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An Exploration of Concept Mapping as a Reflective Approach for Instructors When Evaluating Problem Design Intent

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Abstract

Introduction: The work reported here subscribes to the idea that the best way to learn - and thus, improve student educational outcomes - is through solving problems, yet recognizes that engineering students are generally provided insufficient opportunities to engage problems as they will be engaged in practice. Attempts to incorporate more open-ended, ill-structured experiences have increased but are challenging for faculty to implement because there are no systematic methods or approaches that support the educator in designing these learning experiences. Instead, faculty often start from the anchor of domain-specific concepts, an anchoring that is further reinforced by available textbook problems that are rarely open in nature. Open-ended problems are then created in ad-hoc ways, and in doing so, the problem-solving experience is often not realized as the instructor intended.

Approach: The focus in this work is the development and preliminary implementation of a reflective approach to support instructors in examining the design intent of problem experiences. The reflective method combines concept mapping as developed by Joseph Novak with the work of David Jonassen and his characterization of problems and the forms of knowledge required to solve them.

Results: We report on the development of a standard approach – a template -- for concept mapping of problems. As a demonstration, we applied the approach to a relatively simple, well-structured problem used in an introductory aerospace engineering course. Educator-created concept maps provided a visual medium for examining the connectivity of problem elements and forms of knowledge. Educator reflection after looking at and discussing the concept map revealed ways in which the problem engagement may differ from the perceived design intent.

Implications: We consider the potential for the proposed method to support design and facilitation activities in problem-based learning (PBL) environments. We explore broader implications of the approach as it relates to 1) facilitating a priori faculty insights regarding student navigation of problem solving, 2) instructor reflection on problem design and facilitation, and 3) supporting problem design and facilitation. Additionally, we highlight important issues to be further investigated toward quantifying the value and limitations of the proposed approach.

Introduction

The work presented in this paper is motivated by the idea that the best way to learn is through solving problems yet recognizes that engineering students are generally provided insufficient opportunities to solve the types of problems that they will encounter in practice [1], [2]. Despite a wide variety of pedagogical innovations, engineering curricula still largely rely on well-structured problems as the primary mode of learning [2]. Attempts to incorporate more open-ended, ill-structured experiences through problem- and project-based learning (and other active learning measures) have increased but are often met with resistance by students and are challenging for faculty to implement [3], [4]. We contend that overcoming student resistance and implementation challenges are exacerbated by a lack of tools and methods to help faculty design and facilitate ill-structured problem experiences.

In this paper, we focus on the design of problems for problem-based learning (PBL) environments. In such environments, learning is student-centered and self-directed [5] but the instructor plays a critical role in facilitating problem engagement. This starts with faculty creating problems that are sufficiently ill-defined to allow for learning outcomes that go beyond those possible with well-structured problems. However, such ill-defined problems must be tractable and allow for some level of faculty control for a given academic context (such as class level and credit hours). This requires a number of important considerations in the problem creation process including, the identification of, and design for, specific learning outcomes, setting an appropriate level of problem difficulty, understanding faculty resource constraints (time, materials, etc.), and establishing and communicating assessment criteria for students.

The fundamental research question at the heart of the work reported here is: *How can Jonassen's design theory of problem solving be operationalized to help faculty in developing a range of authentic problem-solving opportunities?*

Toward supporting more systematic design of PBL experiences, we are exploring the potential for concept mapping [6] to serve as a framework for problem design. The proposed framework combines concept mapping as developed by Novak [7], [8] with the work of Jonassen and his characterization of problems and the forms of knowledge required to solve them [9]. In this paper we present an initial standardized approach – a template – to support the concept mapping of problems. We demonstrate the approach by mapping a problem from an introductory aerospace engineering course that has been designed and used by one of the authors. In so much as the approach proved to be a reflective exercise, we discuss insights derived from the concept map. We further discuss the potential of the proposed approach in mapping a variety of problems in aerospace engineering and beyond, and how that might assist faculty in the design of problem experiences.

Literature Review

Problem-based learning

Problem-based learning (PBL) is a pedagogical approach generally categorized as active learning [10]. It is defined as an approach to learning that confronts students with "an open-ended, ill-structured, authentic (real-world) problem" where students work together to construct knowledge in developing a solution and instructors facilitate knowledge construction and solution development [3]. Essential features of PBL include problem-focused (learners engage "simulations of an authentic" problem), student-centered, self-directed (students play a role in determining learning issues), and self-reflective (students monitor learning) [5].

Proper problem design is critical for creating the open-ended, ill-structured experiences needed to authentically prepare students for a career in engineering. Research suggests that students will learn more and be more engaged throughout the problem-solving process when they are working on problems that they feel are authentically relevant to the engineering field [11]. When designing these problems, it is critical to carefully consider the specific objectives and type of problem that best fit each project. De Graaff & Kolmos [12] suggest considering a series of questions when determining the objectives for work in PBL, including (but not limited to): where will the project lead, what goals does it fulfill, and what should students learn? These questions should help the problem designer identify key student learning outcomes that should be highlighted in both the implementation/facilitation and assessment of the activity.

