Exploring the Differences and Manipulation Pathways of Introductory Aerospace Engineering Problems through Concept Mapping

Andrew Olewnik
Department of Engineering Education
University at Buffalo
Buffalo NY, USA
olewnik@buffalo.edu

Scott Ferguson
Department of Mechanical and Aerospace Engineering
North Carolina State University
Raleigh NC, USA
smfergu2@ncsu.edu

Amrith Mariappan
Department of Mechanical and Aerospace Engineering
University at Buffalo
Buffalo NY, USA
amrithma@buffalo.edu

Nadeem Sheikh
Department of Mechanical and Aerospace Engineering
North Carolina State University
Raleigh NC, USA
nasheikh@ncsu.edu

***Abstract* – This full paper is focused on research into how educators might use concept mapping to explore and design learning experiences in a problem-based learning environment. 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. In the reported work, we present an exploratory study toward a systematic approach for comparing and manipulating problems. The approach combines concept mapping with Jonassen's characterization of problems and the forms of knowledge required to solve them. We explore manipulation pathways for a problem that can be pursued by an instructor who is interested in impacting the dimensions of structuredness and complexity. We compare similarities and differences among two problems taken from introductory aerospace engineering courses. We consider manipulation of structuredness and complexity and the change propagation in forms of knowledge and solution pathways.**

Keywords – problem-based learning, concept maps, aerospace engineering

I. Introduction

Increased adoption of active learning [1], [2] approaches reflects a desire to integrate learning experiences that are more learner-centered and where students' play a larger role in constructing knowledge necessary to solve the problem [3]. In this work, we are particularly interested in problem-based learning (PBL) – an approach to learning that confronts students with "an *open-ended*, *ill-structured*, authentic (real-world) problem", In PBL, *students work together* to construct knowledge in developing a solution, and *instructors facilitate* knowledge construction and solution development [4]. Problem- (and project-)based learning are frequently referenced as pedagogical approaches with positive impacts on students' cognitive development, affective dispositions, and professional competences which are used across a range of disciplines and education levels [4]–[10].

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 [4], [11]. This problem is exacerbated by a lack of tools and methods that help faculty develop ill-structured engineering exercises that are properly scaffolded. The benefits of PBL have led some educational researchers to argue for a shift toward studying implementation issues, including consideration of assessment and developing tools and methods to support faculty [7], [12]. The focus of this paper is on the challenge of PBL problem design. 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 [13]. Additionally, the PBL model and considerations of the facilitation process can impact decisions about problem creation [13]. 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 [14] and the "fine-tuning" of problems requires iteration to align with learning outcomes [15]. Among PBL resources highlighted by Kolmos and de Graaff [3] the Aalborg PBL portal provides an evidence-based seven-step process for "problem crafting". However, the process, as presented, is more about the logistical control of information release to students and not about the type of problem nor the integration of domain content [16]. It does not provide guidelines for developing the initial representation of the problem around particular engineering (or other disciplinary) context.

Recognizing this acute challenge in PBL, the work reported here is an initial exploration toward using Jonassen's design theory of problem solving [17] to support problem design. The research question at the heart of this work is: *How can problem characteristics of structuredness and complexity be operationalized in the development of problems suitable for PBL environments?*

In this paper, the manipulation of two problems from introductory aerospace engineering courses is considered. Starting from concept maps of the initial problems, differences in required knowledge, problem solving pathways, and impacts on problem facilitation that result from changes to specific aspects of problem complexity and structuredness are explored. In the next section, the underlying frameworks that support the exploration are briefly described.

II. FRAMEWORKS

Concept mapping and problem representation

A concept map provides a hierarchical representation of knowledge, with specific concepts represented as nodes and connections between nodes describing the relationships among concepts [18], [19]. Concept maps have been used in education for the purposes of assessing student understanding of specific concepts and to support curricular development [20]–[25], and to support educator reflection on problem design [26]. We follow an approach that defines a standard methodology to support consistent mapping of problems. Details of the derived approach are described in [26], but an overview of fundamentals of the approach is briefly detailed here in terms of structure and definitions of knowledge types.

