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Creating and Validating a Model to Support Aerospace Engineering Students' Coordination of Knowledge about a Design

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Introduction

As a general field, design symbolizes the "conception and realisation of new things".[1] However, 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 can also be defined as a structured approach to developing, validating, and implementing complex systems.[2] These complex systems entail multiple points of interaction characterized through overlapping, interdependent, and often conflicting interdisciplinary design parameters, preferences, and constraints.[1-3] 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.[1,4] Aerospace engineering, specifically, integrates technical components from many different disciplines, such as aerodynamics, combustion, avionics, materials science, structural analysis, flight mechanics, optimization, and manufacturing. Thus, successful aerospace engineering design requires multidisciplinary communication, collaboration, and coordination among all stakeholders to balance technical developments within disciplines with design integration across disciplines.

Expert engineering designers are able to manage the complexities involved in integrating multidisciplinary knowledge by using effective strategies for knowledge management and decision-making.[5,6] Further, expert designers are able to modify their reasoning approach to match the complexity of the problem. 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.[7,8] Comparatively, novice designers tend to use a deductive approach and only reason backwards from an assumed design solution.

Another difference in expert and novice approaches to engineering design is their awareness of reasons behind a particular design solution.[6] Expert designers generally have a larger problem space and are able to refer to past projects to find similar designs. They are also able to consider the tradeoffs between multiple design solutions.[6,9] Further, expert designers identify and consider the relevancy of a topic in solving complex design problems.[6] Conversely, novice engineering designers aren't always aware of the information they lack to adequately solve the design problem.[6]

In engineering education, Atman et al has conducted research to examine the design processes utilized by student engineers.[10-12] This research has shown that the engineering design process evolves throughout a student engineer's educational experience.[10,11] For example, senior engineering students generally have more breadth in how they approach design problems.[13] When compared to expert designers, students spend less time on problem scoping and also gather less and less diverse information to solve the design problem.[11] Thus, there is a need for the creation of a model that helps scaffold novice engineers' design knowledge management and problem-solving strategies. Educational approaches to engineering design can be improved by integrating a coordination lens. This paper describes design knowledge coordination and validates this model using an authoritative model of aerospace engineering design.

Design Knowledge Coordination

Gerson (2004) 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." Within the engineering design process, coordination is a mechanism by which multiple individuals align tasks, resources, and knowledge to make integrated decisions about a design.[14] Previous research has investigated the impact of coordination in the context of high-stress, time-sensitive work environments, such as air traffic control, transportation systems, and emergency response system.[15-17] These work environments are typically supported by strict work protocols and processes intended to enable coordinating behaviors. Conversely, coordination in aerospace engineering design is driven by designers sharing pertinent knowledge as they deem necessary in an evolving design process, rather than by following explicit fixed protocols.

One form of coordination in engineering design is through concurrent engineering. Concurrent engineering is the "a systematic approach to the integrated, concurrent design of products and their related processes, including, manufacturing and support." [18] This type of engineering design process is primarily concerned with developing strategies to perform tasks in parallel.[19] The design coordination framework is an extension of concurrent engineering and presents the product development and management perspective from product conception to delivery.[20] 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.[21-24] A review of research by Coates et al found that coordination is a concept that can be used to improve the engineering design process.[25] However, a wide range of models have been developed with little research to integrate these model's views into a cohesive and general perspective of coordination for engineering design.

This paper expands the ideas presented in previous research by describing the development and validation of a general model for interpreting coordination of knowledge about a design. The resulting Design Knowledge Coordination (DKC) model can be used to scaffold coordination of knowledge about a design. Further, this model can be used to enhance novice engineers' strategies for design knowledge management and exchange.

<u>Constructs of Design Knowledge Coordination</u>

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. The DKC constructs were found using a 'scholarship of integration' approach.[26] A scholarship of integration research approach synthesizes information (i.e. literature findings) across disciplines and places major themes into the larger context of the design process.[27] Using this approach, connections were made across various strands of work related to coordinating knowledge underlying design decisions in design teams. In performing this type of critical analysis of prior research, larger intellectual patterns were identified and interpreted in the context of aerospace engineering design.