Once objectives have been considered, the type of problem used to meet that objective can be selected. Pasandín and Pérez [13] identified four types of engineering problems for use for problem-based learning, including (1) simple problems that reflect specific concepts, (2) complex yet structured problems with sufficient information for students to resolve, (3) complete but ill-structured problems with insufficient information given (requiring students to search for information in order to solve the problem), and (4) complex, ill-structured problems that also require analysis to determine a solution. These problems reflect a progression/range of difficulty and complexity levels that students could be asked to solve. Leveraging both progression of difficulty and different problem types gives students an opportunity to ramp into the open-ended, ill-structured nature of authentic problem-solving and increase their familiarity with the process over time. This has been recommended in recent work as a way to counteract the uneasiness some students feel with this often-new style of learning [14], [15].

Problem creation is challenging because there is a significant difference in developing a problem to be solved in a short time (e.g. a one week homework problem) compared with a problem intended to be solved over an entire semester [16]. Additionally, the PBL model and considerations of the facilitation process can impact decisions about problem creation [16]. In trying to develop problems that are "authentic," faculty may feel that a lack of direct field experience can limit their ability to develop appropriate problems [11]. Additionally, the "fine-tuning" of problems requires iteration to align with learning outcomes, adding time to the problem creation process [17].

In general, systematic approaches to crafting problems for engineering PBL environments appears to be understudied. Among PBL resources highlighted by Kolmos and de Graaff [18] the Aalborg PBL portal provides an evidence-based seven-step process for "problem crafting". Yet, the process, as presented, is not about the type of problem nor the integration of domain content but more about the logistical control of information release to students [19]. Guidelines are not provided for developing the initial representation of the problem around particular engineering (or other disciplinary) context. Ideally, students will play a role in defining the problem. However, for many classroom settings, the reliance on students to set the problem may provide insufficient balance between faculty and students in "controlling" the problem such that it focuses on an appropriate set of learning outcomes.

Concept mapping

A concept map provides a hierarchical representation of knowledge, with specific concepts represented as nodes and connections between nodes describing the relationships among concepts [6], [8]. Concept maps have been used in education for the purposes of assessing student understanding of specific concepts and as a tool for curricular planning [20]–[22]. For example, Hoffenson et al. recently explored how student concept maps reflecting the engineering design process changed after being introduced to market-driven design concepts and tools [23]. Bodnar and Hixson asked students to generate concept maps around the content of an "entrepreneurial mindset" [24]. The student-generated concept maps were scored using the Integrated Rubric for Scoring Concept Maps [20], a rubric that permits concept map evaluation on the dimensions of organization, comprehensive, and correctness. Bodnar and Hixson posit that educators and instructors can use these maps for preparing educational activities that align with program/course objectives and that build on the students' current understanding.

The elements of a concept map include concepts, propositions that relate two or more concepts through linking words to form a statement, and crosslinks that relate concepts across knowledge domains that occur in different parts of the map [8], [25]. Concept mapping (CM) is a reflection tool that visually represents knowledge structure and depth within a specified content domain. Within education, CM is typically applied in the classroom where students are tasked to create concept maps given a focus question and parking lot of concepts [25]. Students must take concepts from a parking lot and place them in a hierarchical structure. Students also identify the hierarchical relationships and designate crosslinks that connect concepts across domains. Novak and Cañas recommend that concept mapping begin with a focus question [25].

In this work, we leverage concept mapping to support educator reflection on problem design. Our conjecture is that this form of reflection may help the instructor to better understand the knowledge necessary for solving problems and to better understand how problem solvers might traverse the problem-content workspace in developing a solution. We pursue this work toward developing a problem design approach that might be pursued by individual or groups of faculty within a specific domain, like aerospace engineering. Our focus in this manuscript is a presentation of a standardized approach to developing concept maps – i.e., we present a template toward supporting systematic development of concept maps across problems.

Jonassen's Design Theory of Problem Solving

Supporting faculty problem creation (and eventually, facilitation of students' problem setting/solving) are the challenges motivating this research. We conjecture that Jonassen's design theory of problem solving [9] provides a theoretical foundation for the systematic investigation of both problem creation and problem solving facilitation. This hypothesis is based on Jonassen's theory for both a problem typology and a basis for characterizing the difficulty of a given problem.

Through research, he derived 11 types of problems [1], [5], [9], noting that for engineering the most common problem types encountered by professionals include selection, troubleshooting, and design problems [1], [2]. The use of problem types – inclusive of the case analysis problem type – as a basis for problem facilitation [26] and to support reflection on professional competencies in the context of project-based learning [27] has been explored previously.

In addition to prescribing different types of problems as a foundation for developing problem solving learning environments, Jonassen considered four characteristics by which problems differ. Those characteristics include structuredness, complexity, context, and domain specificity [5], [9]. Well-structured problems, like those typically encountered in educational environments, provide all the necessary information in the problem representation and often require applying a limited set of prescribed rules to generate a single right solution. Conversely, ill-structured problems include problem elements that are uncertain, have multiple evaluation criteria and possible solutions, and require that problem solvers impart judgements or beliefs to arrive at one of multiple possible solution. Complexity considers the number of problem elements, their interactions, and functional relationships among elements. The stability of problem elements and their relationships is also a factor in the complexity of a problem; if problem elements are changing complexity of the problem increases.