The starting point for concept mapping of problems is shown in Fig. 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 key information from the text of the problem statement and may also include a supporting diagram.

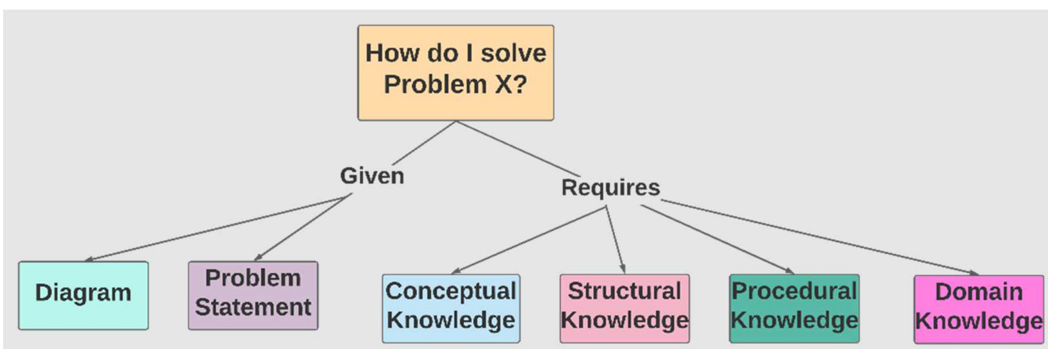

FIGURE 1. CONCEPT MAP TEMPLATE FOR MAPPING PROBLEMS

The right branch of the hierarchy considers the different forms of knowledge necessary for solving the problem. Knowledge types include "Conceptual Knowledge," "Structural Knowledge," "Procedural Knowledge," and "Domain Knowledge." These forms of knowledge often have multiple definitions and relationships to each other in the literature [27]–[30] but we have used the literature as a guide to derive definitions that align with Jonassen [17] 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 [17]. 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 [17].

"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) [30]. 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 [28], which reflects familiarity and experience [17]. 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.

Structuredness and complexity for manipulating problem design

Jonassen described four characteristics by which problems vary. Those characteristics include structuredness, complexity, context, and domain specificity [17], [31], but we limit consideration to structuredness and complexity. Well-structured problems, like those typically encountered in educational environments, provide all the necessary information in the problem representation, and often require a limited set of prescribed rules to generate a single right solution. Conversely, ill-structured problems include problem elements that are uncertain or unknown, 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 the 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. From these descriptions of structuredness and complexity, we considered specific features of each characteristic and how they might be represented within problems. These elements have been formulated as a set of questions, which are reported in Table 1.

TABLE 1. CONSTRUCTS OF STRUCTUREDNESS AND COMPLEXITY BY WHICH PROBLEM VARY [17]

Structuredness	
issues emerge as you solve the primary problem	What aspects of the problem can be considered "emergent"? That is, what issues may emerge in solving the problem that are not apparent from the problem statement?
may require knowledge from multiple content domains	What content domains are relevant to solving the problem? How "distant" are those domains (e.g., math may be relevant but some math principles may be well-established while others may be less so)?
problem elements are unknown or known with low confidence	What problem elements are unknown or known with low confidence?
contain multiple criteria for evaluating solutions	How many criteria are relevant to solution evaluation? Are some criteria more relevant (prioritized) than others?
require judgment or expression of opinions/beliefs	Is it necessary to bring judgement or opinion to the solution or is a purely prescriptive/rational approach possible?
Complexity	
number of problem elements [functions/issues/variables]	How many functions? Issues?
degree of connectivity among elements	What is the degree of connectivity of these elements?
type of functional relationships between elements	What are the functional relationships between elements?
stability of elements or functional relationships	Are the elements stable or unstable? Are the functional relationships stable or unstable?

