to Mach number and our tools; we started varying that, and we saw that there was a curve with a peak. At that peak, or "sweet spot", we determined that at Mach .78 we would maximize our range. So, we decided to use that Mach room before all of our cruise segments," Rocco
	Sensitivity Study: Specific Range vs Altitude	Altitude	"Then, the chart to your right is a specific range versus altitude for different weights that we estimated our aircraft would have in specific cruise segments. So, that's Cruise Segment One, Two and Three. By estimating this weight, and estimating the different altitudes which we could fly, we see that there's also peaks in these curves, and that's how we picked the 26 000, 30 000 and 36 500 ft. of altitude," Rocco
Initial Aircraft Sizing	Historical Weight Regression	Empty weight, B Slope, A Intercept	"We took about twenty different aircraft and we input them into this Excel sheet by looking at their empty weight and maximum takeoff gross weight, and from this data we were able to outline a trend. This trend would then help us calculate, from estimated takeoff gross weight, our empty weight," Rocco

Table 60. List of decisions and Team 1's reasoning for the decision in the final presentation (Cont'd)

High-level task	Detailed-task	Decision	Decisions Evidence
	Select Technologies	Technologies	"So, we did some research to find out the kinds of technologies that could be applied to this aircraft type, and we were able to settle at these five specific ones that actually would be implemented in the aircraft. The first one was a hybrid laminar flow control, which will help to improve our aerodynamic performance. Then, we also selected the raked wingtips, which would help to reduce drag and improve fuel efficiency. Then, we went on to select the propulsion system to be the general electric GENX engine, which is a high bypass ratio turbofan, and this would help to improve our fuel efficiency as well, and also reduce weight, as compared to its predecessors. We also decided that we were going to use advanced composites for aircraft, including the engine as well, to help give us less weight, which also correlates to fuel efficiency. Then, we're going to replace the hydraulic actuators in our aircraft to electromechanical actuators. This would help to reduce maintenance costs, but we'd also have a drawback of increasing operation costs. Just in general, the benefits from using these different types of technologies was that we'd be reducing drag of our aircraft, improving fuel efficiency, and in some cases reducing the total weight of the aircraft, but with a few drawbacks of increasing costs which we'll tell you about later into the cost analysis process, and maybe increasing the complexity of some of the systems," Astrid
	First Weight Estimate	Eta	"Then we went on and decided that we would apply the technologies that I just discussed and got an eta factor of .85, which is the ratio between the new weight once we applied the technologies to the old weight without technologies," Astrid
	Create Weight Sizing Tool	W Empty	"And so, we were able to calculate an empty weight of 237 000 pounds, which was pretty close to what was [allowed] and we also used the FLOPS software provided to us to do the same sizing process, and we were able to find the number of 242 000 empty weight using FLOPS. So, that was a less than 2 percent difference from where we got from less sizing, which helped us validate our results," Astrid
	Class I Drag Polar	CD0	"That's the drag polar that we obtained for this," Astrid
	Class II Drag Polar	Drag Component, CD0	"From the drag buildup chart we saw that the wing was going to contribute the most drag with 10 to 5.6 percentage drag. Just a comparison to the original zero-lift drag coefficient, which was 0.0215 to the Class II drag polar which was about 0.026," Astrid

Table 60. List of decisions and Team 1's reasoning for the decision in the final presentation (Cont'd)

High-level task	Detailed-task	Decision	Decisions Evidence
	Constraint Sizing	T/W, W/S, Swing, TR	"From then we were able to pick the design point there, and we were able to calculate the wing loading which turned out to be 132 pounds per feet squared, and from that we drafted the wing area for the aircraft to be about 5000 feet squared. We also got the thrust to weight ratio from that same design point to be 0.24, and calculated the thrust required to be 165 000 pounds. Then, we went on to compare these to three similar aircraft: the C17, the C5A, and Antonov 225. We found that they fit to the ranges they had, that we were just comparing size-wise," Astrid
	Baseline Weight Tools		
Determine Initial Configuration and Layout of Aircraft	Size Fuselage	Fuselage size	"He suggested it to be between 6 and 13, and we're sitting at about 9. The length of the fuselage is about 216 ft. and the tail cone angle he suggests to be between 7 and 25 degrees, and we're at 15 degrees. So, that's our final design for a fuselage," Damien
	Wing Configuration	Sweep, Aneh, bwing	"We looked at the wing area that we obtained from our constraint sizing and then from that, we were able to get a wing span based on hanger sizes that we looked at, and then get an aspect ratio. The other parameters that you see, taper ratio, anhedral angle, and the sweep angle were based on previous, similar aircraft by just taking an average, and I'll talk to you a bit about airfoils but you can see the design. We've also included the raked wingtips on the ends of the wing design," Damien
	Airfoil Selection	Airfoil at root, airfoil at tip	"Based on that, we selected the SC2 to be the airfoil at the root, and then the BAC1 to be the airfoil at the tip. This has to do with the type of structure. It reduces the structure at the tip as well as it corresponds with the ten percent thickness to chord ratio that we selected for our tip. The clean CLmax that we needed for our aircraft was 0.589, and with the airfoil configuration that we have right now, at an incident angle of 0.5 degrees, we get 0.611. This was done based on lift distribution analysis," Damien
	Select High-lift Devices	High lift devices	"For us, we needed 2.9, so we selected a double-slotted flap and a slat, which, for the actual design on our aircraft, we took the A340's dimensions and transposed those into our wing. So, you can see the double-slotted flap, as well as the other wing, and what you see on top is our fuel tanks, which I'll be talking about in a bit," Damien

Table 60. List of decisions and Team 1's reasoning for the decision in the final presentation (Cont'd)

High-level task	Detailed-task	Decision	Decisions Evidence
	Preliminary Sizing of Empennage	Empennage characteristics: horizontal tail area, vertical tail area, tail placement	"Using the Roskam process we were able to find the volume coefficients, and some of these other parameters for the different aircraft so we could take averages for those. We didn't take averages for our wing area, which we got from our constraint sizing, and then the distance to the empennage was 98 ft. Those were the only things we actually determined and we used those to backsolve for our tail, which we got about 1100 feet squared. These are the results for the horizontal tail. We used the same process for our vertical stabilizers as well. Then, the elevators and the elevators and rudders were estimated, again, based on the fractions from similar aircraft," Damien
	Calculate Weight and Balance	Component/payload placement, x AC components, y AC components, Loading Options	"We had to move them around to get a vehicle in the CG range that I'm going to talk to you about," Damien
	Design Landing Gear	Landing gear placement	"He has several criteria that you can see the results, as well as what's required. The analysis that I show here is the lateral tip-over criterion. It just states that the tip-over angle has to be less than 55 degrees, which for our aircraft is 53. Another thing I want to make a note of is the tail strike. The tail ground clearance Roskam suggests has to be greater than 55 degrees, but we're at 14 degrees. Roskam doesn't account for high-lift devices that our aircraft has to get better CL, so we can take off at a lower angle than that," Damien

Table 60. List of decisions and Team 1's reasoning for the decision in the final presentation (Cont'd)

High-level task	Detailed-task	Decision	Decisions Evidence
	Select Landing Gear Tires	Landing gear tires, #Tires, #Bogies, #Struts LG	The tires selected were from Goodyear, and those are the development tires that they are testing currently. Again, the rated speed 180 miles per hour is well over the speed that we need to approach or take off. So, the tread we selected was the aircraft which is more preferred for military transport vehicles, and then the ply strength which Goodyear has is 30-32 as their highest ply strength. So, the main gear tires are of course going to be stronger than the nose gears. "As far as selecting the number of tires based on the load that each tire could carry, we calculated that we need four tires for the nose gear, and we needed twenty for the main gear, and that's twenty-four total. So, we designed a bogie so it has six tires per bogie, and you can see the designs on the left-hand side. So, the nose gear would be able to carry all four tires, and all the weight that the nose needs to carry in one strut, and in the back, the main gear, we're going to have four different bogies, so four struts. That's our tire selection for our aircraft, as well as our landing gear," Damien
	Design Landing Gear Retraction Method	Retraction mechanism	"So, again, a very simple retraction mechanism, since this is a military aircraft, and we want to reduce the complexity. We selected nose gear that easily goes in and retracts, and you can see the transparency and the actual one that's retracted inside, and then the way the doors would open," Damien
Conduct a performance analysis	Select engine	Engine, T Max, W Engine, d Engine Fan, l Engine	"We did got that we could get a maximum thrust of 83 000 pounds. Two of those couldn't meet our thrust requirement. I have a few engine specifications that we used in order to design it for our 3D model. So, a weight of 12 000 pounds, fan diameter – 111 inches, and a length of 185 inches," Astrid
	Construct Payload/Range Diagram		
	Construct Vn Diagram		
	Calculate stability and control		
	Choose subsystems	Subsystems	"Our aircraft is going to be completely electrically driven, which makes it one of the more electric aircraft. The benefits of that include things like more available power, increased efficiency, and also, they'll be more reliable and more economical in terms of production costs and maintenance costs," Mauro

Table 60. List of decisions and Team 1's reasoning for the decision in the final presentation (Cont'd)

High-level task	Detailed-task	Decision	Decisions Evidence
	Analyze Structure & Manufacturing	Materials and Manufacturing Process	
		Location of manufacturing	"Recently, the Boeing facility announced that it will be closing its Long Beach assembly facility where the C17 was produced for twenty years. So, we were thinking of reusing this production line for the Flying Farasi. The map also shows where different components of the Flying Farasi would be manufactured, and the final assembly would occur in the Long Beach facility in California," Mauro
	Perform Cost analysis		
	Calculate Operation & Support Cost of Aircraft		
	Finalize 3-D Model & Three View		

APPENDIX F - TEAM 2’S DETAILED DATA FROM OBSERVATIONS

Transcripts for Team 2’s midterm and final design presentations were analyzed using a qualitative analysis. The results of this analysis are outlined in Table 61 (midterm presentation) and Table 62. The evidence for identifying the tasks is presented in Table 63 (midterm presentation) and Table 64 (final presentation). Table 65 lists the metrics that were referenced by Team 2 and classifies if the metric was mentioned in the midterm or final presentation. Table 66 is a list of all the metrics that were repeated across and within disciplines. Finally, evidence of Team 2’s decisions are in Table 67 (midterm presentation) and Table 68 (final presentation).

Table 61. Team 2’s detailed design process in the midterm presentation

High-level task	Detailed-task	Decision	Metrics
Requirements Analysis	Requirements Analysis		EIS
			Y Ret_C5
			Cargo Rqmt
			Cargo_C5
			WPay Max
			Time to Climb
			LFL
			MCruise Min
			Maintenance Turnaround Time
Configuration Selection	Figures of Merit	Choose configuration, Figures of Merit (Importance of Criteria)	Data_C5
			FOM
			TOPSIS Output
			Pugh Matrix

Table 61. Team 2's detailed design process in the midterm presentation (Cont'd)

High-level task	Detailed-task	Decision	Metrics
Weight Sizing	Weight Regression	Takeoff weight, L/D, TSFC	MTOW_Similar AC
			W Empty_Similar AC
	Baseline sizing		Time Warmup
			MFF Climb
			Weight Climb
			MFF Cruise
			W Cruise Segment
			MFF Decent
			W Descent
			FF Reserves
			W Fuel Reserves
			WTO_C5
			W Crew_C5
			WPay_C5
			FF_C5
			W Empty Allow
			W Empty Calc
			A Intercept
			B Slope
			DWeight Calc
			h
			ROC
			L/D
			TSFC
			Endurance
			R
			V
			MTOW
	Technology Selection	Percentage composites, Eta	eta
			%Composites by Year
			Y Composite
			%Composites
			eta Composites
		TSFC Sav	Engine Data_GE90
			DTSFC Eff
			M(L/D) Max
			EIS
	Summary		Time Warmup
			MFF Climb

Table 61. Team 2’s detailed design process in the midterm presentation (Cont’d)

High-level task	Detailed-task	Decision	Metrics
			Weight Climb
			MFF Cruise
			W Cruise Segment
			MFF Decent
			W Descent
			FF Reserves
			W Fuel Reserves
			W Empty Allow
			W Empty Calc
			A Adj
			B Adj
			DWeight Calc
			ROC
			L/D
			TSFC
			Endurance
			R
			MTOW
			M Cruise
			h segment
			h Cruise
			WPay
			WPay Max
	Choose Design Mission	Range	WPay
			R
			WPay Max_C5
			R Climb
	Update Aerodynamic Model	Unstated	Data_X38
			CL
			CD
			M
			Re
			L/D
			%Laminar Flow
			Crud Drag Factor
			e
			e Fuse
			K Model
			K Exp