Finally, domain and context specificity impact the nature of actions and considerations for the problem solver. Domain governs the appropriateness of cognitive operations and strategies - e.g., the operations and strategies used in law are quite different than those of engineering. Context can influence which information is relevant and the nature of social interactions. In addition to domain specific knowledge, an individual problem solver's conceptual knowledge, structural knowledge, and procedural knowledge are important factors in the problem solving abilities of an individual [9].

In describing problem solving through the lens of problem types, characteristic attributes, and types of knowledge, Jonassen established a foundation to support problem creation in ways that may allow us to better understand and control the range of difficulty [5], [28]. In this work, we use ideas that he introduced about problem type, characteristics, and forms of knowledge to support the development of a concept mapping standard. This approach is detailed in the next section.

Proposed Approach for Concept Mapping of Problems

Our CM approach defines a standard methodology so that the mapping of problems can be done consistently. The proposed approach is intended to support faculty in designing and reflecting on problems used to engage students, especially in PBL contexts. We began by mapping multiple problems from two core engineering science courses, dynamics and introduction to aerospace engineering. Additionally, we considered both case analysis and design problem types. These early prototypes allowed for the identification of concepts and propositions that might be applied consistently across problems, regardless of domain. The resulting standard or template is described here. We note that in the text of the paper "concepts are placed in quotation marks" and *propositions (linking words between hierarchical concepts) are italicized.* The concept maps themselves do not adopt these formatting conventions.

The standard template, representing the starting point for concept mapping of problems is shown in Figure 1. The focus question is "How do I solve problem X?" The left branch of the first level in the hierarchy establishes concepts that accommodate problem presentation. This includes a "Problem Statement" that provides information in a text format and often (but not always) a "Diagram" providing additional information relevant to the problem. Diagrams may show the real-world system but are often represented by abstractions of the real-world system. The proposition that connects these concepts to the focus question is *given*, such that the statement "How do I solve problem X given a problem statement and diagram?" is described.

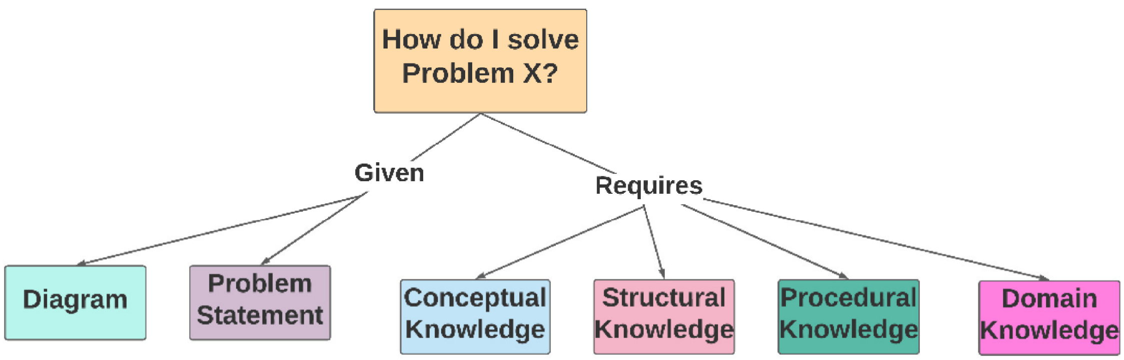

Figure 1. Concept Map Template for Mapping Problems

The right branch of the hierarchy considers the different forms of knowledge *required* for solving the problem. Knowledge types include "Conceptual Knowledge," "Structural Knowledge," "Procedural Knowledge," and "Domain Knowledge." We note that these forms of knowledge often have multiple definitions and relationships to each other in the literature [29]–[32]. It is not the scope of this work to debate or argue for one definition over another. Instead, we have used the literature as a guide to derive definitions that seem to align with Jonassen [9] so that we can work toward a consistent mapping process. We define each knowledge type as:

- "Conceptual Knowledge" is knowledge *of* relevant phenomena for a given problem. This represents the fundamental knowledge in the problem domain. For example, a fundamental understanding of lift as it relates to aerodynamics involves being able to define or explain the phenomena in basic qualitative terms.
- "Structural Knowledge" is knowledge *of* the interrelationships among concepts within a specific domain [9]. We consider structural knowledge to take form in quantitative relations, equations, and analysis methods. In our mapping of problems, we have found that structural knowledge is operationalized to produce problem deliverables (solution

outputs), which may explain why structural knowledge is an important indicator of problem-solving success [9].

- "Procedural Knowledge" is knowledge *of* the steps or procedures necessary to reach a solution to a defined problem. This can take form in mathematical procedures (e.g., solving an algebraic equation) or applying rules to resolve an issue (e.g., following procedures to resolve an issue as in troubleshooting) [32]. Procedural knowledge is necessary for achieving a solution but is not the focus of the curriculum. For example, knowledge of algebra may be necessary to solve the system of equations in a statics problem, but algebra is not the focus of a statics class.
- "Domain Knowledge" is knowledge *of* a particular field [30], which reflects familiarity and experience [9]. We consider domain knowledge to be that which allows a problem solver to make decisions or judgements relative to a problem and its solution. Such knowledge might take form in simplifying assumptions that reduce problem complexity or assessments of the validity or reasonableness of a solution.