The individual features of structuredness and complexity from Table 1 provide a foundation for assessing the difficulty of a problem. In this work, they also provide a basis for manipulating the design of a problem. The use of specific features like those in Table 1, in combination with problem concept maps, is toward developing methods that support problem designers in the creation of problems that might be found in PBL environments. Additionally, such a structured approach might support research exploring the underlying processes and thinking among faculty as they design problems. We consider two existing problems from introductory aerospace engineering courses in the next section.

III. Framework Application

In this section we consider two problems from introductory aerospace engineering courses: a required fuel and an engine analysis problem. These problems were provided by a faculty member at another institution as examples of problems used within their course. Both problems are explored through a process that involved: 1) development of a concept map for the original problem, 2) assessment of the original problem in terms of structuredness and complexity, 3) selection of a structuredness or complexity feature by which to manipulate the problem design, and 4) update of the concept map to reflect the modified problem.

Case 1: Required fuel problem

For our first case, we considered a problem that required estimating the fuel required for a specified aircraft given set cruise and loiter parameters. The text-only problem statement was:

Let's consider a HA-420 HondaJet light business jet whose parameters are given below. The plane is flying from Huntsville to Chicago, which is a distance of 580 miles. At Chicago, the plane needs to loiter at the cruise altitude for 40 minutes. Calculate the minimum total amount of fuel required to do this flight (cruise + loiter). Assume during loiter its flight at max endurance, and at the end of loiter the plane is at empty fuel. Ignore the takeoff and landing portions. Use the weight at the end of cruise for calculating cruise lift and drag parameters.

Wingspan	*39 ft*
AR (straight rectangular wing)	*8.5*
Empty Weight (no fuel, no people/cargo)	*7,200 lbf*
People/cargo weight	*1,000 lbf*
Max thrust, sea level	*4,000 lbf*
TSFC	*1.2 lb/lb-hr*
Cruise altitude	*33,000 ft*
Cruise velocity	*420 mi/hr*
CDo	*0.015*

A concept map for this problem is shown in Fig. 2 with a focus on the cross-links between procedural, domain, and structural knowledge. These crosslinks are important in how knowledge types guide the solution process:

- The problem-solver must recognize that a jet airplane's maximum endurance occurs when the airplane is flying at the minimum thrust required. This is domain knowledge associated with jet aircraft (which has different properties than propeller-driven aircraft).
- The equations that take form in structural knowledge must be used in a nested format that requires a sequential process, a process represented in procedural knowledge.