The constructs of DKC can be used to identify features of information exchanged within the design process. By applying a model of coordination to an analysis of student design reviews in an aerospace engineering capstone design course, patterns of information exchange as well as good and bad strategies of engineering design can be characterized. The DKC model was developed using an example of functional interrelationship as presented in Pahl (2007)[2].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 appropriate in creating the DKC structure as a way to show logical sequencing and order in completing tasks that contribute to the overall design. Figure 1 shows the example breakdown as depicted in Pahl (2007).

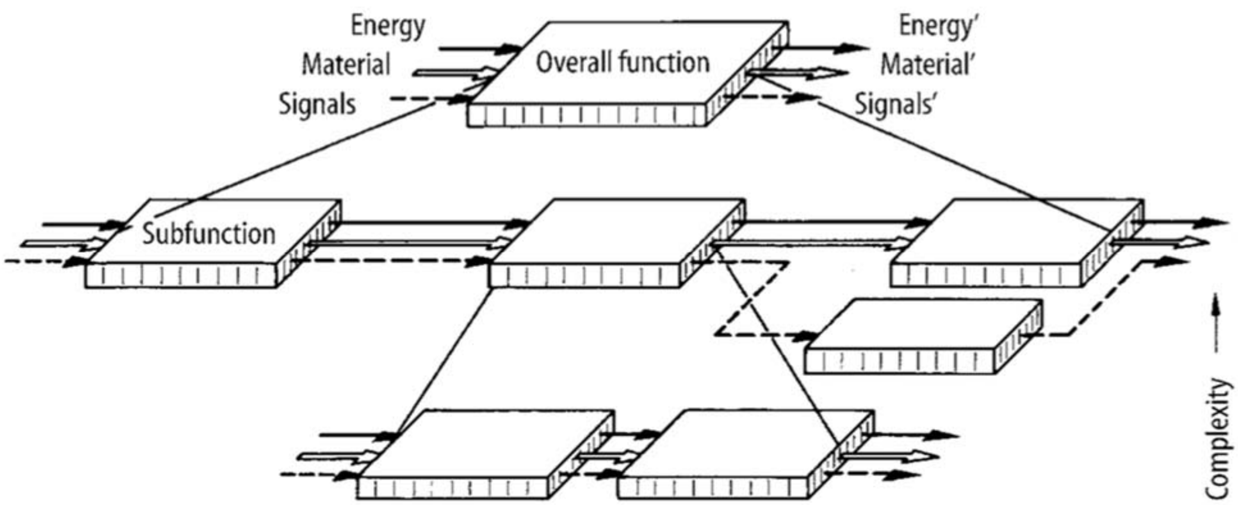

Fig 1. Decomposition of a system structure into functions and subfunctions[2]

Within DKC, instead of functions and subfunctions, a design process incorporates high-level tasks and subtasks. For 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 2 has an abbreviated example of how coordination is embedded within the engineering design process. This model depicts the decision-making process in design as a decomposed system comprising of tasks and subtasks. 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 a decision about the design and are related to how the system is defined. The knowledge about a design is captured by the metrics and decisions.