Table 61. Team 2's detailed design process in the midterm presentation (Cont'd)

High-level task	Detailed-task	Decision	Metrics
			L/D Max Model
			L/D Max Exp
	Constraint Sizing:	W/S	W/S
			T/W
	Updated Aircraft Sizing	MTOW, W_Empty, Sref, Span	MTOW
			W Empty
			W Empty/WTO
			bWing_C5
			Sref
			bWing
			Tail Vol Ratio
	Size cargo bay	Cargo bay size, Cargo bay cg	Cargo Rqmt
			Dim Cargo
			Dim Cargo Bay
			Dim Cargo Bay_C5
			hn
			Fwd CG
			Aft CG
			Max Static Load
			WPay
			LG Track
			LLF
			Safety
	Calculate Impact of Technologies	Technology Selection	Stail Wet
			TSFC
			Drag Ram
			Power Setting Engine
			cf
			eta Composites
			k
			Ext Moduli Materials
			DW due to Composites
	Trade Study	Centerline thickness, W/S, Mach, Altitude	t Airfoil Center
			h cargo bay
			cf
			CD0
			L/D Max
			W/S
			MTOW

Table 61. Team 2's detailed design process in the midterm presentation (Cont'd)

High-level task	Detailed-task	Decision	Metrics
			SR
			M
			h
			CL
	Aerodynamic Analysis	Flap Location, L/Dmax, L/Dcruise	Sweep LE
			d Flaps LE
			M Cruise
			CL Buffet
			c Span
			Spanwise Twist
			CL
			Location of Flaps
			Location of Ailerons
			Location of Engine
			Location of Elevator
			L/D Max
			L/D Cruise
			M(L/D) Baseline
			CD Components
			t Fuse
			h
			M
			CDi
			CD0
	Control Surface Design	High lift devices, Rudder size, Rudder Sweep, Elevator Size, # Vert Tails	CL Ldg Req
			CLMax Fowler
			D cWing LE Slats
			Bank Angle
			dRudder
			Cmbeta
			#Vert Tails
			Tail Vol Ratio
			Dim Rudder
			Location of Elevator
			d Elevon TO
			D Elevon Cruise
			cElevator
			cFlaperon
			cElevon

Table 61. Team 2's detailed design process in the midterm presentation (Cont'd)

High-level task	Detailed-task	Decision	Metrics
			cRudder
	Mission Breakdown		MTOW
			W Empty
			bWing
			Sweep LE
			ct/cr
			W Empty Manuf
			W Fuel Max
			W Max 0 Fuel
			WPay Max
			W Crew
			A Trapezoidal
			t Airfoil Center
			tWing Outboard
			R
			M
			L/D
			CL
			h
			TSFC
			WF Segment
	Payload Range Analysis		WPay
			R
			R_C5
	Preliminary Subsystem Layout	Sub system layout	
	CG excursion		MTOW
			CG Overall
Technology Validation	Check Technology Compatibility		Tech
			TRL
			R
	Calculate Technology Costs		Cost BLI
Calculate Total Aircraft Costs	Overall		Cost Dev
			DCost Operation
			PM Assumed
			Conversion Rate of $
			Time AC Production
			Lifespan of AC
			WPay

Table 61. Team 2's detailed design process in the midterm presentation (Cont'd)

High-level task	Detailed-task	Decision	Metrics
			R
			Flt Hrs per Year_C5
			Flt Hrs per Year
			Cost Manuf
	Structures Costs		Cost Engr
			Cost Tooling
			Cost Dev & Support
			Cost Flt Test
			Cost Manuf Labor
			Cost Manuf & Materials
			Cost Qual Ctl
			Cost Maintenance
			Cost Fuel
			Sav Fuel
			%Al
			%Composites
			%Wempty Sav
			Cost Al
			Cost Composites
			Savings Composites
	Propulsion Technologies Costs	Amount saved by integrating propulsion technologies	Dswet BLI
			DL/D
			Cost Maintenance
			Cost Fuel
			DCost Operation

Table 62. Team 2's detailed model of design knowledge coordination in the final presentation

High-level task	Detailed-task	Decision	Metrics
Identify mission objectives	Outline aircraft requirements		bWing_C5
			DCost
			EIS
			h Cruise
			LCN
			Lifespan of AC
			R
			Range Reserve
			Time Range
			Time to Climb
			Time Turn Around
			Time Warmup
			TO Ldg FL
			Turn Radius
			Vol Fuel Min
			WPay
			WPay Max
			Y Ret_C5
Configuration Selection& Sizing	Configuration Analysis	Configuration	#Engines
			Config Alt
			Config Selection
			Engine Placement
			Pitch Ctl
			Pugh Matrix
			Roll Ctl
			Selection Criteria
			Stakeholders
			TOPSIS Output
			Type of Engine
			Type of LG
			Yaw Ctl
	Estimate weight trend	A,B	a Intercept
			b Slope
			MTOW_Similar AC
			W Empty_Similar AC

Table 62. Team 2's detailed model of design knowledge coordination in the final presentation (Cont'd)

High-level task	Detailed-task	Decision	Metrics
	Baseline sizing	WTO, Wempty	A Intercept
			B Slope
			DWeight Calc
			Endurance
			FF
			FFAvg
			h
			L/D
			M
			R
			ROC
			TSFC
			Vol Reserve Fuel
			W Allow
			W Calc
			W Crew
			W Segment
			WPay
			WTO
	Technology impacts	Eta factor due to technology	%Composites
			EIS
			eta
			FOM
			M(L/D)
			SFC Reduction
			Y Composite
	Sizing Update	Range	h Cruise
			M Cruise
			MTOW
			R
			R_C5
			WPay Max
			WPay Max Rqmt
	Constraint Sizing	Updated MTOW , W/S, WEmpty, Sref, and Span	A Adj
			B Adj
			bwing
			Climb Rqmt
			Crit FL

Table 62. Team 2's detailed model of design knowledge coordination in the final presentation (Cont'd)

High-level task	Detailed-task	Decision	Metrics
			Cruise Rqmt
			L/D Cruise
			M Cruise
			MTOW_Similar AC
			R
			Safety FL
			Sref
			T/W
			TO Ldg FL
			TSFC Cruise
			W Empty Calculated
			W Empty/WTO
			W/S
			WPay
Analyze Aerodynamics	Calculate total drag		AR Wing
			CDi
			CDM
			CL
			cWing
			D Wave
			DInterference
			Drag Friction
			DSwet
			e
			Form Factor
			M
			M Cruise Segments
			Sref
			Sweepc/4
			t Airfoil
	Baseline Aerodynamics	% Laminar Flow, CD, Korn factor	%Laminar Flow
			CD
			CL
			e
			K Exp
			K Model
			Korn Factor
			L/D Max Exp

Table 62. Team 2's detailed model of design knowledge coordination in the final presentation (Cont'd)

High-level task	Detailed-task	Decision	Metrics
			L/D Max Model
	Trade Studies	Thickness, W/S	CD0
			Drag Friction
			MTOW
			t Airfoil Center
			W/S
			W/S MTOW
	Update calculations	Reference Area, AR, Wetted Area, leading edge sweep angle (lamba_c/4), center body length, center body width,	AR Wing
			l Center Body
			Sref
			Sweepc/4
			Swet
			t/c
			w Center Body
	Airfoil design	Airfoil, Chord, Twist, Cm	Cm Trim
			Cmw
			Dim Cargo Bay
			M
			M DD
			L/D
			Drag
			Location of TE
			Carving LE
			Cm
			Cm Outboard
	Spanwise Chord and twist		t Airfoil
			x/c
			c Span
			Spanwise Twist
			e
			CL
			x
			e
			AoA
			M
	CFD		t BL
			Unknown Metric

Table 62. Team 2's detailed model of design knowledge coordination in the final presentation (Cont'd)

High-level task	Detailed-task	Decision	Metrics
			Cp
	Drag Polar update		D Wave
			Drag Friction
			CDi
			CD0
			Cf Components
			h
			M
			CD
			CL
			L/D
	Select Cruise Condition	Cruise Conditions	Cruise Seg Cond
			CL Buffet
			h
			M
			SR
	Summarize Mission		bWing
			CL
			CL Buffet
			Cruise Seg Cond
			h
			L/D
			M
			MTOW
			R Segment
			SR
			Sref
			TSFC
			W Empty Calculated
			WE/WTO
			WE/WTO Segment
Design Advanced Propulsion System	Examine Propulsion Fuel Savings	Sav Fuel	cf
			Drag
			DW due to Composites
			Eff Fuel Burn
			Sav Fuel
			Swet

Table 62. Team 2’s detailed model of design knowledge coordination in the final presentation (Cont’d)

High-level task	Detailed-task	Decision	Metrics
			TSFC
Analyze Static Stability & Design Rudders			
	CG Buildup		Aft CG
			CG Components
			CG Empty
			CG Overall
			CG Systems
			CG_787
			Fwd CG
			MAC
			SM
			SM_Comm AC
			W
			W Sys_787
			WE/WTO_787
	Sizing the Rudders	Rudder size, Number of vertical tails	#Vert Tails
			Bank Angle
			Dim Vert Tail
			dRudder
			Stability Deriv
	High-Lift Devices	High lift devices, Slap to chord ratio, High lift device span, slat deflection, use nose flaps?	bHigh Lift Dev
			Cm LE Slats
			dSlats
			L Nose Flaps
			L Slats
			Slat per Chord
			Trim Angle
	Stability characteristics	Stability augmentation system	Damping Ratio
			Dutch Roll
			Lb
			Lr
			Lvl 1 Rqmt
			Lvl 1 Rqmt SP
			Lvl 2 Rqmt
			Lvl 2 Rqmt DR
			Lvl 2 Rqmt RTC
			Nb

Table 62. Team 2's detailed model of design knowledge coordination in the final presentation (Cont'd)

High-level task	Detailed-task	Decision	Metrics
			Nr
			Phugoid Ratio Ldg
			Phugoid Ratio TO
			RTC
			SP
			Spiral Mode
			w0
Structural Layout	Chose materials	Materials, Lay-up, Lamina thickness,ply orientation	Angle Lamina
			DW due to Composites
			Ext Moduli Materials
			G
			J Materials
			k
			t Lamina
			W
	I-Beam Analysis	Ibeam Size	h I-beam
			l I-beam
			Max d I-Beam
			t I-beam
			w I-Beam
			W per in
	Cargo Bay Floor Analysis	Floor configuration, material thickness, I-Beam size	Crit Stresses
			DW
			DW Floor
			Face Stress
			h I-beam
			Stress Floor
			Stress Test Load
			t Core
			Track Heavy Assault Bridge
			W
			W Floor
			w I-Beam
	Load Test		d Static Load
			DUlt Load
			g Force Sim
			Safety
			WPay

Table 62. Team 2's detailed model of design knowledge coordination in the final presentation (Cont'd)

High-level task	Detailed-task	Decision	Metrics
			YS
			YS Max
	Wing Structure Configuration	Wing Structure Configuration	Pitch Angle Wing
			Pitch Angle Wing Nom
			w Flt Deck
Select and Design the Primary Systems	Size the cargo bay	Cargo Bay Loading Mechanism, Cargo Bay Loading Door Dimensions, Cargo Bay Size	#Pallets
			Aft CG
			Angle Front Ramp
			Angle Rear Ramp
			Cargo
			CG Range
			Dim Cargo
			Dim Cargo Bay
			Fwd CG
			h cargo
			l cargo bay
			l Front Ramp
			Size Pallets
			W cargo
	Landing gear	Number of Bogies, Number of Tires per bogey, Landing Gear Base, Landing Gear Track, Turning Radius, LCN, Landing Gear Placement	#Bogies
			#Tires per Bogie
			Bank Angle
			h LG
			LCN
			LCN_C17
			LG Base
			LG Spec_C17
			LG Track
			ln
			Steering Rqmt
			Tail Strike Constraint
			Tip-Over Criteria
			TOFL
			Turn Radius
			Turn Radius_C17
			W
			W 3rd Bogie
			W NG

Table 62. Team 2's detailed model of design knowledge coordination in the final presentation (Cont'd)