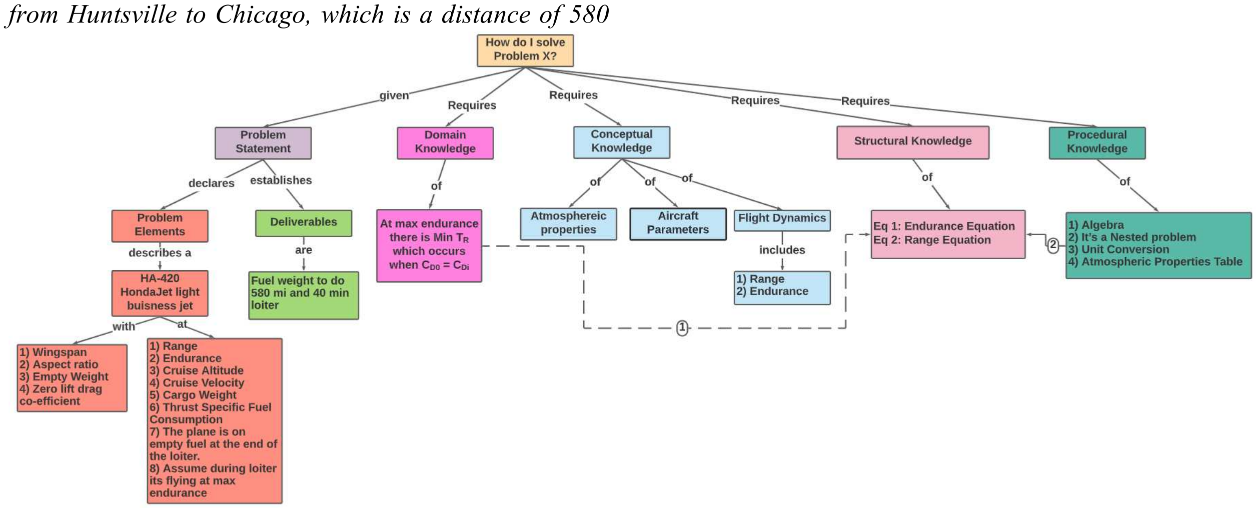

FIG. 2. CONCEPT MAP FOR REQUIRED FUEL PROBLEM

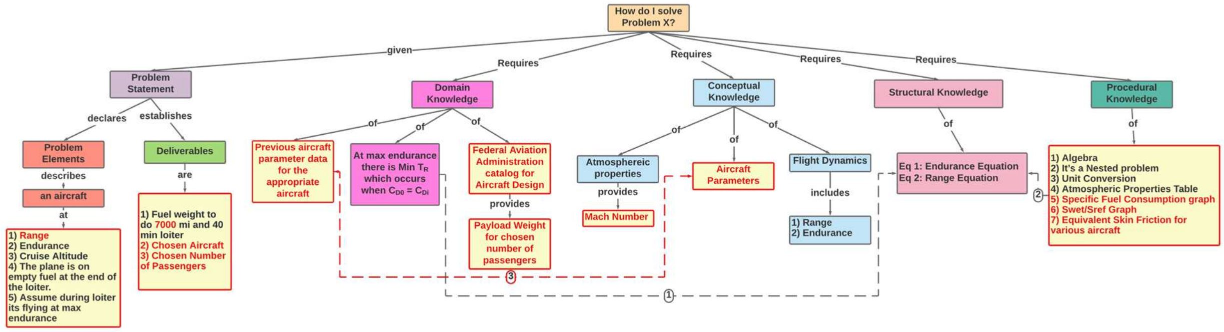

FIG. 3. CONCEPT MAP FOR MODIFIED REQUIRED FUEL PROBLEM

We explored a problem modification by changing the range of the mission and giving the problem-solver the freedom to choose the aircraft and the number of passengers. These changes reflect a change in the structuredness of the problem, as the problem-solver must work with an unknown element and find the relevant properties of *their* selected aircraft. Setting the number of passengers requires domain knowledge about regulations related to estimates of passenger weight.

An updated concept map for the problem is shown in Fig. 3. This problem modification creates two additional cross-links:

- New cross-link #1: Students must select an appropriate aircraft. Here, appropriate is measured by accommodating the number of passengers selected and being able to travel the required distance. From this selection, students must then identify the necessary aircraft parameters that are needed for the remainder of the problem. In the original version, these data were provided. Now, students must link conceptual knowledge of what they need with the domain knowledge of the specific aircraft's properties.

- New cross-link #2: Students must select the number of passengers. Doing so will change the people/cargo weight. Students must use domain knowledge (e.g., U.S. Department of Transportation FAA Advisory Circular that provides guidance on defining weight and balance) to specify regulated estimates of passenger weight for such aircraft sizing/mission analyses.

In summary, the problem is made more ill-structured by converting two known, fixed variables (aircraft, weight of passengers/cargo) to parameters that are selected by the problem-solver. There are two ways that the problem-solver could select an aircraft. The first involves researching a variety of aircraft and their capabilities so that an appropriate craft is chosen. The second involves searching for any aircraft that meets the problem "constraints" of range and number of passengers. Problem-solvers pursuing the second strategy will arrive at a selection without gaining much domain knowledge, as they are simply satisfying a criterion of the problem without seeing the value of their selection.