The "Problem Statement" *declares* "Problem Elements" and *establishes* the "Deliverables" expected in a solution. A "Diagram" also *declares* additional "Problem Elements." "Problem Elements" *describe a* "Problem Scenario" or "Object of Interest" *with* "Assigned-Value Variables" or *at* "Prescribed Operating Conditions." "Deliverables" *are* "Designated variables" or "End States" which solve the problem. These aspects of problem design are part of problem representation, which can impact how problem solvers understand and approach the problem [9]. Thus, there are other possible elements of problem representation that can be included in concept mapping (e.g., data tables). The current elements relevant to the example problem considered in the next section are shown in Figure 2.

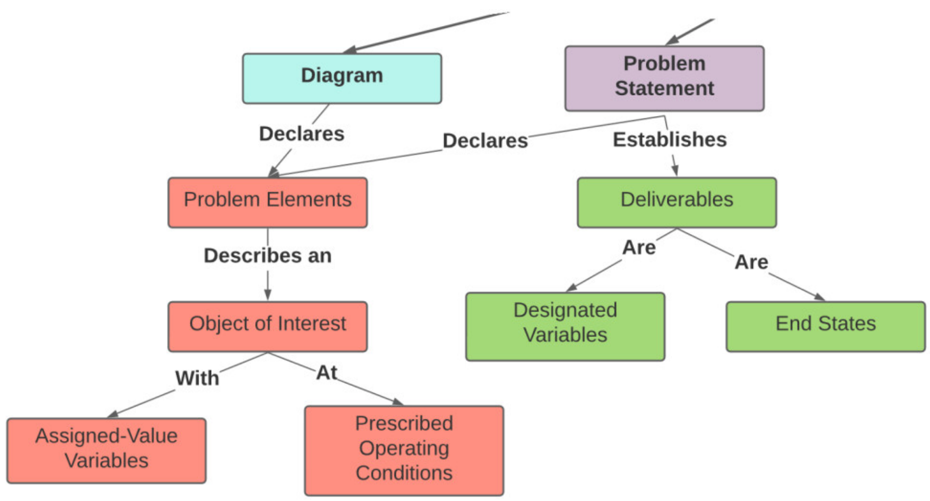

Figure 2. Problem Statement and Diagram Hierarchies

Propositions (hierarchy links) and crosslinks have specified line types from which they may connect concepts (Figure 3). Propositions (hierarchy links) are represented by solid lines and must point in towards a concept from the top side and point out towards another concept from the bottom. Crosslinks are represented by dotted lines and may point in towards a concept or out towards other concepts from either the left or right side.

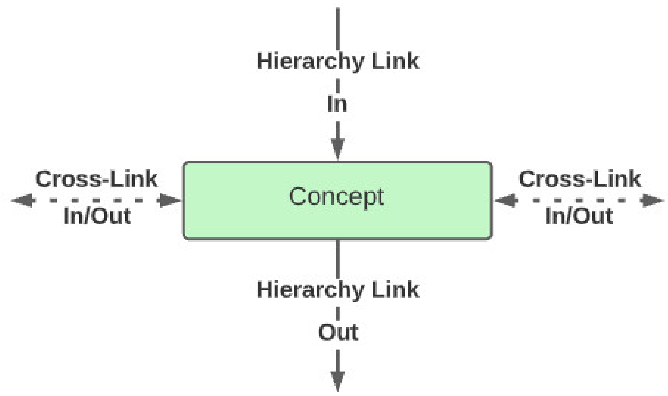

Figure 3. Link Orientations

As more example problems are mapped, concepts and linking word nomenclature will be iteratively refined. We acknowledge that the propositions used in this paper, and in many concepts, can take on multiple definitions. For consistency, Table 1 provides our working definitions for a subset of propositions used in our work.

Table 1. Nomenclature for propositions (linking words) related to problem definition as provided by problem designer

Propositions	Definition
given	Information provided as part of the initial problem statement; this reflects information established by the problem design for the problem solver
requires	Necessitates the use of; associated with types of knowledge previously defined
declares	Specifies known or unknown elements of the problem
establish	Designates problem deliverables or goals
with or *with a*	Sets values for problem variables
at	Describes operating state for problem objects

Preliminary Application to an Aerospace Analysis Problem

Figure 4 shows the results of applying the CM approach to an introductory aerospace engineering problem. The problem statement is as follows. There is no diagram for this problem.