High-level task	Detailed-task	Decision	Metrics
			W_C17
			Wing Strike Constraint
	Calculate Fuel Tank Fill and Dimensions	Fuel Storage Dimensions	%Chord
			CG Fuel
			Dim Cargo
			Fill Factor
			Geom Factor Fuel Tank
			Vol Fuel
			W Fuel
Performance Analysis: Check if requirements are met	Payload Range		R
			R Airport Base
			R Rqmt
			R_C5
			WPay
			WPay_C5
	Flight Envelope: V-n diagram		V Max
			WPay Max
	Takeoff Performance		Balanced FL
			Crit FL
			Drag Flaps
			L/D TO Est
			T/W Est
			V/Vstall
	Engine Out Performance		hmax OEI
			TOFL
Cost Analysis	Technology Risk	Cost of Technology vs Technology Saving: Worth it to implement?	%Composites
			Cost Al
			Cost composites
			Cost Dev BLI
			Cost Elements
			Cost Maintenance
			Cost Production Composites
			DCost due to Composites
			DCost Operation
			DL/D
			DW due to Composites
			R
			Sav Fuel

Table 62. Team 2's detailed model of design knowledge coordination in the final presentation (Cont'd)

High-level task	Detailed-task	Decision	Metrics
			Savings Op BLI
			Savings Op Composites
			TRL
			Vol Fuel
	Fly Away Cost		Cost Elements
			Cost Flt Test
			Cost Total
			Cost_Similar AC
	Operational Costs		Cost Maintenance BLI
			Cost Maintenance Composites
			DCost Operation
			DW due to Composites
			Sav Fuel BLI
			Sav Fuel Composites

Table 63. Task breakdown of Team 2's midterm design review

High-level task	Detailed-task	Task Quotes
(1) Requirements Analysis	(1.01) Requirements Analysis	"So we are going to start by going through the sizing and design process first from requirements analysis all the way to what preliminary design we have gotten and done so far...So just looking at the very top level of the RFP, it is asking for outside capable strategic cargo transport that gone to service in 2030," Gary
(2) Configuration Selection	(2.01) Figures of Merit	"So these are the figures in merit that we judge it on every use two selection methods a TOPSIS matrix and a Pugh matrix and then we basically altered in our inputs to rate different alternatives face on these figures and then did a weighted average and then we took those results and averaged those to come where the blended wing body is the optimal configuration," Gary
(3) Weight Sizing		On Slide
	(3.01) Weight Regression	"With configuration we can move on to weight regression you can see we use there wide range of transport plus aircraft from C-130J all the way to the An-225," Gary
	(3.02) Baseline sizing	"so we got our Roskam style coefficients and there is a baseline sizing just spreadsheet level for the C5 using these coefficients," Gary
	(3.03) Technology Selection	"Now because this is going to effect some 50 years later there is obviously known to be some technology factors," Gary
	(3.04) Summary	
	(3.05) Choose Design Mission	"So we have to choose our own design mission," Gary
	(3.06) Update Aerodynamic Model	"Concurrent with that we tried to get a better aerodynamic model," Gary
	(3.07) Constraint Sizing:	"We also did constraint sizing with that model," Gary
	(3.08) Updated Aircraft Sizing	"So incorporating all that into the MATLAB model we got this revised sizing with maximum take off of 630,000 pounds empty weighed around 240, which is empty weighed fraction of just 40%," Gary
	(3.09) Size cargo bay	"So we developed a MATLAB program to automatically size a cargo bay and sort of configure everything to fit with tie down allotments and stuff like that," Gary

Table 63. Task breakdown of Team 2's midterm design review (Cont'd)

High-level task	Detailed-task	Task Quotes
	(3.10) Calculate Impact of Technologies	"So in order to absolutely minimize weight and increase performance much possible we are so looking at technologies to incorporate on propulsion side obviously we want to use as efficient in engine that will exist at the time," Gary
	(3.11) Trade Study	"Then we start try to optimize our design through trade studies," Gary
	(3.12) Aerodynamic Analysis	On Slide
	(3.13) Control Surface Design	"So for control service design we use the AVL model that is optimized to go with high lift devices, rudder sizing an elevator," Gary
	(3.14) Mission Breakdown	"So on a mission breakdown for sizing mission like I said before you get distance credit for climb, but not for descent so that is how we did that," Gary
	(3.15) Payload Range Analysis	"This is just our payload range show looks a lot optimistic, but blended wing payload ranges tend to be I guess I do not know we compare to conventional," Gary
	(3.16) Preliminary Subsystem Layout	"So we also did preliminary subsystem layout that help with CG," Gary
	(3.17) CG excursion	"Okay so based on that we have a very basic estimated CG excursion obviously we are going to make a more detail look at different payloads in the future," Gary
(4) Technology Validation		"So as the design process and it was very dependent on for technologies being incorporated so now we are going to take a look at these technologies and see A will they work and B are they worth it," Gary
	(4.01) Check Technology Compatibility	"So basically technology compatibility these are all the technologies we considered and the ones in green are the one that we selected so they do all work together," Gary
	(4.02) Calculate Technology Costs	"So looking at whether it is a good idea from cost perspective I look at boundary layer ingestion to development cost versus operating savings and composite construction production cost versus operating savings ," Gary
(5) Calculate Total Aircraft Costs	(5.01) Overall	
	(5.02) Structures Costs	
	(5.03) Propulsion Technologies Costs	

Table 64. Task breakdown of Team 2's final design review

High-level task	Detailed-task	Quote Task
(1) Identify mission objectives	(1.01) Outline aircraft requirements	
(2) Configuration Selection& Sizing	(2.01) Configuration Analysis	"Now we break down to concept selection, and the sizing process," Gary
	(2.02) Estimate weight trend	On Slide
	(2.03) Baseline sizing	On Slide
	(2.04) Technology impacts	"Baseline in hand we start looking at the deltas that we could have expect from 50 years of new technology being applied in this aircraft, versus the C5A," Gary
	(2.05) Sizing Update	
	(2.06) Constraint Sizing	"So, also, at this point we ran constraint sizing, based on cruise requirement, the climb requirement, take-off and landing ," Gary
(3) Analyze Aerodynamics	(3.01) Calculate total drag	On Slide
	(3.02) Baseline Aerodynamics	"And then, using that tool, we constructed aerodynamics baseline," Ward
	(3.03) Trade Studies	"And then there is the trade study," Ward
	(3.04) Update calculations	And then, after these trade studies we will get our second, which is the final iteration.
	(3.05) Airfoil design	"And then comes the airfoil design," Ward
	(3.06) Spanwise Chord and twist	"And then also we did some spanwise chord and twist analysis," Ward
	(3.07) CFD	"And then, finally, we have the CFD to run everything up, to prove that this thing will actually work," Ward
	(3.08) Drag Polar update	On Slide
	(3.09) Select Cruise Condition	"And then we need to choose our cruise condition,"
	(3.1) Summarize Mission	
(4) Design Advanced Propulsion System	(4.01) Examine Propulsion Fuel Savings	"Okay. Regarding propulsion," Dane
(5) Analyze Static Stability & Design Rudders		"So, looking at the stability control, the first thing that we considered was the static stability," Gary

Table 64. Task breakdown of Team 2's final design review (Cont'd)

High-level task	Detailed-task	Quote Task
	(5.01) CG Buildup	"So, taking that layout within the CG buildup…" Gary
	(5.02) Sizing the Rudders	"For sizing the rudders, we look at two conditions," Buck
	(5.03) High-Lift Devices	"For high lift devices we chose to use leading edge slats and we designed those on procedure in volume 6 of airplane design by Roskam," Buck
	(5.04) Stability characteristics	"To determine these stability characteristics for the aircraft, we used Nelson's flight dynamics textbook," Buck
(6) Structural Layout	(6.01) Chose materials	"For structures we first decided composite materials to reduce weight on the structure," Calvin
	(6.01) I-Beam Analysis	"Here we looked at the I-beams; we looked at different thicknesses," Calvin
	(6.01) Cargo Bay Floor Analysis	"For the cargo bay floor we wanted to reduce weight more by taking the floor and creating a honeycomb composite sandwich," Calvin
	(6.01) Load Test	"For the static load test we found that the max deflection of floors is going to be 26 inches, and for the ultimate testing of the 62.5 PSI load, we find that the maximum deflection is going to be 1.6 inches," Calvin
	(6.01) Wing Structure Configuration	"This is the wing structure," Calvin
(7) Select and Design the Primary Systems		"So looking into the primary systems…" Maximo
	(7.01) Size the cargo bay	"When designing the actual size of the cargo bay, we'll recall from the RFP that we're required to load either 44 master pallets or one Wolverine Assault Bridge," Maximo
	(7.02) Landing gear	"So, never have a plane that can fly that cannot land. So, in designing the landing gear we first wanted to meet stability steering requirements, and then maximize the flexibility," Gary
	(7.03) Calculate Fuel Tank Fill and Dimensions	"The last system that we looked at was fuel estimation," Gary
(8) Performance Analysis: Check if requirements are met		"So, as we designed the plane, we need to see how it stacks up to our requirements," Gary
	(8.01) Payload Range	"First and foremost, we are carrying payload for a range; this is the payload range," Gary
	(8.02) Flight Envelope: V-n diagram	"This is our flight envelope cruise," Gary

Table 64. Task breakdown of Team 2's final design review (Cont'd)

High-level task	Detailed-task	Quote Task
	(8.03) Takeoff Performance	"So the RFP is big on take-off performance. So this is ours," Gary
	(8.04) Engine Out Performance	"We also wanted to look at engine out performance, namely what's the worst altitude condition you can still take-off, climb to pattern altitude and land," Gary
(9) Cost Analysis		"So, our technical stuff as we're going to look at cost and business," Gary
	(9.01) Technology Risk	"So, first, we incorporated all these technologies, are they viable," Gary
	(9.02) Fly Away Cost	"This is the fly-away cost buildup," Gary
	(9.03) Operational Costs	On Slide

Table 65. Metrics referenced by Team 2 in the midterm and final presentations.

Abbreviated Metrics	Midterm	Final
#Vert Tails	x	x
%Composites	x	x
%Laminar Flow	s	x
A Adj	s	s
A Intercept	s	s
Aft CG	s	x
B Adj	s	s
B Slope	s	s
Bank Angle	x	x
bWing	x	x
bWing_C5	x	x
c Span	x	x
CD	x	x
CD0	x	x
CDi	x	x
cf	x	x
CG Overall	x	x
CL	x	s
CL Buffet	x	x
Cost Al	s	s
Cost Composites	x	s
Cost Flt Test	x	x
Cost Maintenance	x	x
DCost Operation	x	x
Dim Cargo	s	x
Dim Cargo Bay	x	x
DL/D	s	x
dRudder	x	x
DW due to Composites	x	x
DWeight Calc	s	x
e	s	x
EIS	x	x
Endurance	s	s
eta	x	x
Ext Moduli Materials	s	x
FOM	x	x
Fwd CG	x	x
h	x	x
h Cruise	x	x
k	s	x

Table 65. Metrics referenced by Team 2 in the midterm and final presentations. (Cont'd)

Abbreviated Metrics	Midterm	Final
K Exp	s	s
K Model	s	s
L/D	x	x
L/D Cruise	x	s
L/D Max Exp	x	s
L/D Max Model	x	s
LG Track	x	x
Lifespan of AC	x	x
M	x	x
M Cruise	x	x
MTOW	x	x
MTOW_Similar AC	x	s
Pugh Matrix	x	x
R	x	x
R_C5	x	x
ROC	s	s
Safety	x	x
Sav Fuel	x	x
Spanwise Twist	x	x
SR	x	s
Sref	s	x
t Airfoil Center	x	x
T/W	s	s
Time to Climb	x	x
Time Warmup	s	x
TOPSIS Output	x	x
TRL	x	x
TSFC	x	x
W Crew	s	s
W Empty_Similar AC	x	x
W Empty/WTO	x	x
W/S	x	x
WPay	x	x
WPay Max	x	x
WPay_C5	s	x
#Engines		s
bHigh Lift Dev		s
Cost Elements		s
Cp		s
cWing		s

Table 65. Metrics referenced by Team 2 in the midterm and final presentations. (Cont'd)

