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An Emerging Methodological Toolkit to Support Design of Problem-Based Learning Environments: Connecting Problem Characteristics and Knowledge Types

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Introduction

The design of problem-based learning (PBL) environments is difficult and there is a seeming lack of methodological tools to support faculty in design, facilitation, and assessment in PBL. In this theory/methods paper we put forth a "methodological toolkit" that is emerging from our exploratory design-based research in a PBL setting. Emerging from our research are reflective activities in which an instructor might engage to identify the components of a problem, including the knowledge, activities, and deliverables required to solve the problem. Further, how *ill-structuredness* and *complexity* are represented within a particular problem [1], and how they might be resolved are supported through reflection.

A central goal of this work is to discuss and share these reflective activities recognizing their potential to provide instructional support for the PBL design process, including problem development and facilitation. Our research team sought to explore what it *means* for an instructor to develop and facilitate a problem in a PBL environment, and what a reflection on this facilitation might look like. This aim is motivated, in part, by what Wiggins and McTighe refer to as the "twin sins" of learning design – "activity focus" and "coverage" [2] – which may be unintended results owing to a lack of methodological tools for PBL. Beyond supporting instructors' planning of PBL, we envision that the materials instructors produce when using this toolkit might contribute to discussion and the sharing of PBL materials among fellow engineering instructors. Implementing PBL into the classroom presents an opportunity to provide rich, authentic engineering experiences for students, but implementation is a notoriously difficult task [3], [4]. We envision a future where educators collaborate in the sharing of PBL resources with their peers, thereby lowering the barriers to adoption. The toolkit described in this paper represents an initial step toward this goal.

The primary items that make up this toolkit include concept maps and learning hierarchy analysis, intersected with ideas of knowledge types, and dimensions of problem structuredness and complexity. The following sections treat each of these items on multiple levels: first, we offer a theoretical background on each of these components, demonstrating how they are grounded in theories of learning as well as ongoing research. Next, we advance guidelines for employing each item into the design and facilitation of PBL experiences. Here, we aim to provide practical advice for incorporating these items into curriculum design and instruction based on our research team's pedagogical experiences, review of literature, and our research deliberations. Our discussion on the items included in our toolkit then showcases explorations conducted by our research team that have aimed to indeed operationalize these items into undergraduate PBL classrooms. Finally, we share examples of these specific items, which members of our research team have leveraged for use in designing PBL undergraduate engineering experiences.

Theoretical Foundations

Ongoing research is focused on operationalizing ideas from Jonassen's design theory of problem solving [1]. That work has led to reflective exploration of existing problem statements typically found in textbooks [5], [6] and problems created by one author for a PBL setting. That reflective exploration has been enabled by use of concept maps and hierarchical analysis, with a specific focus on systematically representing elements of the problem in terms of knowledge types and characteristics (structuredness and complexity). These four elements–concept maps, hierarchy analysis, knowledge types, and structuredness/complexity – form the theoretical foundations for this work. Each is discussed here.

Concept Mapping

A concept map provides a graphical, hierarchical representation of knowledge, with specific concepts represented as nodes and connections between nodes describing the relationships among concepts [7], [8]. 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 that occur in different parts of the map [7], [9]. Concept maps have been used in education to assess student understanding of specific concepts and as a tool for curricular planning [10], [11], [12]. We focus on the latter purpose.

Jonassen and Marra [13] advanced a theoretical perspective on concept mapping grounded in a constructivist framework. We offer three salient items from this perspective that aim to support educators' creation of concept maps as tools for curriculum design and reflection. Concept mapping functions from a constructivist perspective in that engaging in this activity presents its creator(s) with the task of internally negotiating their own knowledge and understanding about a particular topic or domain [13]. As a result of this negotiating process, they argue that creating an external representation of what is usually an implicit thinking process requires one to *commit* to a specific representation of one's knowledge—internal dilemmas might be left unresolved in the mind, but an external representation requires one to take a position. Concept maps are not truly knowledge externalized, but rather representations of this knowledge [13]. This claim reveals the potential limitations in creating these artifacts as there might be room for representing this knowledge in multiple ways. Finally, a concept map might never be completely finished [13]: as educators find themselves incorporating new information into their existing knowledge bases, or discovering aspects of a PBL problem that weren't included in an initial concept map, a concept map artifact might never truly reach what its creator(s) might consider to be a finalized state.