> *The **Cessna Cardinal**, **a single-engine light plane**, has a **wing with an area** of 16.2 m^2 and an **aspect ratio** of 7.31. Assume that the **span efficiency factor** is 0.62. If the airplane is flying at **standard-sea level conditions** in **straight-level flight** with a **velocity** of 251 km/h, what is the **induced drag** when the **total weight** is 9800N?*

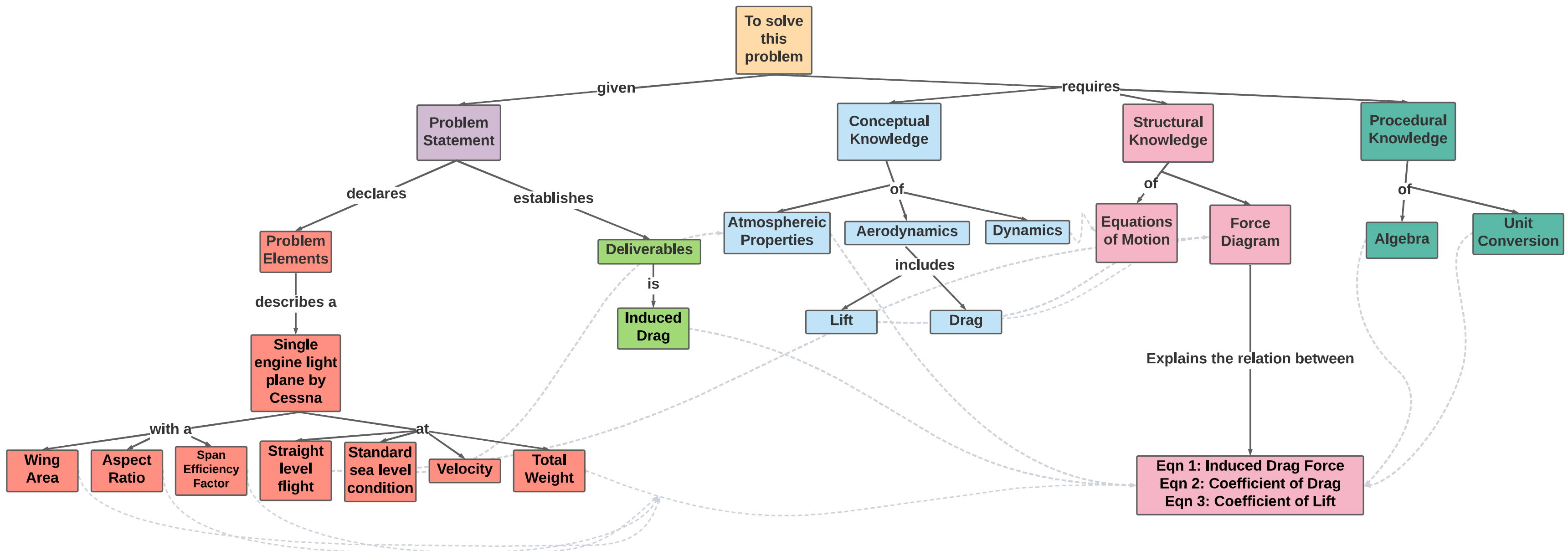

Figure 4. Concept map for induced drag problem (including crosslinks)

The problem statement branch of the full concept map is enlarged in Figure 5. Bolded terms from the problem statement are represented in this branch of the concept map. These terms are individual problem elements with known variable values (*with a*) or stated operating conditions (*at*). A single deliverable in the form of an induced drag estimate is also represented.

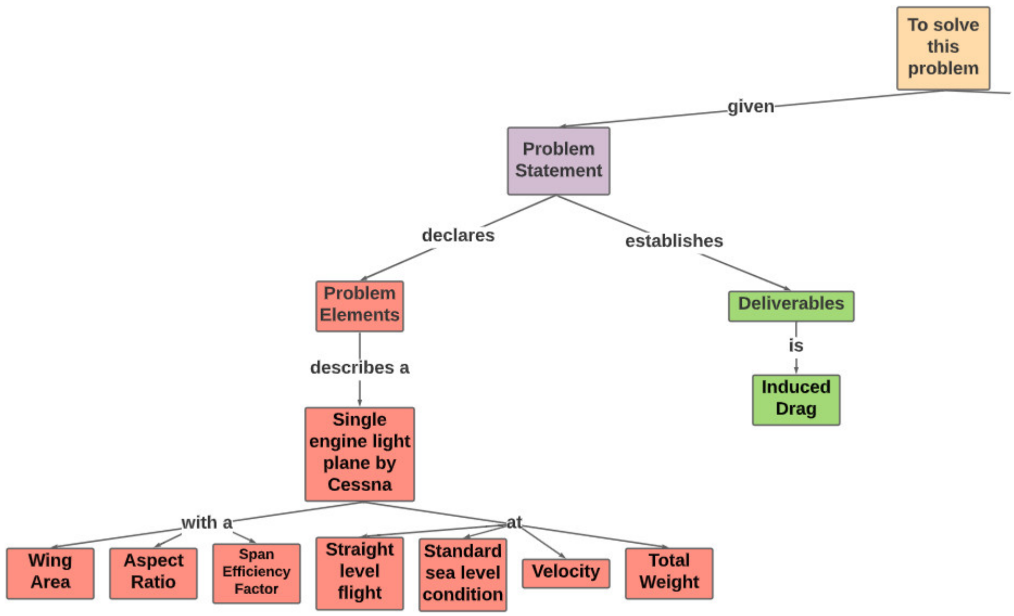

Figure 5. Problem statement (left side) of concept map for induced drag problem (crosslinks not shown)

The knowledge required to solve the problem is shown on the right branch of the concept map, which is enlarged in Figure 6. In this problem, specific conceptual knowledge, structural knowledge, and procedural knowledge are represented. For this problem, we find that there is no domain knowledge necessary. Problem solvers are expected to have (or develop) conceptual knowledge related to atmospheric properties, aerodynamics (specifically lift and drag), and dynamics (as it relates to fundamental concepts of Newton's laws). The structural knowledge necessary for solving this problem includes establishing equations of motion and relating lift and drag for the stated operating conditions (shown by the diagram) that take form in the equation for induced drag. Procedural knowledge necessary to process equations and solve for induced drag includes algebra and unit conversions.