Abbreviated Metrics	Midterm	Final
d Static Load		s
dSlats		s
Engine Placement		s
FF		s
FFAvg		s
l cargo bay		x
l Center Body		x
l Front Ramp		x
l I-beam		x
L Nose Flaps		s
L Slats		s
L/D TO Est		x
Lb		x
LCN		x
LCN_C17		x
LG Base		x
LG Spec_C17		x
ln		x
Location of TE		x
Lr		x
Lvl 1 Rqmt		x
Lvl 1 Rqmt SP		x
Lvl 2 Rqmt		x
Lvl 2 Rqmt DR		x
Lvl 2 Rqmt RTC		x
M Cruise Segments		s
M DD		x
M(L/D)		x
MAC		x
Max d I-Beam		s
Nb		x
Nr		x
Phugoid Ratio Ldg		x
Phugoid Ratio TO		x
Pitch Angle Wing		x
Pitch Angle Wing Nom		x
Pitch Ctl		s
R Airport Base		x
R Rqmt		x
R Segment		s
Range Reserve		x

Table 65. Metrics referenced by Team 2 in the midterm and final presentations. (Cont'd)

Abbreviated Metrics	Midterm	Final
Roll Ctl		s
RTC		x
Safety FL		x
Sav Fuel BLI		x
Sav Fuel Composites		x
Savings Op BLI		x
Savings Op Composites		x
Selection Criteria		x
SFC Reduction		x
Size Pallets		s
Slat per Chord		s
SM		x
SM_Comm AC		x
SP		x
Spiral Mode		x
Stability Deriv		s
Stakeholders		x
Steering Rqmt		x
Stress Floor		x
Stress Test Load		x
Sweepc/4		s
Swet		x
t Airfoil		s
t BL		s
t Core		x
t I-beam		x
t Lamina		x
t/c		s
T/W Est		x
Tail Strike Constraint		x
Time Range		x
Time Turn Around		x
Tip-Over Criteria		x
TO Ldg FL		x
TOFL		x
Track Heavy Assault Bridge		x
Trim Angle		x
TSFC Cruise		s
Turn Radius		x
Turn Radius_C17		x
Type of Engine		s

Table 65. Metrics referenced by Team 2 in the midterm and final presentations. (Cont'd)

Abbreviated Metrics	Midterm	Final
Type of LG		s
Unknown Metric		s
V Max		x
V/Vstall		s
Vol Fuel		x
Vol Fuel Min		x
Vol Reserve Fuel		s
W		x
W 3rd Bogie		x
W Allow		s
W Calc		s
W cargo		x
w Center Body		x
W Empty Calculated		x
W Floor		x
w Flt Deck		x
W Fuel		x
w I-Beam		x
W NG		x
W per in		x
W Segment		s
W Sys_787		x
W_C17		x
W/S MTOW		s
w0		x
WE/WTO		s
WE/WTO Segment		s
WE/WTO_787		x
Wing Strike Constraint		x
WPay Max Rqmt		x
WTO		s
#Bogies		x
#Pallets		x
#Tires per Bogie		x
%Al	s	
%Chord		x
%Composites by Year	x	
%Wempty Sav	x	
A Trapezoidal	s	
Angle Front Ramp		x
Angle Lamina		x

Table 65. Metrics referenced by Team 2 in the midterm and final presentations. (Cont'd)

Abbreviated Metrics	Midterm	Final
Angle Rear Ramp		x
AoA		x
AR Wing		x
Balanced FL		x
bwing		X
Cargo		x
Cargo Rqmt	x	
Cargo_C5	s	
Carving LE		x
CD Components	x	
CDM		x
cElevator	x	
cElevon	x	
Cf Components		x
cFlaperon	x	
CG Components		x
CG Empty		x
CG Fuel		x
CG Range		x
CG Systems		x
CG_787		x
CL Ldg Req	x	
Climb Rqmt		x
CLMax Fowler	x	
Cm		x
Cm LE Slats		x
Cm Outboard		x
Cm Trim		x
Cmbeta	x	
Cmw		x
Config Alt		x
Config Selection		x
Conversion Rate of $	x	
Cost BLI	X	
Cost Dev	x	
Cost Dev & Support	s	
Cost Dev BLI		x
Cost Engr	s	
Cost Fuel	x	
Cost Maintenance BLI		x
Cost Maintenance Composites		x

Table 65. Metrics referenced by Team 2 in the midterm and final presentations. (Cont'd)

Abbreviated Metrics	Midterm	Final
Cost Manuf	x	
Cost Manuf & Materials	s	
Cost Manuf Labor	s	
Cost Production Composites		x
Cost Qual Ctl	s	
Cost Tooling	s	
Cost Total		x
Cost_Similar AC		x
Crit FL		x
Crit Stresses		x
Crud Drag Factor	s	
cRudder	x	
Cruise Rqmt		x
Cruise Seg Cond		x
ct/cr	x	
D cWing LE Slats	x	
D Elevon Cruise	x	
d Elevon TO	x	
d Flaps LE	s	
D Wave		x
Damping Ratio		x
Data_C5	x	
Data_X38	x	
DCost		x
DCost due to Composites		x
Dim Cargo Bay_C5	x	
Dim Rudder	s	
Dim Vert Tail		x
DInterference		x
Drag		x
Drag Flaps		x
Drag Friction		x
Drag Ram	x	
DSwet		x
Dswet BLI	x	
DTSFC Eff	x	
DUlt Load		x
Dutch Roll		x
DW		x
DW Floor		x
e Fuse	s	

Table 65. Metrics referenced by Team 2 in the midterm and final presentations. (Cont'd)

Abbreviated Metrics	Midterm	Final
Eff Fuel Burn		x
Engine Data_GE90	x	
eta Composites	x	
Face Stress		x
FF Reserves	s	
FF_C5	s	
Fill Factor		x
Flt Hrs per Year	x	
Flt Hrs per Year_C5	x	
Form Factor		x
G		x
g Force Sim		x
Geom Factor Fuel Tank		x
h cargo		x
h cargo bay	x	
h I-beam		x
h LG		x
h segment	x	
hmax OEI		x
hn	x	
J Materials		x
Korn Factor		x
L/D Max	x	
LFL	x	
LLF	x	
Location of Ailerons	x	
Location of Elevator	x	
Location of Engine	x	
Location of Flaps	x	
M(L/D) Baseline	x	
M(L/D) Max	x	
Maintenance Turnaround Time	x	
Max Static Load	x	
MCruise Min	x	
MFF Climb	s	
MFF Cruise	s	
MFF Decent	s	
PM Assumed	x	
Power Setting Engine	x	
R Climb	x	
Re	s	

Table 65. Metrics referenced by Team 2 in the midterm and final presentations. (Cont'd)

Abbreviated Metrics	Midterm	Final
Savings Composites	x	
Stail Wet	x	
Sweep LE	x	
t Fuse	x	
Tail Vol Ratio	x	
Tech	x	
Time AC Production	x	
tWing Outboard	s	
V	s	
W Crew_C5	s	
W Cruise Segment	s	
W Descent	s	
W Empty	x	
W Empty Allow	s	
W Empty Calc	s	
W Empty Manuf	s	
W Fuel Max	s	
W Fuel Reserves	s	
W Max 0 Fuel	s	
Weight Climb	s	
WF Segment	s	
WPay Max_C5	x	
WTO_C5	s	

Table 66. Team 2 metrics that are repeated across and within disciplines

Critical Metrics	Number of Cross-Discipline Integrations	Mission/Rqmts Outline	Weight Calculation	Performance Estimation	Configuration	Aerodynamics	Structures	Stability	Cost	Subsystems	Technologies	Propulsion	Landing Gear	Fuselage	Empennage	Within-Task Elements
W (W Technology, W Empty)	7	X	X	X			X		X		X		X			X
Cost (Flight Test, Fuel, Maintenance, Operation)	4						X		X		X	X				
Sav Fuel	4						X		X		X	X				
R	4	X	X	X							X					
cf	3			X							X	X				
Drag	3			X		X						X				X
L/D	3		X	X		X										X
M (M Cruise)	3		X	X		X										X
h (h, h Cruise)	3	X	X	X												X
TOFL	3	X	X										X			
CG Overall	2							X							X	
CL	2			X		X										
Dim Cargo Bay	2					X								X		
LG Track	2												X	X		
Location of Elevator	2					X		X								
Safety	2						X							X		
Spanwise Twist	2					X		X								
Tail Vol Ratio	2		X					X								

Critical Metrics	Number of Cross-Discipline Integrations	Mission/Rqmts Outline	Weight Calculation	Performance Estimation	Configuration	Aerodynamics	Structures	Stability	Cost	Subsystems	Technologies	Propulsion	Landing Gear	Fuselage	Empennage	Within-Task Elements
TSFC	2		X									X				

Table 66. Team 2 metrics that are repeated across and within disciplines (Cont'd)

Critical Metrics	Number of Cross-Discipline	Mission/Rqmts Outline	Weight Calculation	Performance Estimation	Configuration	Aerodynamics	Structures	Stability	Cost	Subsystems	Technologies	Propulsion	Landing Gear	Fuselage	Empennage	Within-Task Elements
W Empty/WTO	2		X	X												
bwing	2	X		X												X
EIS	2	X									X					
FOM	2	X									X					X
LCN	2	X											X			X
Pugh Matrix	2	X			X											X
TOPSIS Output	2	X			X											X
Turn Radius	2	X											X			X
#Vert Tails	1							X								X
%Composites	1										X					X
Bank Angle	1							X								X

Chord	1					X										X
CD (CD0, Cdi)	1					X										X
dRudder	1							X								X
eta	1										X					X
Fuel Eff	1										X					X
I-beam	1						X									X
TRL	1										X					X
W/S	1			X												X

Table 67. List of decisions and Team 2's reasoning for the decision in the midterm presentation

High-level task	Detailed-task	Embedded Decision	Decision Quotes
Requirements Analysis	Requirements Analysis		
Configuration Selection	Figures of Merit	Configuration, Figures of Merit	"So these are the figures in merit that we judge it on every use two selection methods a TOPSIS matrix and a Pugh matrix and then we basically altered in our inputs to rate different alternatives face on these figures and then did a weighted average and then we took those results and averaged those to come where the blended wing body is the optimal configuration," Gary
Weight Sizing	Weight Regression	Takeoff weight, L/D, TSFC	
	Baseline sizing		"So we got our Roskam style coefficients and there is a baseline sizing just spreadsheet level for the C5 using these coefficients all the green inputs come from our research into actual numbers all from C5 and then the yellow inputs what we played with adjusting L/D, TSFC until we got the maximum takeoff sizing to max the actual numbers. Because there is uniqueness issue with L/D and TSFC both affecting the sizing, we also verify their performance for their admission where we are looking at the maximum take off, but ferry weights since it is lots of data for ferry and for both cases we are within 1%. So, we are happy with there baseline numbers." Gary
	Technology Selection	Percentage composites, Eta	"So one of the technologies that we look to adjust our sizing for structures was composites based on industry trends and forecasts we assume 62% composite usage on the aircraft and then structural weight savings per composite element of 26% so it gave us an eta weight factor of around 0.815," Gary
		TSFC	"From propulsion we baseline based on the GE90 115 engine deck and again based on publish data and forecast we assume the TSFC saving is 20% that from the GenX delta projected onward for another 15 years," Gary
	Summary		
	Choose Design Mission	Range	"So we have to choose our own design mission. We use the payload of 300,000 pounds and for range of 3500 nautical/miles and this is a nice number because one it exceeds the max payload range of C5, which is just shy of 3000 nautical/miles and 3500 is the distance that the airports uses for on route planning which includes island hopping in the pacific," Gary
	Update Aerodynamic Model	Unstated	"Concurrent with that we tried to get a better aerodynamic model. We baselined off of the X48 to buy blended wing that I did extensive wing power testing on so basically we took the drag equation with all the factors and multipliers and all that staff and basically played with the numbers until we got our model to meet the wind tunnel results," Gary

Table 67. List of decisions and Team 2's reasoning for the decision in the midterm presentation (Cont'd)