Keeping these ideas in mind, instructors might acknowledge both struggles and advantages that might result from developing concept maps as a part of their curriculum materials. First, in regards to internally negotiating one's knowledge of a particular problem, engaging in this activity might simply prove difficult for newcomers and experienced problem designers alike [13]. Our other two points involving knowledge representation and finality above might serve to support those who share work with fellow PBL researchers and educators. We envision a community of practice whose members, including both educators and researchers, share concept maps and other PBL materials. In this way, we make note of the likelihood that in scenarios where multiple educators individually develop concept maps for a single problem, their form and content might differ as there are almost always multiple interpretations of and approaches to solving an engineering problem. Such differences might encourage dialogue around problem design and facilitation in future PBL research communities.

Finally, given that concept maps seldom reach a finalized form due to their constructivist nature, we draw attention to the iterative forms these concept maps might take in practice. In this way, we embrace the reality that concept maps might undergo slight or major revisions once educators implement a PBL problem into a course. For example, an educator might have outlined the conceptual knowledge required to solve a problem while designing the problem, but after implementing the problem into a course, the instructor might realize upon reflection that students had required some degree of conceptual knowledge which wasn't included in the initial concept map. We encourage educators to continually revise concept maps and take the viewpoint that these tools are constant works-in-progress. We feel that this point especially applies to situations where educators share their maps with peers who wish to implement the same problem into their own course. Our current work involving concept maps created for problem design emphasizes the practice as reflective and communal in character. By characterizing concept mapping in these ways, we underscore the tool's utility based on its sequencing within the overall learning design process (in supporting both problem design and instructor reflection), and its practicality as an artifact for circulating among members of a PBL research and education community.

Knowledge types

When designing a PBL activity, educators might find it helpful to consider the knowledge required to solve a problem. We consider the likelihood that due to the complex character typical of PBL problems, learners' diverse educational experiences will mediate their ability to solve a problem. We include the knowledge required to solve a problem, distinguished by four types, in our concept mapping tool as a means for educators to identify this knowledge to intentionally respond to knowledge gaps they might encounter during problem facilitation. In turn, we also consider this exercise as useful for reflecting on a problem after it has been implemented into a classroom. The following section defines these knowledge types and provides our rationale for attending to these four types specifically.

Knowledge types include *conceptual, structural, procedural,* and *domain knowledge*. These forms of knowledge have multiple definitions and relationships to each other in the literature (e.g., [14], [15], [16], [17]). 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 further definitions that align with Jonassen [1] to support consistency in our discussions. As we have documented previously [5], [6]:

- *Conceptual knowledge*: 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*: knowledge of the interrelationships among concepts within a specific domain [1]. We consider structural knowledge to take form in quantitative relations, like equations, and qualitative descriptions of interactions among conceptual knowledge. In engineering classrooms, structural knowledge is often operationalized to produce problem deliverables (solution outputs), which may explain why structural knowledge is an important indicator of problem-solving success [1].
- *Procedural knowledge*: 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), analysis methods (e.g., statistical tests), or applying rules to resolve an issue (e.g., following procedures to resolve an issue as in troubleshooting) [17].
- *Domain knowledge*: knowledge of a particular field [15], which reflects familiarity and experience [1]. 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 support formation of simplifying assumptions and/or assessments of the validity/reasonableness of a solution.

Though other knowledge types have been described in the literature, we focus on these four to stay close to Jonassen [1], whose work is frequently cited in engineering problem solving contexts and whose notional theory grounds our ongoing research. Problem solving ability varies along multiple dimensions, and in identifying these dimensions, an individual's ability to solve a problem can be determined, in part, by considering an individual learner's standing relative to these types of knowledge [1]. Whereas some learners might possess the prerequisite knowledge required to solve a problem, others might need information scaffolded into facilitation activities. This might happen through discourse, or any other modality as decided by the instructor. In considering this viewpoint, our goal in including knowledge type work concerns the instructor's facilitation of a problem: we contend that identifying the knowledge required to solve a problem prepares educators to readily respond to students' knowledge gaps on both an individual and group level.