The freedom to select the number of passengers takes a fixed value of weight in the original problem and makes it variable in the new one. This increases complexity in that to operationalize the FAA guidelines, the problem-solver must now identify passenger composition (i.e., ratio of men to women to children) and consider time of year (i.e., winter or summer) to define the weight estimates used. This introduces an element of domain knowledge that connects to the conceptual knowledge of aircraft parameters (i.e., that aircraft weight is defined by empty weight, fuel weight, passenger/cargo weight, etc.).

Case 2: Engine analysis problem

The text-only problem statement for the selected engine analysis problem is as follows:

An airplane is flying at an altitude of 10 km at 120 m/s. Its jet engines, which for now can be approximated as a converging duct, have an inlet diameter of 1.50 m and exit diameter of 0.3 m. The exit of the engine has a temperature altitude of 11 km, and pressure altitude of 10.5 km. What is the velocity at the engine exit to 0 decimal place?

A concept map is shown in Fig. 4 where the focus is on the cross-links between procedural, domain, and conceptual knowledge. Based on consideration of the solution to this problem, these crosslinks stand out as particularly important in terms of how knowledge guides the solution:

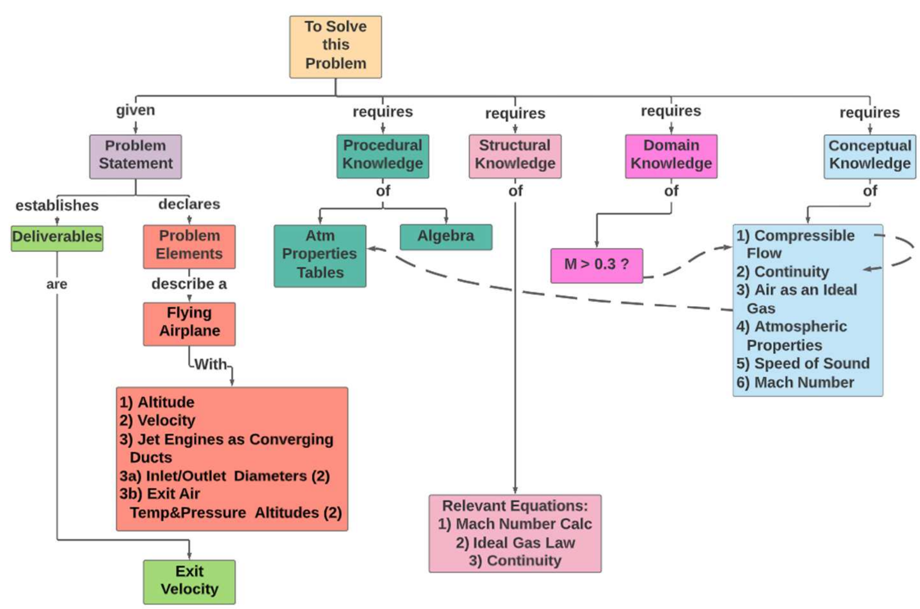

FIG. 4. CONCEPT MAP FOR ORIGINAL ENGINE ANALYSIS PROBLEM

- The problem-solver must recognize that the aircraft is traveling at a speed greater than a Mach number of 0.3, and that air is treated as a compressible fluid at these speeds.
- Because air is modeled as a compressible fluid, the problem-solver must also establish a connection that the Continuity principle is used here, as Bernoulli's principle is only valid for compressible fluids up to a Mach number of 0.3.
- The problem-solver must also connect that pressure and temperature altitudes can be converted into pressure and temperature using atmospheric property tables (procedural knowledge).