High-level task	Detailed-task	Embedded Decision	Decision Quotes
	Constraint Sizing:	W/S	"We also did constraint sizing with that model. You can see there is a local minimum at 84 pounds per square foot, which is very low for a transport aircraft, but it is not very low for blended wing. So we move forward with that because it is definitely the best place to be on that chart," Gary
	Updated Aircraft Sizing	MTOW, W_Empty, Sref, Span	"So incorporating all that into the MATLAB model we got this revised sizing with maximum take off of 630,000 pounds empty weight around 240, which is empty weight fraction of just 40% and then we also did constrain the span throughout to be less than the C5, which is around 223 so we could use all C5 infrastructure I have to build new gigantic hangars that obviously that incurs a lot of cost. The four panels are to achieve semi-conventional tail volume fraction I believe it is around 0.06 in this model," Gary
	Size cargo bay	Cargo bay size, Cargo bay cg	"So we developed a MATLAB program to automatically size a cargo bay and sort of configure everything to fit with tie down allotments and stuff like that," Gary
	Calculate Impact of Technologies	Technology Selection	"So in order to absolutely minimize weight and increase performance much possible we are so looking at technologies to incorporate on propulsion side obviously we want to use as efficient in engine that will exist at the time," Gary
	Trade Study	Centerline thickness, W/S, Mach, Altitude	"Then we start try to optimize our design through trade studies. So, the centerline thickness because we have a set height that is restricted by cargo bay it is a trade off between at lower thickness ratios cutting a lot of skin friction drag and high thickness ratios having a lot of profile drag. So we determined that there is a peak in L/D at around 16%," Gary
			"Mach/altitude this is specific range optimization you will notice so first to clarify these contours are for initial cruise altitude we assume that step cruise of 1000 foot steps. The other points are just to show reference for altitude at the red points the one that is actually important," Gary
	Aerodynamic Analysis	Flap Location, L/Dmax, L/Dcruise	"So we use that to optimize our trefftz plane looking at the chord and twist distribution. Our peaks where I will start around 75 feet from the center line, which is over inboard section of our upward wings. So that is where flaps are so it is good because anywhere else it will be screwed. You'll either stall ailerons, engines or elevator so that is really the only place we could have it. So excellent," Gary
			"So we have a max L/D just shy 25 and we are cruising at an L/D projection 21.2 I believe. So consistent with M(L/D) projection," Gary
	Control Surface Design	High lift devices, Rudder size, Rudder Sweep, Elevator Size, # Vert Tails	"So we have to use Fowler flaps and that's around inner portion of the wing and we have to use upper surface volume, which we found estimated can give us around 12% increase in CL max and we are also using leading edge slats 10% increase in chord. So it is a tough number to meet, but if we do that we can do," Gary

Table 67. List of decisions and Team 2's reasoning for the decision in the midterm presentation (Cont'd)

High-level task	Detailed-task	Embedded Decision	Decision Quotes
			"So we actually got rid of two of our vertical tails because it is still high and this is with two vertical tails and tail volume ratios of 0.008," Gary
			"So our rudder sizing did kind of weird we can bank both these conditions out to 0.4 degrees bank we basically do not need rudder and then we look across the landing at 35 knot crosswind and -0.723 bank we again do not need rudder. The one reason I think for this that we are really high Cn Beta it is low 0.2s. So I am not sure why we have a high Cn Beta. We have sweep, but not like excessive sweep...So then elevator is at the outboard section of the center body and upward section of the wing we have elevons and then at take off -18 degrees deflection and cruise -6. So nothing too ordinary there or concern. This is a very power point engineered control service layout and see center body elevator and then flaps and elevens. They're all 30% chord. The rudder's not shown, but this is a normal rudder. So at the end of all that this is our configuration. It's nice and curvy. The maximum takeoff weight of around 575 with empty weight of around 215 and the ratio of around 37%. Wing span meets are constraints and leading sweep of 37 taper ratio of 25 nothing too crazy there." Gary
	Mission Breakdown		
	Payload Range Analysis		
	Preliminary Subsystem Layout	Sub system layout	"So we also did preliminary subsystem layout that help with CG. So you can see we do not have few here for CG reasons. We put it there instead so it is probably just not being empty other than that significant things to note we are using electric actuators instead of hydraulic and landing gear will still be hydraulic just because they carry so much load on it heavy cargo," Gary
	CG excursion		
Technology Validation	Check Technology Compatibility		
	Calculate Technology Costs		
Calculate Total Aircraft Costs	Overall		
	Structures Costs		
	Propulsion Technologies Costs	Amount saved by integrating propulsion technologies	

Table 68. List of decisions and Team 2's reasoning for the decision in the final presentation

High-level task	Detailed-task	Decision	Evidence
Identify mission objectives	Outline aircraft requirements		
Configuration Selection& Sizing	Configuration Analysis	Configuration	"We took both these results and just sort of an average came out and the blended wing body is the optimum configuration for this mission," Gary
	Estimate weight trend	A,B	"But we got a nice linear trend; we got our coefficients, and we applied them to the baseline sizing," Gary
	Baseline sizing	WTO, Wempty	"Everything in green we took from hard numbers from research ; everything with yellow are the numbers that we played with, get the numbers to work out; and everything in red is the deltas from the result. So, we looked at both the baseline, classic Briguet Range sizing, with the [00:09:10] and then also performance verification looking at ferry mission mission; this is a well-documented performance point. And then, ultimately, we got all of our deltas within one percent. So, we are happy with the results from our baseline," Gary
	Technology impacts	Eta factor due to technology	So, it's just simple algebra that gives you eta factor of around 81.5 percent.
	Sizing Update	Range	"So based on research into air force planning factors, on-route planning in the Pacific, like island hopping, where they decide where to put their air stations, based on range of 3500 nautical miles," Gary
	Constraint Sizing	Updated MTOW , W/S, WEmpty, Sref, and Span	"And you can see that there's a distinct minimum around 84 PSF wing loading; that's the value that we went forward with, that is really low for a transport class airplane, but not for a blended wing, and we thought that the lower wing loading would also help us with the tactical landing. So, we moved forward with that...And this gives us these results: 630 000 pounds for an empty weight fraction is around 37 percent. So, after our first sizing round, this is the airplane," Gary
Analyze Aerodynamics	Calculate total drag		
	Baseline Aerodynamics	% Laminar Flow, CD, Korn factor	"Such as laminar flow percentage, which is 16 percent, which falls into the 10-20 percent suggested by the [text] book. And then we have a Cruise drag multiplier and a Korn factor," Ward
	Trade Studies	Thickness, W/S	"First centerline thickness. So by using a thicker airfoil centerline we have larger profile drag but smaller frictional drag. However if you use a thinner airfoil you have a larger frictional drag by smaller profile drag. There is a tradeoff between the other. From our analysis 16% would be the best," Ward
			"And then there is the wing loading. The wing area does have a huge effect on the drag polar. This analysis will give us the correct wing loading, the best wing loading, so we can proceed with this number," Ward

Table 68. List of decisions and Team 2's reasoning for the decision in the final presentation **(Cont'd)**

High-level task	Detailed-task	Decision	Evidence
	Update calculations	Reference Area, AR, SWing, Sweep, Center Body Length	And then, after these trade studies we will get our second, which is the final iteration. So the reference area is 6765 with an aspect ratio of 7.2. And then, the center body length is 150 feet by 40 feet. And the thickness of the center body is 0.16.
	Airfoil design	Airfoil, Chord, Twist, Cm	"And then comes the airfoil design. Airfoil dominates the aerodynamics. And in terms of blended body airfoil design there are lots of challenges. Such as first we need to introduce the trim moment because we don't have a tail to control trim. So we need a smaller pitching down moment to help trim. Then we have physical constraints because you have to put the cargo bay inside the center body, so we need to make sure there's enough space to fit, so the tail should be designed in a specific shape, because we want to put a cargo door. Also there are other requirements such as super critical nature because it is flying at Mach .7. We want as high divergence drag as possible. Also we need to compare L/D. If it's too low the plane won't fly. And so for the center body the baseline is NASA/Langley SC(2)-071 super critical airfoil. It has drag of over 100. So we did two adjustment. First we adjusted the trailing edge using Y=ax^b. So the a will adjust just the magnitude of the trailing edge adjustments and then b will adjust the location of the adjustment. The leading edge carving is adjusted using this equation. C is the magnitude of how much is inside and d is the leading edge carving adjustment. And then there's the Cm which is .14 to 0.026," Ward
			"Here is the lift distribution along span. As you can see the Oswald Factor here is 0.9 which is pretty good. And at cruise condition which is alpha equals 4 and Mach number equals 0.7," Ward
	CFD		"we have the CFD to run everything up, to prove that this thing will actually work," Ward
	Drag Polar update		
	Select Cruise Condition	Cruise Conditions	"The red one is the initial cruise condition, 40 k feet plus a Mach number of .7 and the second segment is 41 000 feet and the third segment is 42 000 feet," Ward
	Summarize Mission		
Design Advanced Propulsion System	Examine Propulsion Fuel Savings	Vol Fuel	we estimate that our total propulsion fuel savings are anywhere from 16 to 25 percent.

Table 68. List of decisions and Team 2's reasoning for the decision in the final presentation **(Cont'd)**

High-level task	**Detailed-task**	**Decision**	**Evidence**
Analyze Static Stability & Design Rudders	CG Buildup		
	Sizing the Rudders	Rudder size, Number of vertical tails	"Configuration we choose was two vertical tails with rudders running the entire height. And they'll be located at the wing tips with a height of 15 feet and rudder-to-chord ratio of .3," Buck
	High-Lift Devices	High lift devices, Slap to chord ratio, b High Lift, Slat Deflection	"For high lift devices we chose to use leading edge slats and we designed those on procedure in volume 6 of airplane design by Roskam. The configuration we chose was a slat-to-chord ratio of 0.2, a total span of 50 feet, and a slat deflection of 25 degrees," Buck
	Stability characteristics	Stability augmentation system	
Structural Layout	Chose materials	Materials, Lay-up, Lamina thickness,ply orientation	"For structures we first decided composite materials to reduce weight on the structure. And we did some research and found out that the quasi isentropic lay-up is the best to replicate the isotropic material. We went with the ply orientation shown in that...The T300 has 32 to 35 percent of weight reduction. So we went with T300 composite," Calvin
	I-Beam Analysis	I-beam Size	"And we found that the 12 inch width and 16 inch height was the optimal to reduce weight per inch, and have the least deflection for the cargo bay floor," Calvin
	Cargo Bay Floor Analysis	Floor configuration, material thickness, I-Beam size	"To reduce weight even further and still have structural integrity, top I-beams are 6 inches in width by 8 inches in height, and then it goes down to 12 inches in width to 16 inches in height, and we that we did a stress analysis loading two of the M104 heaviest Heavy Assault Bridges. Each track has again 25 PSI," Calvin
	Load Test		
	Wing Structure Configuration	Wing Structure Configuration	This is the wing structure. We have each is 50 inches in pitch, traditional aircraft with aluminum, typically between 18 to 22 inches. Composite materials are stronger and light weight so you can spread them out some more. So a 50 inch pitch there and you can also see the forward slats there.
Select and Design the Primary Systems	Size the cargo bay	Cargo Bay Loading Mechanism, Cargo Bay Loading Door Dimensions, Cargo Bay Size	"We chose a longer configuration as opposed to a wider configuration, which is used by NASA's analysis, because we thought that having a longer cargo bay would help us if we wanted to move the wings forward and back for CG balancing. You can see that we have a rough estimate of the CG. Cargo CG is right here and here. We used the combination of the primary cargos, so the

Table 68. List of decisions and Team 2's reasoning for the decision in the final presentation **(Cont'd)**

High-level task	**Detailed-task**	**Decision**	**Evidence**
			pallets, the tanks as well as the secondary cargos shown here in different configurations, and we got these as our most forward cg and most aft cg. And these are measured from the nose," Maximo
	Landing gear	Number of Bogies, Number of Tires per bogey, Landing Gear Base, Landing Gear Track, Turning Radius, LCN, Landing Gear Placement	"So what we need to look at is introducing a third main boogey, and then moving the nose gear back behind, where the ramp comes down, which is about 30 feet off the nose. So this doesn't make a problem statically indeterminate, which is pain. And the question comes, how do we control and ultimately determine the amount of load that will be carried by the third bogey, and therefore by the nose gear. We can get that around 8 percent or 15 percent...So, you can see, we have really tall gear, because of the tail strike compartment; in this case a wing strike requirement. So the bank angle is not an issue so we are constrained by the tip-over requirement." Gary
	Calculate Fuel Tank Fill and Dimensions	Fuel Storage Dimensions	The chord percentage is 20; the fill factor I took a conservative 65 percent to account for structure, and is not able to fill in all the way.
Performance Analysis: Check if requirements are met	Payload Range		
	Flight Envelope: V-n diagram		
	Takeoff Performance		
	Engine Out Performance		
Cost Analysis	Technology Risk	Cost of Technology vs Technology Saving	
	Fly Away Cost		
	Operational Costs		

APPENDIX G - TEAM 3'S DETAILED DATA FROM OBSERVATIONS

Transcripts for Team 3's midterm and final design presentations were analyzed using a qualitative analysis. The results of this analysis are outlined in Table 69 (midterm presentation) and Table 70 (final presentation). The evidence for identifying the tasks is presented in Table 71 (midterm presentation) and Table 72 (final presentation). Table 73 lists the metrics that were referenced by Team 3 and classifies if the metric was mentioned in the midterm or final presentation. Table 74 is a list of all the metrics that were repeated across and within disciplines. Finally, evidence of Team 3's decisions are in Table 75 (midterm presentation) and Table 76.