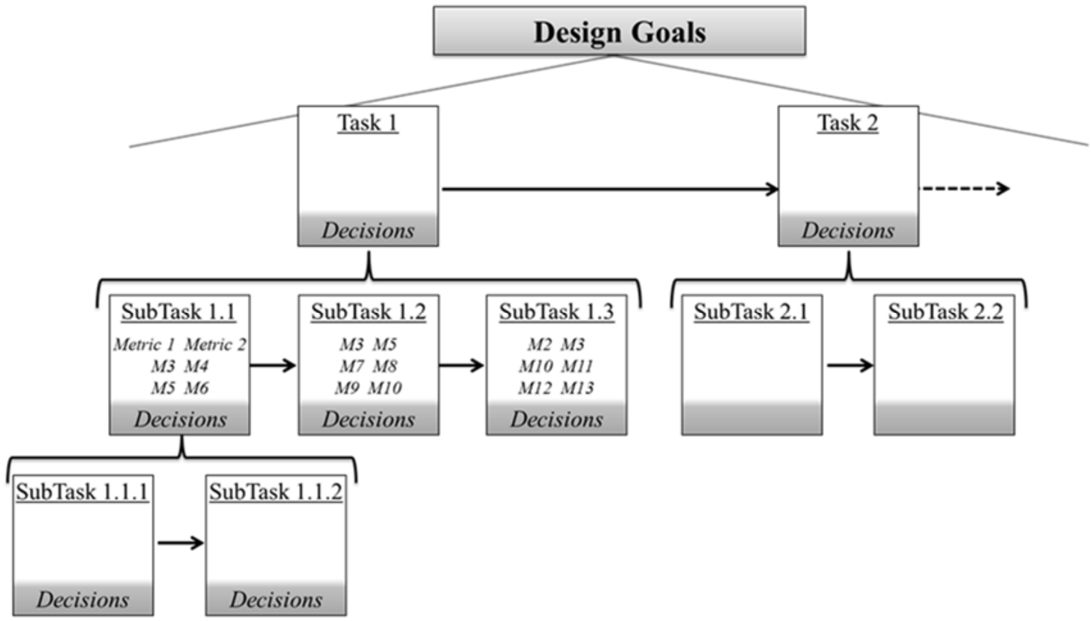

Fig 2. Model of coordination of knowledge about a design

The intent of this paper is to characterize and validate the constructs of coordination so we can identify how coordination impacts novice designers' decision-making process. A model of coordination gives a glimpse as to how engineers make decisions about a design from the perspective of tasks and metrics. Overall, coordination describes the flow of information about a design between tasks and subtasks and provides a bounded method to evaluate the effectiveness of engineers' reasoning for making a specific decision. For example, coordination would exemplify if an engineering team incorporated a range of metrics, or information, 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.

Task Definition: Tasks are necessary to dictate the direction and future content of overall work within the complex engineering design process.[28-30] 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 product 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. Larger 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.

Subtask Breakdown: 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. 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 tasks (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.

The next larger task would take the resulting decisions from the previous task to work on another aspect of the system. For example, in designing a vehicle, the first task might be to outline the type of vehicle (e.g. car, truck, or van). Once the type of vehicle is selected, the next task might be to perform a conceptual design of a component only found on one of those vehicles. If the vehicle were a truck, the next task might have a goal of deciding on the size of the truck bed. Sizing the bed of the truck might involve knowing average axle sizes for the wheels or the average weight per square foot of materials for the truck.

Metric Determination and Use: Metrics are a representation of information about the design that is available to or needed by the designer. Metrics are information that is required to complete the design tasks and subtasks. 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. It should be insured that the designers are using equal 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 a truck, one phase of design would require knowing an approximate weight of the truck, where the weight is a type of 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 information about the design that is not yet available, adding to the subtasks for design completion. 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 gives 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, however 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 of who are 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.

Decision: The outcome of a task is generally a decision about the design. Decisions are often a part of setting values for metrics, 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.

The next section of this paper connects DKC to the aerospace engineering design process using different textbooks' interpretations of conceptual design.

Validation of Design Knowledge Coordination

Aerospace engineering design can be characterized by many different representations of the engineering design process.[4,31,32] To manage design complexity, an aircraft's specific technical components, such as the propulsion system or avionics, are segmented into separate design tasks. Technical component design teams must iteratively integrate critical information from adjacent technical systems into their decision-making process.[31] Thus, communication of knowledge about the design of an aerospace vehicle needs to occur through time as the design evolves.

Aerospace engineering capstone design courses are typically one to two semester courses that ask students to design an aerospace vehicle using a given set of requirements while interacting on a team. While there is some variability in the requirements of a design task, most capstone design projects cover the conceptual design phase of the aerospace engineering design process.[33] Fixed wing design course projects generally ask students to conceptually design commercial or transport aircraft.