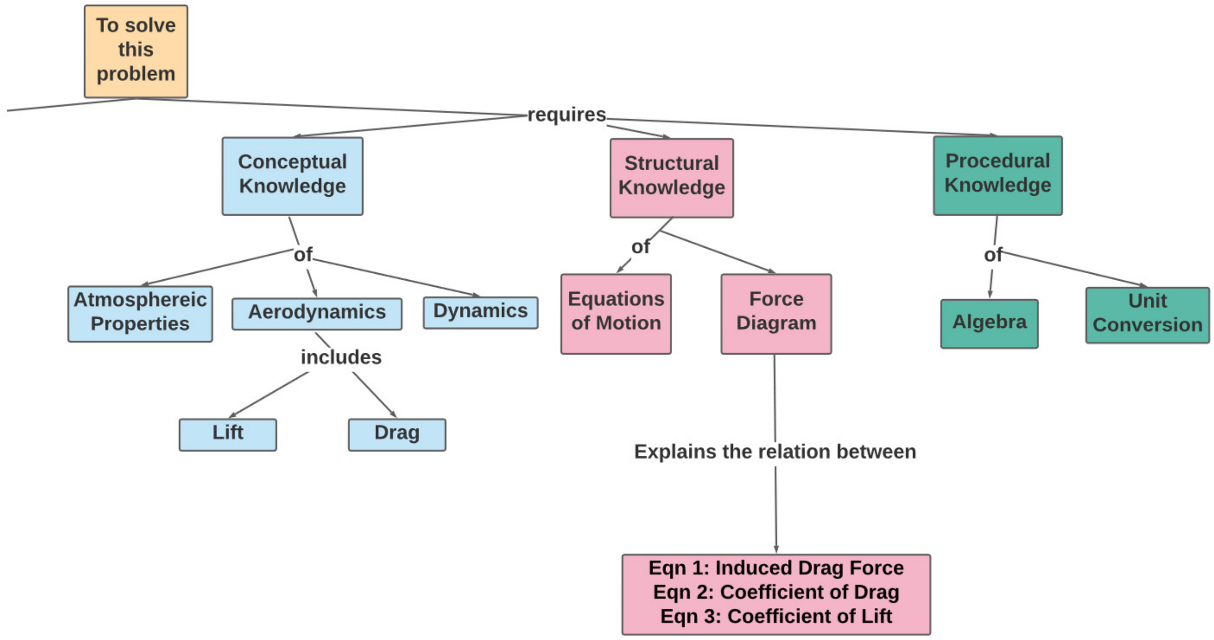

Figure 6. Required knowledge (right side) of concept map for induced drag problem (crosslinks not shown)

The crosslinks in Figure 4 connect the "Problem Statement" branch of the concept map with the "Knowledge" branch of the map. There are two key mappings. First is from variable declarations to the equations under "Structural Knowledge." The second is the mapping of operating states of the aircraft through "Conceptual Knowledge." Additionally, the relationships among the different forms of knowledge specific to this problem are mapped through crosslinks. This includes the pathway from "Conceptual Knowledge" (which originates with operating condition information from the problem statement) through to "Structural Knowledge" and a pathway from "Procedural Knowledge" to "Structural Knowledge" as it relates to solving the system of equations.

The concept map shown in Figure 4 reflects that of a relatively simple and structured problem. In the next section, we discuss potential value of this exercise and implications to be pursued through additional development.

Discussion, Implications, and Conclusions

The approach presented in this paper is in response to the lack of tools available to faculty and instructors when designing and reflecting on the problems that they create or use in their classes. This concept mapping approach is not intended for students. Rather, we see the concept mapping approach described here as the foundation of a sandbox that faculty can use for creating problems of different types that have varying levels of structuredness and complexity. We have introduced a standardized approach for developing concept maps for engineering problems so that faculty have a consistent and defined means of exploring how students must connect the given information in the problem statement with different knowledge types when solving the problem. Additionally, this process allows for the identification of cross-links that indicate how knowledge is connected across type. This effort fits within a broader research agenda to support the design and facilitation of problem-based learning experiences in engineering curricula. We see it as a first step in answering our fundamental research question: *How can Jonassen's design theory of problem solving be operationalized to help faculty in developing a range of authentic problem-solving opportunities?*

In this work, we focused on an initial standardization, which emerged from mapping of multiple problems. This exploratory effort is framed by Jonassen's design theory of problem solving with particular focus on forms of knowledge that reflect "individual difference" and problem "representation" [9], as well as establishing standard propositional phrases (hierarchical links). We demonstrated the standardized approach to a relatively simple and well-structured problem (Figures 4-6). While the problem we considered here is relatively easy the mapping process provides some insights about the problem design and eventual facilitation, which we discuss on three fronts: 1) facilitating a priori faculty insights regarding student navigation of problem solving, 2) instructor reflection on problem design and facilitation, and 3) supporting problem design and facilitation.