Table 69. Team 3's detailed design process in the midterm presentation

High-level task	Decision	Metric
Requirements		Design Obj
		EIS
		WPay
		R
		WPay Max
Identify Stakeholders		Stakeholders
Baseline Aircraft		AC Geom
		AC Perf
		Cargo
		#Crew_C5
		Cargo_C5
		l_C5
		h cargo bay_C5
		Swing_C5
		W Empty_C5
		W Loaded_C5
		MTOW_C5
		Cost per AC_C5
		bWing_C5
		l fuse_C5

Table 69. Team 3's detailed design process in the midterm presentation (Cont'd)

High-level task	Decision	Metric
		h Tail_C5
		bStabilizer_C5
		V Max_C5
		M Cruise_C5
		R_C5
		h Service_C5
		ROC_C5
		W/S_C5
		T/W_C5
		TOFL_C5
		LFL_C5
		Vol Fuel Storage Avail_C5
		h cargo bay_C5
		w cargo bay_C5
		l cargo bay_C5
		Pallet Capability_C5
		WPay Max_C5
Mission Profile		WPay
		R_C5
		FF
Configuration Selection	Configuration	Type of Tail
		#Fuselages
		#Engines
		Location of Engine
		Wing Config
		Type of LG
		Loading Style
		FOM
		FOM Score
		FOM Grade
		FOM Weight
Technology Selection	Select technology to integrate in design	Type of Technology
	Cdi, Drag Friction	Drag Friction
		CDi
		Drag Total
	DW due to Composites	%Composites
		Engine Tech

Table 69. Team 3's detailed design process in the midterm presentation (Cont'd)

High-level task	Decision	Metric
		DW due to Composites
		%Composites AC Component
		eta
	TSFC, T, #Engines	TSFC_CF6
		DTSFC GenX
		TSFC Est
		EIS
		DTSFC Eff
		TR
		T_CF6
		#Engines
Weight Sizing	WTO, L/D	WPay Nom Scenario
		RNom
		WPay Max
		R Max Pay
		WTO
		L/D Cruise
		L/D Climb
		FF Segment
		W Segment
		W Fuel Segment
		%Fuel Used Segment
		W Crew
		WPay
		W Allow
		W Empty
		A Intercept
		B Slope
		eta
		V
		h
		ROC
		TSFC
		R
		Endurance
		Eff Engine
		FFAvg
		L/D Cruise

Table 69. Team 3's detailed design process in the midterm presentation (Cont'd)

High-level task	Decision	Metric
		TSFC
		M
		h
		L/D Segment
		WPay
		Mach Segment
		h Segment
Specific Range Plots	Altitude, Mach	R
		h Constraint
		Time to Climb
		h
		M
Drag polar		e
		c Coef
		d Coef
		AR Wing
		e
		t/c
		W/S
		WTO
		CD0
		K
		bWing
		Cf
		Swet
		SWing
		Swet/S
		W Segment
		Density Air
		h Segment
		CL Segment
		CD Segment
		L/D Cruise Segments
		V Sound
		CL
		CD
		Eff Aero Tech
		Tech Aero
	Range for 300000 lb case	R

Table 69. Team 3's detailed design process in the midterm presentation (Cont'd)

High-level task	Decision	Metric
Select Range		W Empty
		R
Constraint Analysis	W/S, T/W, S, AR	WPay
		W/S
		T/W
		WPay
		h Approach
		WTO Case 2
		Wpay Case 2
		W Fuel Max Pay
		Wpay Case 1
		W Fuel Nom
		WTO Case 1
		W/S
		T/W
		TR
		S
		AR Wing
		bWing
Outline Cargo	Cargo layout	Type of Cargo
		Dim Cargo
		Pallet Capability
Sizing the fuselage	fuselage geometry	Dim Fuse_C5
		Dim Fuse_Roskam
		lf/df
		lf/df
		FCA
		lf/df_C5
		lf/df_C5
		FCA_C5
		Dim Fuse
		l fuse
		l fuse_C5
		d fuse
		d fuse_C5
		l Flt Deck
		l Flt Deck_C5
		l cargo bay
		l Ramp

Table 69. Team 3's detailed design process in the midterm presentation (Cont'd)

High-level task	Decision	Metric
		l cargo bay_C5
		l Ramp_C5
		h cargo
		h cargo
		w cargo bay
		wPallets
	Loading scheme	Loading Style
		h Aft Loading
Wing sizing	Wing Config, S Wing, b Wing, AR Wing, croot, c Mean, ct/cr, t Airfoil Center	Type of Wing
		V
		Wing Config
		Visibility
		Lateral Stability
		Drag Interference
		S Wing
		bWing
		AR Wing
		c Mean
		croot
		cWing
		ct/cr
		t Airfoil Center

Table 70. Team 3's detailed design process in the final presentation

High-level task	Detailed-task	Decision	Metric
Define Requirements and Outline Mission	Outline RFP		WPay Nom Scenario
			RNom
			WPay Max
			R Max Pay
			MCruise Min
			h
			TO Ldg FL
			TLC Rqmt
			Performance OEI
			Tactical Appr
			Cargo
			Vol Fuel
			Cost
			R <10K
			Dim Cargo
			WPay Max_C5
			WPay Max
			R_C5
			WPay_C5
			Pallet Capability_C5
			Pallet Capability
			Pallet Capability RFP
			Cargo_C5
			W Empty_C5
			WPay_C17
			Pallet Capability_C17
			Cargo_C17
			W Empty_C17
			R_C130
			Pallet Capability_C130
			Cargo_C130
			W Empty_C130
			Pallet Capability
			Cargo
			h cargo
			W Empty
			W cargo
			Cargo

Table 70. Team 3's detailed design process in the final presentation (Cont'd)

High-level task	Detailed-task	Decision	Metric
			MTOW
			R
			Cost
			Eff Engine
			Vol Fuel
			Loading Turnaround Time
			W
			Performance
		Range, Mission Profile	RNom
			WPay Nom Scenario
			WPay Max
			R Max Pay
	Stakeholder Identification		Stakeholders
Configuration Selection	Figure of merit analysis	Aircraft Configuration	FOM
			FOM Weight
			Stakeholders
			Turnaround Time
			Cost
			Similar AC
			Config_Similar Aircraft
			#Engines
			#Fuselages
			Type of Wing
			Type of LG
			Type of Tail
			Loading Style
			FOM
			W
			FOM Score
Technology Identification	Technology Identification	Number of Engines, Engine Type, Winglet Incorporation, Oswald Efficiency Factor, Induced Drag Reduction,	TSFC
			Year AC
			#Engines
			Eff Engine
			Year Engine Dev
			CDi
			D

Table 70. Team 3's detailed design process in the final presentation (Cont'd)

High-level task	**Detailed-task**	**Decision**	**Metric**
		Weight Reduction, Percentage material incorporation, Riblet Incorporation, Coefficient of Friction	e
			DCDi
			Eff Fuel Burn
			Cost Operation
			Materials
			density materials
			%Composites
			DW due to Composites
			CD0
			D Viscous
			Cf
Sizing	Weight Sizing	L/D, ROC, Mach, Altitude	Mission Profile
			L/D
			ROC
			R Climb Segments
			W Cruise Segment
			VCruise Segment
			SR Cruise Segments
			L/D Cruise Segments
			M Cruise Segments
			TSFC Segment
			SR
			h
			ROC
			Time to Climb
			M
	Drag Polar	CL, CD, L/D	CL
			CD
			L/D
			V
			L/D Cruise Segments
			M
			h
			SR
			Climb Rqmt
	Constraint Sizing	T/W, W/S	T/W
			W/S
			Error Allowance
Physical Design			Vol Cargo

Table 70. Team 3's detailed design process in the final presentation (Cont'd)

High-level task	Detailed-task	Decision	Metric
	Cargo Design	Pallet Arrangement, h cargo bay, l cargo bay, w cargo bay	Pallet Arrangement
			Cargo
			W cargo
			h cargo
			h Fuse
			h cargo bay
			l cargo bay
			w cargo bay
			W cargo
	Fuselage Design	l fuse, d fuse, w Aft Loading, h Aft Loading	Fuse Proportions_C5
			l fuse
			d fuse
			TCA
			h cargo
			l Flt Deck
			l cargo bay
			h cargo bay
			w cargo bay
			w Aft Loading
			h Aft Loading
	Wing Design	S Wing, b Wing, AR Wing, Vol Fuel Storage Avail, Location of Front Spar, Location of rear Spar	SWing
			SWing_C5
			W Empty
			W Empty_C5
			bWing
			AR Wing
			G Wing
			Vol Fuel Storage Avail
			Vol Fuel Max
			Location of Front Spar
			cWing
			Location of Rear Spar
			ct Wing
			croot
			c Mean
			MAC
			t/c
			ct/cr
			Sweep Wing

Table 70. Team 3's detailed design process in the final presentation (Cont'd)

High-level task	Detailed-task	Decision	Metric
			Location of Flaps
			SWinglet
			bWing
			ct Winglet
			croot Winglet
			Cant Angle Winglet
			Sweep Winglet
	Empennage Design	Shoriz Tail, Sweep Horiz Tail, Sweep Vert Tail	SHoriz Tail
			SVert Tail
			ct Vert Tail
			croot Horiz Tail
			Sweep Horiz Tail
			Sweep Vert Tail
			iHoriz Tail
			iVert Tail
			G Horiz
			G Vert Tail
			bHoriz Tail
			ct Horz Tail
			t/c Horiz Tail
			AR Horiz Tail
			ct/cr Horiz Tail
			bVert Tail
			ct Vert Tail
			t/c Vert Tail
			AR Vert Tail
			ct/cr Vert Tail
	Landing Gear Design	#Struts LG, #Tires NG, #Tires MG	#Tires NG
			#Tires MG
			#Struts LG
			Pn
			Pm
			lm
			ln
			Pn
			Pm
			d MG
			bt MG

Table 70. Team 3's detailed design process in the final presentation (Cont'd)

High-level task	Detailed-task	Decision	Metric
			Pressure MG
			d NG
			bt NG
			Pressure NG
Weight and Balance and Stability	Calculate the center of gravity	Aircraft detailed layout	CG Components
			CG Overall
			WPay Max
			WPay Nom Scenario
			CG Shift
			CG Empty
			CG TO
			W Components
			Tip-Over
			Ground Clearance
			Location of the Wing
			Location of Empennage
			Tip-Over Criteria
			Ground Clearance Rqmt
	Stability Calculations		SM
			Cm
			CL
			DAoA
			Clp
			CYp
			Clp
			Cmp
			Cnp
			Clq
			Cyq
			Clq
			Cmq
			Cnq
			Clr
			CYr
			Clr
			Cmr
			Cnr
Cost	Parametric Cost		Roskam Values
			Dim Flaps_A340

Table 70. Team 3's detailed design process in the final presentation (Cont'd)

High-level task	Detailed-task	Decision	Metric
			#AC
			Cost Procurement
			Cost per AC_C5
			Cost per AC_C5
			%Savings per Aircraft
			#Manufacturers
			Cost Engr
			Cost Tooling
			Cost Dev
			Cost Flt Test
	Operation & Support		Cost Fuel
			Mission Profile
			Mission Duration
			Fuel per Hr
			Vol Fuel
			Flt Hrs per AC
			Cost Fuel per Gal
			Lifespan of AC
			#AC
			#Man Hours
			Flt Hrs per AC
			Maintenance Hrs per AC
			#AC
			Cost Maintenance per Year
			Cost Maintenance 20 Years
			Lifespan of AC
			Cost Technician
			Cost Maintenance Labor
			Cost MPS per Flt Hr per Year
			Cost MPS per Year in 1999
			Cost MPS per Year in 2015
			Cost MPS per Year in 2015
			Cost MPS 20 Years
			Cost Maintenance per AC
			Cost Salary per Crew
			Cost Crew Benefits
			Cost per Crew Member
			Cost Crew per Year