In conceptual design projects, the students are given a set of customer requirements detailed typically within a Request for Proposal. This RFP has a list of the main components that must be included in the aircraft as well as the performance requirements the aircraft must achieve to be successful in mission design. The instructors will typically suggest a textbook design process that outlines a conceptual design process that the students can follow. While the textbooks vary in idiosyncrasies of what aspect of design is emphasized, the overall approach to the process is consistent. 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).[4,31,32] All three texts heavily emphasize the use of mathematical models to make design decisions. Thus, students' design reasoning is dependent on their understanding and use of traditional mathematical representations of the system. Further, aircraft metrics are generally quantifiable indicators of design specifications or performance.

The DKC framework was applied to aerospace engineering design by examining the textbooks' prescribed approaches to design for indicators of coordination (e.g. tasks, subtasks, metrics, and decisions). This examination was conducted by first defining the high-level tasks detailed in the textbooks. Once the high-level tasks were defined, each task was broken into subtasks and metrics. The decisions that resulted from each subtask could then be identified.

Because of the complex process presented in the textbooks, the high-level tasks were defined using he process described by Anderson (1999).[34] These seven components were compared to the process presented in the other textbooks for any differences in approach. In general, Anderson's approach could be rephrased to meet the approach prescribed by the other textbooks.

Anderson divides the conceptual design process into seven components.[34]

1. Define Requirements and Outline Mission
2. Perform 1st estimation of weight
3. Determine Critical Performance Parameters
4. Determine Configuration and Layout of Aircraft
5. Improve Aircraft Weight Estimation
6. Conduct a Performance Analysis
7. Optimize the Design

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 are presented in this paper.

To understand the design knowledge coordination perspective, one must first consider the important tasks, subtasks, metrics, and decisions that are included in the conceptual design process. By dividing the conceptual design process into goals, tasks, metrics, and decisions, we can get a detailed analysis of how each component of the design process fits together to enable design knowledge coordination.

The metrics from each mathematical modeling equation listed in Roskam were placed into an excel spreadsheet, along with its high-level and subtask classification, and this list was analyzed for cross-disciplinary features. 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 metrics.

Ultimately, 44 metrics were identified in the process as being cross-disciplinary, including factors such as weight, wing area, aspect ratio, angle of attack, mach, and range. These metrics enable design knowledge coordination by linking together tasks within different disciplines. For example, the coefficient of lift and coefficient of drag (CL and CD) are used within aerodynamic analyses as their primary function. However, these values are also used to analyze structural properties through a V-n diagram (evaluates the aircraft flight envelope by examining velocity and structural load capabilities). Additionally, CL and CD are used in the performance analysis to determine mathematical constraints on the vehicle. They are also used 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 to linking together tasks and subtasks. This intuitively makes sense, because both values determine the inherent performance capabilities of the aircraft and drive subsequent decisions on aircraft design.

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 a Request for Proposal, 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, a Request for Proposal 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.

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.

The subtasks required to successfully define the aircraft requirements and outline the aircraft's mission includes decomposing the information that is available about the aircraft's performance and stakeholder requirements. Another subtask includes evaluating or ranking the importance of each requirement. If any information is missing but is necessary to define the aircraft's requirements, then the designers must have a subtask to identify the unknown information.

Table 2. Application of DKC constructs to the requirements definition component of conceptual design

High-level Task	Define Requirements and Outline Mission
Decision	Define and rank the aircraft performance and stakeholder requirements
Subtasks	• decompose the information that is available about the aircraft's performance and stakeholder requirements • identify the unknown aircraft requirements • define figures of merit to assign importance to each requirement • rank the importance of each requirement
Metrics	range, payload weight, cruise altitude, takeoff distance, maximum velocity, service ceiling, and program cost, etc

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 non-coordinated, but structured approach to design would discuss the goals, but not present the goals in any meaningful context to how they impact the overall design capabilities. 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 tradeoffs that are presented by having specific goals.