Facilitating a priori faculty insights regarding student navigation of problem solving

Visualizing how concepts/data/information flow from one branch of the hierarchy to the other provides a lens by which the instructor can visualize and assess the possible different solution pathways that might be taken by a student when they are solving the problem. Crosslinks can also be used for identifying possible misconceptions (i.e., failure modes) in problem-solving, as they represent the interpretation steps that a student must make when converting a "Problem Element" into a form of "Knowledge", or when connecting multiple forms of knowledge. That is, the concept map may expose cognitive complexities that students face when navigating the problem, which problem designers may underappreciate given their expertise, familiarity with the domain, and their inherent knowledge as problem designer.

Contrast the visualization of potential cognitive complexity in the concept map of Figure 4 with the written solution to the same problem in Figure 7. The solution might provide an impression that there is a linear thought process to follow in solving this process. We expect that students take a much more non-linear navigation of the concepts. This is not expressed in the solution format. As a result, important opportunities for understanding and reflection from both student and instructor may be hidden.

This reinforces a contention from Bucciarelli that for well-structured problems, a presumption accommodated by students is that "all critical information required to solve the problem, and only that information, is given [33]." Similarly, the concept map of Figure 4 reveals a pathway from given information about the variable values directly to the structured knowledge that takes form in the system of equations necessary to find a solution. This shows that students may be able to provide a solution to the problem without a need to understand important concepts relevant to the problem domain. This direct mapping from variable to equations has been summarized by Jonassen as a "problem avoidance" strategy wherein students find and solve equations, arriving at correct answers while avoiding understanding of the concepts and principles that underly the equation [1]. Students practicing such behavior can be successful in a course while harboring conceptual “misconceptions” [34].

Figure 7. Solution for induced drag problem

Instructor reflections on concept map

The concept mapping approach presented in this paper is motivated by a perceived need to provide systematic approaches to support design and facilitation of problem experiences, and to do so with a reflective lens. The faculty member who assigned the original problem in their introduction to aerospace engineering course (who is also co-author on this paper) considered the concept map after it was completed. Three insights were revealed through the mapping process.

First, the problem statement defines the plane as a ***Cessna Cardinal, a single-engine light plane.*** However, nothing about the aircraft brand or type feeds into the problem solution. As such, this piece of information seems like it is given to make the problem feel like an “engineering problem." Yet, since it is not used in the problem-solving process, it becomes an inauthentic element of context. The information about the plane could be replaced with an arbitrary airplane and nothing about the solution changes. Increasing the authenticity of the problem could be achieved by providing the student with the aircraft but not providing as many givens. This would require students to find relevant information about the aircraft on their own. If they can't find the information directly, they would have to make assumptions based on information they can find about similar aircraft of that type. This would help incorporate engineering judgment (domain knowledge) into this problem.

Second, given all the provided information, the key to solving this problem relies on the cross-link between conceptual and structural knowledge. Students must recognize that the phrase 'straight-and-level flight' ties into their conceptual knowledge of lift as being the aerodynamic concept that creates a force in the vertical dimension. Application of this conceptual knowledge takes form in structural knowledge, where the students create a force diagram. If they do not recognize that 'straight-and-level flight' is a statement telling them that there is no acceleration in the vertical direction, they will not balance the lift and weight forces. They should know this from their dynamics course, but the key is them putting the phrase 'straight-and-level flight' in the right context.

Third, the procedural nature of this problem is very linear and is mostly algebra. Students do have to convert units, but in hindsight, it isn't clear what value the unit conversions bring to this problem – i.e., it may seem like "busy work" to students. After seeing the concept map, it raises the question if trying to reinforce this procedural knowledge might take away from focus on the structural knowledge that is important to solve this problem, but that also extends to many scenarios in aerospace engineering.

Supporting problem design, facilitation, and (eventually) assessment

The primary objective of introducing concept mapping is to enhance our collective ability to design and facilitate PBL environments. As it relates to problem design, starting from an existing problem, concept mapping might support specific design considerations for faculty. One design consideration relates to problem representation and its impact on student understanding and approach. For example, the problem mapped in this paper does not include a diagram; should it? Does the lack of a diagram make this problem less accessible to some students compared with others? Consideration of representation as it relates to cues/clues about the problem and pathways to specific forms of knowledge that students are expected to engage may be made more evident through the concept map. If a problem designer chooses not to include a diagram, this may inform the facilitation of problem engagement – in this case, developing a diagram as a way to expose certain concepts may become an important element of facilitation that should be specifically accommodated.

The concept map may also help problem designers understand how turning "on" and "off" problem elements will change navigation of the problem – i.e., supports prediction of change propagation. This becomes important as designers move problems from "easy" to increasingly difficult, which is inherent to creating more open-ended problem experiences that reflect engineering practice. In future stages of this research, we will investigate changing problem design through controls of structuredness and complexity and concept mapping will support systematic evaluation of how those controls change the navigation of the problem. We briefly consider how these changes might take form through Jonassen's framework of problem typology and characterization of problem structuredness and complexity [9].