Table 70. Team 3’s detailed design process in the final presentation (Cont’d)

High-level task	Detailed-task	Decision	Metric
			#AC
			#Crew per Aircraft
			Cost Crew Salary 20 Years
	Total Cost Summary		Cost Operation
			Cost R&D
			Cost Maintenance
			Cost Total
			Cost per AC

Table 71. Task breakdown of Team 3's midterm design review

High-level task	Task Quote
(1) Requirements	"First off is the RFP summary and mission requirements," Alexandra
(2) Identify Stakeholders	"So our main stakeholders are the US Department of Defense..." Alexandra
(3) Baseline Aircraft	"For our baseline aircraft we came up with ultimately the c-5 as our baseline," Alexandra
(4) Mission Profile	"This is the mission profile that we decided to do for the 120,000 pound payload case over 6300 nautical miles," Asa
(5) Configuration Selection	"The next one is the configuration selection," Alexandra
(6) Technology Selection	"So we have three different main categories of technologies," Asa
(7) Weight Sizing	"This is our final spreadsheet we came up with a takeoff weight of 648 000 pounds," Asa
(8) Specific Range Plots	"Like I said, we did the specific range plots for both specific range versus altitude and specific range versus mach number," Asa
(9) Drag polar	"This is a screen shot of our drag polar," Asa
(10) Select Range	"So we took—we had to chose a range for the 300 000 pound mission case and that range would possibly drive the size of our vehicle empty weight. So what we did we looked at missions the C-5 currently does looked at air force bases that are located in different places around the world and decided that the 300 000 pound mission needs to do 2000 nautical mile range," Garth
(11) Constraint Analysis	"So the constraint analysis was done for the 300 000 and the 120 000 pound cases," Garth
(12) Outline Cargo	"So next we're going to outline our basic cargo area. " Alexandra
(13) Sizing the fuselage	"And then when sizing the fuselage I compared the dimensions of the C5 to ours," Alexandra
(14) Wing sizing	"Next up is wing sizing," Demetri

Table 72. Task breakdown of Team 3's final design review

High-level task	Detailed-task	Task Quote
(1) Define Requirements & Outline Mission	(1.01) Outline RFP	"So basically we had the AIAA came out with a Request for proposal for a strategic military airlift next generation this semester because the next generation is expected to outdo all the present ones," Garth
	(1.02) Stakeholder Identification	"The next step is to identify our stakeholders," Alexandra
(2) Configuration Selection		"Next was our configuration selection," Alexandra
	(2.01) Figure of merit analysis	We identified these 8 figures of merit and assigned them weights based on importance to our stakeholders and for our design.
(3) Technology Identification	(3.01) Technology Identification	"Before beginning our sizing process we decided to look into different type of technology that would impact our weight sizing," Alexandra
(4) Sizing		"Next up in our design process is sizing. This is based on weight sizing, drag polar, and constraint sizing," Garth
	(4.01) Weight Sizing	"The first part of this is weight sizing," Garth
	(4.02) Drag Polar	"The drag polar was calculated for our aircraft class I," Garth
	(4.03) Constraint Sizing	"Next in the process is constraint sizing," Garth
(5) Physical Design		"The next part of our design process was to do the actual physical design of our different components," Garth
	(5.01) Cargo Design	"We started off with cargo because cargo is going to be the driving factor for our fuselage and for the rest of our aircraft," Alexandra
	(5.02) Fuselage Design	"Next was the fuselage design once we had the pallets designed," Alexandra
	(5.03) Wing Design	"Next we worked on our wing model," Alexandra
	(5.05) Empennage Design	"Next was our empennage which is the T tail," Alexandra
	(5.05) Landing Gear Design	"The final point for our design was the landing gear which has one nose landing gear strut and three struts of the main landing gear. ," Alexandra

Table 72. Task breakdown of Team 3's final design review (Cont'd)

High-level task	Detailed-task	Task Quote
(6) Weight and Balance and Stability		"The next part of the design process was weight and balance. ," Garth
	(6.01) Calculate the center of gravity	"After we design each component for the first time, we estimate the CG on each component and then we merge all that into one CG to arrive at the CG on the aircraft," Garth
	(6.02) Stability Calculations	On slide
(7) Cost		"The cost part can be broken down into two parts. The first one is the parametric cost the second part is the operational and support cost," Sanford
	(7.01) Parametric Cost	"For the parametric cost, we break it down into two parts. is the RTD&E and is also called the non-reoccurring cost," Sanford
	(7.02) Operation & Support	"The second part operation support cost we bring it down to three parts which are fuel cost, maintenance cost and the crew cost," Sanford
	(7.03) Total Cost Summary	"Just a summary of our aircraft total operation cost will be 32.0216 billion dollars and the total cost for 20 years will be 55.564 billion dollars," Sanford

Table 73. Metrics referenced by Team 3 in the midterm and final presentations.

Metrics	Mid	Final
#Engines	X	X
#Fuselages	X	X
%Composites	X	X
AR Wing	X	X
bWing	x	X
Cargo	X	X
CDi	X	X
cWing	x	X
d fuse	X	X
Dim Cargo	X	X
DW due to Composites	x	X
e	X	X
EIS	X	X
FOM	X	X
FOM Score	X	X
h	X	X
h cargo	X	X
l fuse	X	X
Loading Style	X	X
M	X	X
Pallet Capability	X	X
R Max Pay	X	X
R_C5	X	X
RNom	X	X
Stakeholders	X	X
T/W	X	X
Time to Climb	x	X
TSFC	X	X
Type of LG	X	X
Type of Tail	X	X
Type of Wing	x	X
V	x	X
W Empty	X	X
W/S	X	X
WPay Max	X	X
WPay Nom Scenario	X	X
c Mean	x	S
croot	x	S
ct/cr	x	S
h Aft Loading	X	S
l cargo bay	X	S
l Flt Deck	X	S

Table 73. Metrics referenced by Team 3 in the midterm and final presentations. (Cont'd)

Metrics	**Mid**	**Final**
R	X	S
w cargo bay	X	S
CD0	S	X
Cf	S	X
CL	S	X
Cost per AC_C5	S	X
Eff Engine	S	X
FOM Weight	S	X
L/D Cruise Segments	S	X
Pallet Capability_C5	S	X
ROC	S	X
SWing	S	X
Swing_C5	S	X
W Empty_C5	S	X
WPay Max_C5	S	X
Cargo_C5	S	s
CD	S	S
t/c	S	S
%Composites AC Component	X	
AC Geom	X	
AC Perf	X	
d fuse_C5	X	
Design Obj	X	
Dim Fuse	X	
Dim Fuse_C5	X	
Dim Fuse_Roskam	X	
Drag Friction	X	
Drag Interference	x	
DTSFC Eff	X	
DTSFC GenX	X	
Engine Tech	x	
eta	X	
FF	X	
h Approach	x	
h Constraint	x	
h Segment	X	
l cargo bay_C5	X	
l Flt Deck_C5	X	
l fuse_C5	X	
l Ramp	X	

Table 73. Metrics referenced by Team 3 in the midterm and final presentations. (Cont'd)

Metrics	**Mid**	**Final**
l Ramp_C5	X	
L/D Climb	X	
L/D Cruise	X	
L/D Segment	X	
Lateral Stability	x	
Location of Engine	X	
Mach Segment	X	
S	X	
S Wing	x	
t Airfoil Center	x	
T_CF6	x	
TR	X	
TSFC Est	X	
TSFC_CF6	X	
Type of Cargo	X	
Type of Technology	X	
Visibility	x	
W Fuel Max Pay	X	
W Fuel Nom	X	
Wing Config	X	
wPallets	X	
WPay	X	
Wpay Case 1	X	
Wpay Case 2	X	
WTO	X	
WTO Case 1	X	
WTO Case 2	X	
#Crew_C5	S	
%Fuel Used Segment	S	
A Intercept	S	
B Slope	S	
bStabilizer_C5	S	
bWing_C5	S	
c Coef	S	
CD Segment	S	
CL Segment	S	
d Coef	S	
Density Air	S	
Drag Total	S	
Eff Aero Tech	S	
Endurance	S	

Table 73. Metrics referenced by Team 3 in the midterm and final presentations. (Cont’d)

Metrics	Mid	Final
FCA	S	
FCA_C5	S	
FF Segment	S	
FFAvg	S	
FOM Grade	S	
h cargo bay_C5	S	
h Service_C5	S	
h Tail_C5	S	
K	S	
l_C5	S	
lf/df	S	
lf/df_C5	S	
LFL_C5	S	
M Cruise_C5	S	
MTOW_C5	S	
ROC_C5	S	
Swet	S	
Swet/S	S	
T/W_C5	S	
Tech Aero	S	
TOFL_C5	S	
V Max_C5	S	
V Sound	S	
Vol Fuel Storage Avail_C5	S	
W Allow	S	
w cargo bay_C5	S	
W Crew	S	
W Fuel Segment	S	
W Loaded_C5	S	
W Segment	S	
W/S_C5	S	
#AC		X
#Man Hours		X
#Manufacturers		X
#Struts LG		X
#Tires MG		X
#Tires NG		X
%Savings per Aircraft		X
CG Components		X
CG Overall		X
CG Shift		X

Table 73. Metrics referenced by Team 3 in the midterm and final presentations. (Cont'd)

Metrics	**Mid**	**Final**
Climb Rqmt		X
Cm		X
Config_Similar Aircraft		X
Cost		X
Cost Crew Benefits		X
Cost Crew per Year		X
Cost Fuel		X
Cost Fuel per Gal		X
Cost Maintenance		X
Cost Maintenance 20 Years		X
Cost Maintenance per Year		X
Cost Operation		X
Cost per Crew Member		X
Cost Procurement		X
Cost R&D		X
Cost Salary per Crew		X
Cost Total		X
croot Horiz Tail		X
ct Vert Tail		X
D		X
D Viscous		X
DAoA		X
DCDi		X
density materials		X
Dim Flaps_A340		X
Eff Fuel Burn		X
Error Allowance		X
Flt Hrs per AC		X
Fuel per Hr		X
Fuse Proportions_C5		X
G Horiz		X
G Wing		X
Ground Clearance		X
Ground Clearance Rqmt		X
h cargo bay		X
h Fuse		X
iHoriz Tail		X
L/D		X
Lifespan of AC		X
Loading Turnaround Time		X
Location of Empennage		X

Table 73. Metrics referenced by Team 3 in the midterm and final presentations. (Cont'd)

Metrics	**Mid**	**Final**
Location of Front Spar		X
Location of Rear Spar		X
Location of the Wing		X
M Cruise Segments		X
Maintenance Hrs per AC		X
Materials		X
MCruise Min		X
Mission Duration		X
Mission Profile		x
MTOW		X
Pallet Arrangement		X
Pallet Capability RFP		X
Pm		X
Pn		X
R <10K		X
R Climb Segments		X
Roskam Values		X
SHoriz Tail		X
Similar AC		X
SM		X
SR		X
SR Cruise Segments		X
SVert Tail		X
Sweep Horiz Tail		X
SWing_C5		X
SWinglet		X
TCA		X
Tip-Over		X
Tip-Over Criteria		X
TSFC Segment		X
Turnaround Time		X
VCruise Segment		X
Vol Cargo		X
Vol Fuel		X
Vol Fuel Max		X
Vol Fuel Storage Avail		X
W		X
W cargo		X
W Cruise Segment		X
WPay_C5		X
Year AC		X

Table 73. Metrics referenced by Team 3 in the midterm and final presentations. (Cont'd)