Perform 1st estimation of weight

For aircraft design, most decisions are made based on knowing the aircraft weight. The empty weight of an aircraft is 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 equations that are outlined by design textbooks. Many values in this equation are estimated or assumed using suggestions from the textbook 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 effected by the amount of fuel required to fly a specific distance, an optimal 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 is the inclusion of expected performance gains from incorporating technologies. At this point, the 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 3 has a similar breakdown of the DKC constructs within this high-level design task. Fig 3 also incorporates a model perspective of the DKC constructs. Information from each subtask is fed into the next subtask. Overall, the high-level tasks have to maintain consistent information flow in order to appropriately update design considerations.

Table 3. Application of DKC constructs to the weight estimation component of conceptual design

High-level Task	Estimate takeoff and empty weights
Decision	empty weight, gross takeoff weight, volume of fuel carried, optimum range, technology factor
Subtasks	• Use historical aircraft weights to create a regression • Perform 1st weight estimation using mathematical relationships • perform sensitivity studies
Metrics	empty weight, takeoff weight, technology factor (eta), fuel volume, maximum range, range, payload weight, cruise altitude, estimated lift to drag ratio, historical aircraft weights, fuel fraction, etc

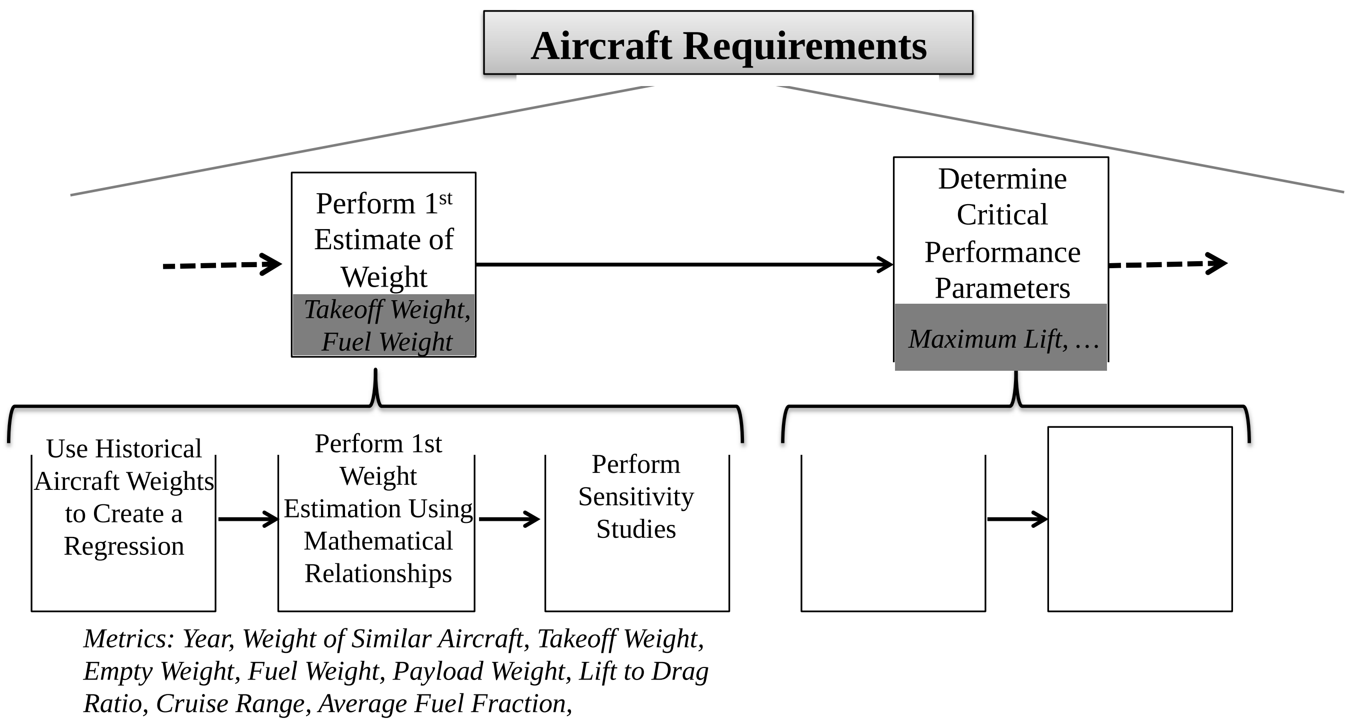

Figure 3. Example Breakdown of the weight estimation component of conceptual design