We explored a problem modification by introducing an unstable variable - i.e., a change to complexity (changes to problem statement in bold). The problem-solver must now determine how the engine exit velocity changes over a range of altitudes:

You are designing an airplane that flies between altitudes of ***10 and 13 km*** *at 120 m/s. Its jet engines, which for now can be approximated as a converging duct, have an inlet diameter of 1.5 m and exit diameter of 0.3 m.* ***Previous data tells us that, when flying at an altitude of 10 km****, the exit of the engine has a temperature altitude of 11 km, and pressure altitude of 10.5 km. What is the velocity at the engine exit to 0 decimal places* ***throughout the altitude range?***

For all altitudes defined in the problem statement, the air must be treated as compressible, much like the original problem formulation (i.e., the Mach number still exceeds 0.3 for the altitude range). What changes, however, is that the student no longer has information about the temperature and pressure altitudes of the air as it exits the engine over the range of altitudes. The problem designer must now provide students with additional information so that they can complete the required calculations. Possible pathways include:

- Modification #1: The problem designer adds to the problem statement by providing the necessary temperature and pressure altitudes for the full altitude range. This turns the problems into a series of repetitive calculations that does not add new knowledge elements to the solution process.
- Modification #2: The problem designer could use this as a platform for introducing more advanced representation of engine design and performance properties. This provides opportunities for faculty-student discussion and problem framing in understanding how engines work and how altitude and speed are related in aircraft performance. An updated concept map for the second modification is shown in Fig. 5. Students given this modified problem will gain conceptual knowledge about jet engine thermodynamics and the pilot's control over the engine. Additionally, students will develop structural knowledge that connects the relationship between altitude, aircraft speed, and aircraft performance.