Metrics	**Mid**	**Final**
Year Engine Dev		X
#Crew per Aircraft		S
AR Horiz Tail		S
AR Vert Tail		S
bHoriz Tail		S
bt MG		S
bt NG		S
bVert Tail		S
Cant Angle Winglet		S
Cargo_C130		s
Cargo_C17		s
CG Empty		S
CG TO		S
Clp		S
Clq		S
Clr		S
Cmp		S
Cmq		S
Cmr		S
Cnp		S
Cnq		S
Cnr		S
Cost Crew Salary 20 Years		S
Cost Dev		S
Cost Engr		S
Cost Flt Test		S
Cost Maintenance Labor		S
Cost Maintenance per AC		S
Cost MPS 20 Years		S
Cost MPS per Flt Hr per Year		S
Cost MPS per Year in 1999		S
Cost MPS per Year in 2015		S
Cost per AC		S
Cost Technician		S
Cost Tooling		S
croot Winglet		S
ct Horz Tail		S
ct Wing		S
ct Winglet		S
ct/cr Horiz Tail		S
ct/cr Vert Tail		S

Table 73. Metrics referenced by Team 3 in the midterm and final presentations. (Cont’d)

Metrics	**Mid**	**Final**
CYp		S
Cyq		S
CYr		S
d MG		S
d NG		S
G Vert Tail		S
iVert Tail		S
lm		S
ln		S
Location of Flaps		S
MAC		S
Pallet Capability_C130		S
Pallet Capability_C17		S
Performance		S
Performance OEI		S
Pressure MG		S
Pressure NG		S
R_C130		S
Sweep Vert Tail		S
Sweep Wing		S
Sweep Winglet		S
t/c Horiz Tail		S
t/c Vert Tail		S
Tactical Appr		S
TLC Rqmt		S
TO Ldg FL		S
w Aft Loading		S
W Components		S
W Empty_C130		S
W Empty_C17		S
WPay_C17		S

Table 74. Team 3 metrics that are repeated across and within disciplines

Critical Metrics	**Number of Cross-Discipline Integrations**	**Mission/Rqmts Outline**	**Weight Calculation**	**Performance Estimation**	**Configuration**	**Aerodynamics**	**Structures**	**Stability**	**Cost**	**Subsystems**	**Technologies**	**Propulsion**	**Landing Gear**	**Fuselage**	**Empennage**	**Within-Task Elements**
W	6	X	X	X	X	X		X						X		
h	3		X	X												
M	3		X	X												
#Engines	2				X						X					
AR Wing	2			X		X										
Cargo	2	X	X											X		
e	2			X							X					
L/D	2		X	X												
Loading Style	2				X									X		
Mission Profile	2		X						X							
R	2	X	X	X												
SR	2		X	X												
Time to Climb	2		X	X												
TR	2			X							X					
TSFC	2		X								X					
Type of Wing	2				X	X										
#AC	1								X							X
#Fuselages	1				X											
Cost	1	X							X							
Dim Cargo	1	X												X		
Eff Engine	1	X									X					
EIS	1	X									X					

Table 74. Team 3 metrics that are repeated across and within disciplines (Cont’d)

Critical Metrics	**Number of Cross-Discipline Integrations**	**Mission/Rqmts Outline**	**Weight Calculation**	**Performance Estimation**	**Configuration**	**Aerodynamics**	**Structures**	**Stability**	**Cost**	**Subsystems**	**Technologies**	**Propulsion**	**Landing Gear**	**Fuselage**	**Empennage**	**Within-Task Elements**
FOM	1	X			X											
h cargo	1	X												X		
Pallet Capability	1	X												X		
Stakeholders	1				X											X
Type of LG	1				X											X
Type of Tail	1				X											X
V	1			X		X										X
Vol Fuel	1	X							X							

Table 75. List of decisions and Team 3's reasoning for their decision in the final presentation

Tasks	Decision	Decision Quote
Requirements		
Identify Stakeholders		
Baseline Aircraft		
Mission Profile		
Configuration Selection	Configuration	"These are the different configurations we came up with. These are the first 3," Alexandra
Technology Selection	Select technology to integrate in design	
	Cdi, Drag Friction	"So we're using technology for this. First is the riblets. Which are estimated to reduce the viscous drag 2 to 3 percent. We show the riblets there. So that's what we're going to use. And then our second one is just winglets which are estimated to decrease the induced drag by 20% by minimizing vortex effects," Demetri
	DW due to Composites	"One of the main technologies that we're including is composites on approximately 50 percent of the aircraft. And at the beginning of the process we were able to incorporate in our weight sizing based on the 787 which had 20% empty weight reduction by using composites," Asa
	TSFC, T, #Engines	"So the C5 uses the TF39-GE-1C and that was developed in the CF6 series so the numbers we looked at the CF6 for TSFC. The GEnx is already in use and that's a 15% increase from the CF6. So we were thinking we know we're going to have that much but we're going to extrapolate based on the regression from TSFC versus year so next slide," Garth
Weight Sizing	WTO, L/D	"This is our final spreadsheet we came up with a takeoff weight of 648 000 pounds. The L/D's, cruise will be on the next slide, Climb L/D and all the other are hovering around 20. Which we thought was pretty good. This is after we incorporated the composite technology, aerodynamic technology, and the improved engines," Asa
Specific Range Plots	h, M	"We found 39 000 feet was maximized with specific range at a Mach of .72," Asa
Drag polar		
Select Range	R	"So what we did we looked at missions the C-5 currently does looked at air force bases that are located in different places around the world and decided that the 300 000 pound mission needs to do 2000 nautical mile range," Garth
Constraint Analysis	W/S, T/W, SWing, ARWing	"This is for the 120 000 pound. The wing loading point we picked was 131 and the thrust to weight was .265. We have tables of summaries on later slides," Garth

Table 75. List of decisions and Team 3's reasoning for their decision in the final presentation (Cont'd)

Tasks	Decision	Decision Quote
Outline Cargo	Cargo layout	"So at the bottom we have the basic cargo layout in the form of 3x15 for the pallets. So that's what made— that was the driving factor in our length and width of the cargo," Alexandra
Sizing the fuselage	Fuselage Geometry	"And these are just the different sizing parameters. So our final design is—The fuselage length is 292 feet compared to the 230 of the C5," Alexandra
	Loading scheme	"We decided as of right now to go without the forward loading opening because we just wanted to go from the back. So our aft loading opening is 17.5 feet which is the height of the cargo to get the helicopter out," Alexandra
Wing sizing	Wing Config, S Wing, b Wing, AR Wing, croot, c Mean, ct/cr, t Airfoil Center	"We decided to use the cantilever wing because when we find subsonic speeds. We also looked at a configuration and we decided on a high wing because of how long it's going to be, and we have cargo coming from the back. Better visibility, improved lateral stability, and improved interference drag. And we went back and fixed the surface area and wing span. We have a higher aspect ratio of 12.83 now. Right there you can see the numbers that we use for the mean chord, root chord, tip chord, taper ratio, and the thickness," Demetri

Table 76. List of decisions and Team 3's reasoning for their decisions in the final presentation

High-level task	Detailed-task	Embedded Decision	Decision Quote
Define Requirements & Outline Mission	Outline RFP	Range, Mission Profile	
	Stakeholder Identification		
Configuration Selection	Figure of merit analysis	Aircraft Configuration	"We put all of these different configurations into a table with their different figures of merit and their weights and assigned them a grade, and that's how we came up with a score of 66 for our final configuration. Our final configuration was a single fuselage, high wing, T-tail with tricycle landing gear," Alexandra
Technology Identification	Technology Identification	#Engines, Engine Type, Winglet Incorporation, e, CDi, dW, %Composites, Riblet Incorporation, Cf	"Based on this historical plot we propose using two engines that are projected to be 5% more efficient than the GEnx engines currently in use," Alexandra
Sizing	Weight Sizing	L/D, ROC, Mach, Altitude	"The L/D's and TSFCs are shown here and the process that's chosen to find the Mach number and the altitude it needs to be flown at was an iterative process using specific range as a parameter to incorporate the aspects of lift to drag ratio, the TSFC as well as the velocity which are co-dependent terms that you cannot look at just one at a time to decide your Mach or altitude, so specific range is the appropriate parameter to analyse," Garth
	Drag Polar	CL, CD, L/D	
	Constraint Sizing	T/W, W/S	"We chose our design point to where we had a 5% error allowance, so we didn't actually as close to the line as possible, because we allow for errors in our calculations since we're using weight sizing tools," Garth
Physical Design	Cargo Design	Pallet Arrangement, h cargo bay, l cargo bay, w cargo bay	"If you take a look here, the pallets are the type of cargo that were the most constraining in terms of volume, so we laid out these pallets and came up with an arrangement of 3 by 15. You have the overhead view of the 45 pallets and then a picture of the rear loading and unloading of these pallets and of all the cargo," Alexandra

Table 76. List of decisions and Team 3's reasoning for their decisions in the final presentation (Cont'd)

High-level task	Detailed-task	Embedded Decision	Decision Quote
	Fuselage Design	l fuse, d fuse, w Aft Loading, h Aft Loading	"Since the C5 is our baseline aircraft, we used proportional values based on our cargo size per aircraft, using the C5. Our overall fuselage length, just some highlights are 292 feet, the diameter was 28 feet, then the tail cone angle was 13 degrees. Our cargo height was 17.5 feet based on the apache that's about 17 feet so really close clearance but it definitely fits," Alexandra
	Wing Design	S Wing, b Wing, AR Wing, Vol Fuel Storage Avail, Location of Front Spar, Location of rear Spar	"We had a surface area that was two thirds that of the C5, which can be attributed to using composites on the wing, and therefore having a lower weight than the C5. Our wing span is 220 feet, and we have a high aspect ratio of 10, and we have a small and anhedral because it's similar to other similar aircrafts. The fuel on the wing- the maximum model on the wing that we calculated is 250 000 pounds and the maximum fuel used is 188 000 pounds. That shows that all the fuel's that required is going to fit in the wing. The front spar's located 0.20 of the cord length, and the rear spar is 0.745 of the cord length. The winglet parameters are in the bottom right. Just the surface area and span," Alexandra
	Empennage Design	Shoriz Tail, Sweep Horiz Tail, Sweep Vert Tail	"The horizontal surface area and the vertical surface area as you can see are very close in area, which is something that we wanted to achieve. The tip length of our vertical tail and the root length of our horizontal tail are almost the same which is another important design point that we wanted to ensure we had. Our sweep angle for both parts of the tail are 30 degrees and have a zero incidence angle. The anhedral angle for the horizontal tail is 5 degrees which is the same as the wing," Alexandra

Table 76. List of decisions and Team 3's reasoning for their decisions in the final presentation (Cont'd)

High-level task	Detailed-task	Embedded Decision	Decision Quote
	Landing Gear Design	#Struts LG, #Tires NG, #Tires MG	"The final point for our design was the landing gear which has one nose landing gear strut and three struts of the main landing gear. The nose landing gear has eight tires and each of the main landing gear struts has four tires. This was done iteratively based on weight and balance and stability which we will cover in a little bit, but we wanted to show you a visual of what the landing gear looks like. So, as I said, we have three struts at the main landing gear. These are just the weight per nose gear is 6,923 pounds and the weight per main gear is 44,577 pounds," Alexandra
Weight and Balance and Stability	Calculate the center of gravity	Aircraft detailed layout	"There is a center of gravity excursion plot for case two on the table plot detailing each CG rotation in the X direction starting from the nose as a percentage of the fuselage length and the corresponding weights. As you can see our CG shifts from about 41% to 42% on the fuselage length to approximately 46. So that's about 4 or 5% travel of the fuselage length," Garth
	Stability Calculations		
Cost	Parametric Cost		
	Operation & Support		
	Total Cost Summary		

APPENDIX H – SEMI-STRUCTURED FOCUS GROUP PROTOCOL

As a future aerospace design faculty, I hope to be teaching a senior design course. So, I want your perspective on how you view the design process and the most important components of this process. Take 5 minutes and individually reflect on the process you used this semester in completing your aircraft design. Write this process on the paper I've handed out as if you were having to explain it to another person not in aerospace senior design. Feel free to use any format to convey your process (for example, bullet points, a diagram, a picture).

[Following the individual reflection] Using your individual perceptions, work with your group to draw this process on the white board.

[Follow-up questions]
How did you transition between phases?
How did you know you had enough information to move forward?
What information did you need to make this transition?
[Notes for facilitator]
Make sure to have the students clarify their comments. For example, if a student refers to "constraint analysis"—what did they mean by this? What information do they use in constraint analysis? Etc.

If Time Questions
How is senior design going so far?
What would you change about the course if you could? Are there particular topics that you found helpful either this semester or last semester? What about any additional topics you would have found helpful during the fall semester, in preparation for this term?
Clarify components of presentations as necessary.

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