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Determine Critical Performance Parameters

The performance of an aircraft is determined by several critical metrics including the maximum lift coefficient, lift to drag ratio, wing loading, and thrust to weight ratio. Before a more detailed analysis of aircraft performance can be made, these values must first be calculated. An initial value for the maximum lift coefficient is determined using historical data of similar aircraft. Following, a Class I Drag Polar Convergence is performed using an estimation of other performance parameters (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. Performing a sensitivity analysis gives a better estimation of these performance parameters, 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 grows. Ideally, you would be able to maximize both lift to drag and the takeoff weight. But, because of the negative relationship, an optimal value is selected. Other 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 4. Application of DKC constructs to determining the critical performance parameters component of conceptual design

High-level Task	Determine the critical performance parameters
Decision	Maximum lift coefficient, lift to drag ratio, wing loading, thrust to weight ratio
Subtasks	• estimate aircraft lift coefficient using historical data • calculate the Class I Drag Polar • perform sensitivity/trade studies • perform energy-based constraint analysis
Metrics	Maximum lift coefficient, lift to drag ratio, wing loading, thrust to weight ratio empty weight, coefficient of friction, takeoff weight, technology factor (eta), fuel volume, maximum range, range, payload weight, cruise altitude, estimated lift to drag ratio, historical aircraft weights, fuel fraction, etc

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. First, an overall configuration of the aircraft is selected using a quantification of the criteria required to meet 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 technical information about the performance of the aircraft 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 it's 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 5. Application of DKC constructs to determining the configuration and layout of aircraft component of conceptual design

High-level Task	Determine configuration and layout of aircraft
Decision	Aircraft configuration and size, wing placement, airfoil type, high-lift devices, subsystems, payload loading scheme, landing gear placement, etc
Subtasks	• evaluation of figures of merit and aircraft configuration • select major component arrangements • size the aircraft layout • analyze and select subsystems • analyze Class I Stability and Control
Metrics	Wing size, airfoil thickness, payload weight, lift coefficient, landing gear placement, lift to drag ratio, wing loading, thrust to weight ratio, empty weight, fuel volume, range, cruise altitude, estimated lift to drag ratio, historical aircraft weights, fuel fraction, etc

The three remaining high-level tasks (improve aircraft weight estimation, conduct performance analysis, and optimize the design) iteratively update and improve information about the aircraft. The metrics are iteratively fed back into the design cycle to update initial estimates and to improve aircraft performance. Within the high-level task 'conduct performance analysis,' a very detailed outlook of aircraft design is performed. Each technical component is analyzed in more detail to ensure the aircraft is able to meet the previously defined requirements. Additionally, the metrics are checked for 'common sense' values (do the values make sense for this particular aircraft design?).

Application of DKC Framework in Educational Contexts

While the discussed model of design is fairly one-dimensional, coordination is introduced through the breakdown of the tasks and subtasks as well as through the information sharing between the tasks. Recalling the earlier definition of design as stated by Gerson (2004), coordination involves both connecting two items while also keeping them distinct. Thus, the DKC model should incorporate a level of distinction between design tasks while also recognizing the interdependent pieces that are required to continue toward the workflow. This level of distinction can be maintained by viewing the aircraft as a discipline-centric system. In creating curriculum for aerospace engineering design, the aircraft is divided into disciplines and courses are structured to teach material from within the disciplinary boundary. For example, at one institution students complete coursework focused in six technical areas: aerodynamics, propulsion, structures and materials, structural dynamics and aeroelasticity, fluid mechanics and control, and performance and design. In general, while the students learn about each of the technical areas, little educational opportunities are given to connect the material between the areas. Capstone design is an opportunity to make these connections.