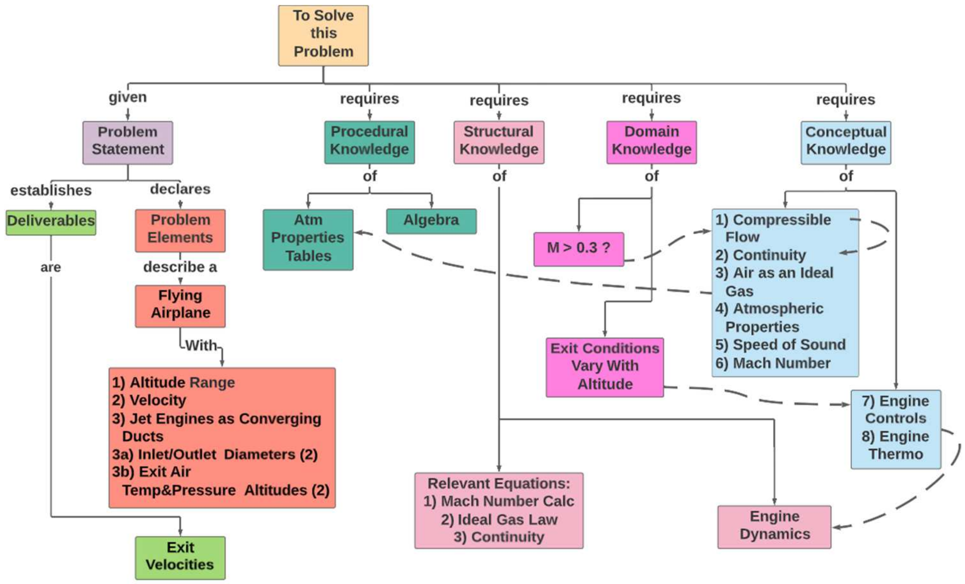

FIG. 5. CONCEPT MAP FOR MODIFIED ENGINE ANALYSIS PROBLEM

In summary, the complexity of the modified problem increases by converting a known, fixed variable (flight altitude) to a range of altitudes. This results in an "unstable" element in the problem formulation, where the ramifications become the need for additional conceptual and structural knowledge. The numerous functional relationships within engine design will quickly outpace a novice student's knowledge, providing opportunities for faculty-student engagement in exploring this new conceptual knowledge and shared responsibility over knowledge development. For example, students may become responsible for understanding the fundamental concepts behind engine function and the structures that drive that function. Students will conceptually connect that as altitude changes, the air becomes less dense. As the air becomes less dense, the engine throttle must be increased for the aircraft to maintain the same velocity. By changing the engine throttle, the pressure and temperature altitudes at the engine exit will change as well. This offers students a glimpse into aircraft propulsion, a topic that may be studied later in the course (such as in an introductory class) or later in the curriculum in a class devoted to aircraft propulsion. Merging the two modification pathways, a faculty member could give students the necessary temperature and pressure altitudes for the different flight altitudes, only after students have explored and connected the concepts listed above.

IV. DISCUSSION

In this early investigation, we explored two well-structured problems from an introductory aerospace engineering course to understand how manipulation of the problem might be accomplished through consideration of dimensions of structuredness and complexity.

We found that it was easiest, or perhaps more obvious, to modify a problem by manipulating structuredness, as in the first case. By recasting a previously fixed element as open (i.e., allowing the problem-solver to specify an element, like the type of aircraft) represents a pathway for making a problem more ill-structured. By doing so, new cross-links between knowledge types were established as a need for additional domain knowledge was introduced. In this case, the additional domain knowledge increases the authenticity of the problem by allowing for engagement with industry (FAA) regulations. Further, it forces students into an activity in which they must make judgements regarding the ratio of passenger type and justify their decisions. In this way, making the problem more ill-structured led to an increase in complexity by introducing variables related to payload, like ration of men to women, and adults to children.

For the engine analysis (Case 2), increased complexity is achieved by making a variable unstable (i.e., consider exit velocity at multiple altitudes). This required the need for new conceptual knowledge related to aircraft engine design, analysis, and performance. This change reveals complexity of aircraft design that is otherwise hidden to students by introducing functional relationships between engine control, engine thermodynamics, and the performance of fluids within such a system.

Increasing the complexity of both problems raises important questions about the types of learning outcomes desired from an introductory course. The use and interpretation of FAA regulations can provide students opportunity to work with forms of "accountable disciplinary knowledge" [32] that help to demystify the profession. Facilitating discussion about engine design can help to establish an interconnectedness among individual courses in the curriculum – in this case, establishing a link to propulsion. Such considerations should be set in the design of the course but manipulating the complexity of well-structured textbook problems can serve as a possible path to accommodating higher level learning outcomes and disciplinary connections.

While complexity was relatively easy to manipulate, it appears more difficult to change the structuredness of the original problems. That is, many of the dimensions of structuredness outlined in Table 1 seem more difficult to manipulate than those of complexity. The textbook problems explored here are designed to be worked on independently without input from outside sources or people. Both problems are purely quantitative in their original framing (and solution). There is nothing qualitative about the problems that require interpretation and framing by the problem solver, and they appear design to minimize any emergent issues. Thus, we two questions for further investigation: 1) How might we further reduce structure within an existing well-structured problem? and 2) What are the limits for a priori concept mapping of ill-structured problems?

V. CONCLUSIONS

The work reported in this paper is toward exploring how characteristics of structuredness and complexity might be operationalized in the development of problems suitable for PBL environments. Though this exploration is limited to two problems from a single domain, we find support for using the dimensions of problem structuredness and complexity in reshaping well-structured problems for PBL environments. As we continue our research, we recognize three areas for future work. First, expansion to more problem types beyond the case analysis problems considered here (like design and selection), other domains, and re-consideration of the structuredness dimension is necessary. Second, specific to the complexity changes in this work, we wonder if students would perceive these problems as having different levels of complexity? If so, how would they describe those differences and how does that align with the concept maps? Finally, reflection with other faculty toward understanding the process of problem design and the extensibility of the approach developed here is important both as a research lens and for supporting a potential community of practice that can share insights and lessons related to design, facilitation, and assessment in PBL.

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