The problem considered in the concept map of Figure 4 is an engineering case analysis, a problem type oriented around modeling and/or experimenting to build understanding and/or to support recommendations for a particular scenario. Like all problems, the relative difficulty can be changed by varying structuredness and complexity. For example, ill-structuredness of a problem increases with increasing ill-defined goals and unclear criteria. Problem complexity increases as the stability of problem elements and the interconnectedness and form of relationships among those elements increases. For the well-structured, simple problem of Figure 4, we could consider increasing the complexity of the problem by making one of the variables "unstable" [9]. For example, we could have students explore how the aircraft's induced drag changes over a range of velocities. Or the weight of the aircraft could be made unstable (by changing the number of passengers, fuel, etc.) and students could model and explain how this affects the induced drag of the aircraft.

The problem could also be varied by changing the type from case analysis to one of several other common engineering problems like troubleshooting, selection, and design [1],[2]. We expect that such modifications would change the concept map in the following ways:

A *troubleshooting* problem is a scenario where students are presented with a malfunctioning system where success is dependent on efficient fault isolation and treatment [9]. Here, problem solving activities include system examination, fault hypothesis formation, and testing. We envision changing the case analysis problem in this paper into a troubleshooting one by stating that the aircraft is not flying at straight-and-level flight as desired. This modification would change the problem statement branch in that different information would be provided. Students could be given flight data that shows the aircraft's altitude and speed as a function of time. Conceptual knowledge would allow students to identify that altitude changes correspond to a force imbalance. This force imbalance is operationalized through structural knowledge. Posing hypotheses about what variables could be changed to solve the problem would require domain knowledge. For example, the student would have to identify what things can be changed after the aircraft is designed. Thus, a change to a troubleshooting problem may require a deeper dive into the specifics of a particular aircraft, which can provide the foundation for a more involved learning experience that fits PBL environments.

A *selection* problem is a decision situation that has limited alternatives [9]. Here, problem solving activities are oriented around considering benefits and limitations, weighing options, and justifying the selection of an alternative. An additional problem element that defines the criteria (or criterion) about what makes the most effective concept would have to be provided to keep the problem relatively simple and well-structured. Introduction of domain knowledge to support weighing different options, and a selection decision made in the presence of multiple criteria would require procedural knowledge of using (mathematically sound) decision support tools. Alternatively, the identification of appropriate evaluation criteria could be left open – making the problem less structured -- becoming a part of the learning experience by involving students in the identification of those criteria.

A *design* problem has a vague objective, few constraints, and multiple ill-defined criteria. This type of problem requires activities that are oriented toward developing solution principles and producing an artifact in the form of hardware, software, or a process [9]. We see design problems as significantly changing the concept map shown in Figure 4. Many of the problem elements would no longer be defined, except for the aircraft flying at sea-level conditions in straight-and-level flight. Design problems can rely heavily on domain knowledge and initial analysis of the high-level concepts will require multiple instances of linking conceptual knowledge with structural knowledge to obtain early performance estimates, either through computational or empirical modeling. As noted by Jonassen, design is often the most ill-structured of problems [9]. Thus, consideration of an appropriate design scope that fits within a reasonable knowledge set, while still allowing students to engage in the full range of design activities, inclusive of concept development, represents a significant challenge for faculty.

The importance of cross-links in the conceptual model is highlighted by the discussion above. Managing where, and how many, cross-links are in the problem will reflect the structuredness and complexity of the problem. Further, cross-links illustrate where students must *ideally* make connections between different knowledge types in solving the problem. For the problem described in this paper, the student only needs conceptual knowledge of lift, and that knowledge is leveraged structurally in the form of describing the acting direction of the lift force. After this, the student can “equation hop” using procedural knowledge to solve the series of equations. The closed and linear pathway of the solution reflects the limited number of cross-links the student must navigate. As problems become more open, we expect the number of cross-links to increase.

We acknowledge that this paper is limited in in that it only considers the concept map for one problem, one problem type, and that the problem we illustrate is rather easy (well-structured and simple). The focus of the paper is to introduce a formalized approach for the concept mapping of problems, as the reflective nature of concept mapping has potential to support instructors within the learning environment. In many learning environments, the instructor has limited knowledge regarding the background and prerequisite knowledge of individual students. Implementing concept maps in the design of problems can foreground necessary knowledge in ways that help faculty better predict potential sticking points for students. Further, it can put the knowledge relationships into the context of specific problems. In future work, we plan to apply the approach to multiple problems, from multiple faculty. Additionally, we plan to explore the differences in concepts for the same starting problem as the structuredness, complexity, and problem type are changed.

In concluding, we note that this paper presents initial work that is exploratory but has potential to support faculty in the design and facilitation of PBL environments. Given the exploratory nature of this work, there are important issues that need to be investigated. The lack of clarity on definitions for the types of knowledge is a potential issue that may impact the usefulness of our proposed approach and deserves a deeper review of the literature. As a consequence, we recognize that there will be a need to refine the concept mapping approach introduced in this work and to understand the limits of concept mapping in meaningfully mapping increasingly ill-structured and complex problems. Finally, as we work with others in the community to develop concept maps for multiple problems, understanding how to navigate resulting concept maps in meaningful ways, perhaps through automation, will be important to informing the methodology and its potential to support PBL environments in practical ways.

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