A fully coordinated model would incorporate aspects of keeping the disciplines distinct while also recognizing the interdependencies within the design process. Table 5 breaks down the engineering design process to show the movement from a general approach to design to a more integrated perspective, using the constructs of coordination. Designs with the lowest level of coordination would follow the general approach to design. This approach has little to no effort in connecting the disciplines and rarely uses an iterative approach to balance the constraints on the design with the design goals. The next-highest level of coordinated design includes a discipline-centric perspective of design. Here, the design is decomposed into disciplines or performance areas, but there still lacks coordination between the disciplines. Finally, the highest-level of a coordinated design is an integrated perspective. In the integrated perspective, every decision can be traced to other decisions made earlier in the design, and it's clear that the designer considered tradeoffs between the different areas. While, designers would ideally be fully in the integrated perspective, their approach to design may incorporate aspects of each level of coordination.

Table 5. A coordinated perspective of design

	General Approach to Design	**Discipline-Centric Perspective**	**Integrated Perspective**
Goal	Design goals are specified for the general design characteristics	Design goals are decomposed into more specific goals for each discipline	Design goals within the disciplines are connected to tradeoffs between the disciplines
Tasks	There are clear and defined tasks and subtasks	The tasks and subtasks have an order and hierarchy that align with engineering disciplines	Linkages between tasks and subtasks are evident
Metrics	Metrics are embedded within tasks and subtasks	Metrics are specific to each discipline	Metrics are consistent between the disciplines and support linking between tasks and subtasks
Decision	Decisions are outcomes of completed tasks	Decisions are justified through discipline-oriented metrics	Decisions account for across discipline considerations and tradeoffs using a variety of metrics

Thus, this breakdown of the AE conceptual design process can be used as a way to scaffold novice engineering designers' movement from a general approach to design to a more integrated (fully-coordinated) perspective. Within capstone design courses, a list of the essential metrics that inform the design boundaries could be given to the students, with an explicit note of when to watch for interdependencies. Additionally, students should be able to recognize the task and subtask decomposition of the design process, similar to how Roskam (1990) decomposes the design process.

Outside of the capstone design course, the DKC framework offers a new perspective toward designing technical courses in AE. Courses should not only incorporate their primary content, but technical courses should also present a discussion of how that technical content aligns with and integrates into the engineering design process. Additionally, the students should be given opportunities to practice integrating the design considerations of each area into a design context. This might be done through a hands-on project or through reflective design portfolios.

Conclusions/Future Work

Throughout the conceptual design process, many constructs of coordination of knowledge about a design are apparent. First, the tasks set forth by textbooks of aerospace design align with a high-level task and subtask structure. It's also noted that each task has a goal or expected outcome. For example, the first high-level task's goal is to develop an initial estimation for aircraft weight. The subtasks align with this goal and work toward calculating the aircraft's empty and takeoff weights.

In general, the metrics in the aerospace engineering conceptual design process are quantifiable. A crucial part of using DKC to interpret novice designers' decision-making process is in connecting students' decision to their quantitative literacy.[35,36] Mathematical models assist in justifying decisions and perceptions about real world behaviors. Thus, engineers should be able to interpret mathematical models and use the information to make and justify decisions. Research has shown that experienced engineers have the ability to select and refine known models.[35,37] However, students may not be able to generate and interpret mathematical representations of their decisions. By using DKC to decompose students' communication of their design decisions, instructors can quickly determine how the students use mathematical reasoning to justify their design decisions. Instructors can also determine if the students are using appropriate representations of the design environment to derive a design solution.

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 and externally by the course instructor or facilitator. Key to this context is the idea that the course instructor is a stand-in for managers in a professional environment. However, while instructors can serve as a manager in a professional environment, they are still able to provide guidance on student performance and guide students to alternate approaches to decision-making, if necessary. Thus, instructors must understand where students are lacking in their decision-making in the design process. However, student confusion within the design process isn't always identifiable. The DKC framework provides a method for scaffolding students' decision-making within the complex engineering design process.

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