Learning hierarchy analysis

To visualize the skills and knowledge that students need when engaging a problem, we employ the use of a learning hierarchy analysis. The concept of the learning hierarchy was first developed by Robert Gagné who investigated how an individual could successfully perform a task if they were only provided with instructions, and specifically what capabilities that individual would need to have to complete the task [18]. This work established that when an individual is able to perform a prerequisite lower-level hierarchical task, they are more likely to then be able to perform a related higher-level task. Gagné also states that a learning hierarchy represents the expected way a learner will navigate through the problem as opposed to the most efficient way. Additionally, the intellectual skills the learner uses in the lower-level tasks allows for positive transfer to occur so progression to the higher-level tasks can be completed [19].

The objective of a learning hierarchy is to identify prerequisite skills or knowledge needed in order to achieve the final learning outcome [20]. A learning hierarchy can be a useful tool in specifying the intended delivery of instruction and flow of knowledge that students follow throughout the problem. Additionally, it provides insight into the lower-level prerequisite knowledge and skills that students should have prior to beginning the problem. Multiple studies examine the effects of implementing a learning hierarchy into different types of classrooms. Yasak and Alias used a learning task analysis in the context of a technical and vocational education and training program to demonstrate the different skills that a task requires [21]. They assert that instructors benefit from viewing the hierarchical relationships of these skills since they can assess where and when training may need to occur so students can be successful [21]. Additionally, implementation of a learning hierarchy in an 8th grade female classroom found that it was effective in improving both the cognitive and metacognitive skills of the students [22]. Other studies have shown that using learning hierarchies inform both teachers and students of present learning barriers and provides a way for student learning achievement to be evaluated [23].

Learning hierarchy analysis may be helpful in predicting and foregrounding "threshold concepts" [24]. Threshold concepts are "akin to a portal, opening up a new and previously inaccessible way of thinking about something." We see potential for hierarchy analysis to identify 'troublesome knowledge' -- threshold concepts become troublesome for students when the knowledge is ritual, inert, conceptually difficult, alien, tacit, or contains troublesome language [24], [25]. Taking troublesome knowledge into account is vital when designing problems of appropriate difficulty and considering appropriate forms of facilitation that support students in overcoming difficulties encountered in problems [26].

Upon survey of others' uses of learning hierarchies and the idea of threshold concepts, we believe the use of a learning hierarchy has the potential to be a valuable tool for instructors in understanding pre-requisites for different stages of a problem and how success can ultimately be achieved. Through learning hierarchy analysis, the instructor may gain insights that inform the curation of relevant content to support student learning as they engage the problem. Further, learning hierarchy supports identification of necessary pre-requisites and where they will be engaging with ill-structured and complex problem elements. We believe the addition of the learning hierarchy analysis to our methodological toolkit has potential value in demonstrating how ill-structuredness and complexity are not only represented in problems, but also how they might be resolved.

Structuredness and complexity

Jonassen described four characteristics by which problems vary, including structuredness and complexity [1], [27]. Well-structured problems, like those typically encountered by engineering students [28], provide all the necessary information in the problem representation, and often require a limited set of prescribed rules to generate a single correct 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. Structuredness of a problem can be considered in terms of "transparency, stability, and predictability" [29]. Complexity considers the number of problem elements, their interactions, and the functional relationships among elements [1]. 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. Complexity can include the breadth of the problem as well [29].

From these descriptions specific features of each characteristic and how they might be represented and operationalized in the development of PBL should be considered. Such consideration might support both the (re)design of problems to vary the structuredness and complexity intentionally [5], [6], while also supporting consideration of how ill-structuredness and complexity can be resolved as part of meaningful problem engagement. It is this latter issue that is particularly in focus in this manuscript. In the context of designing PBL experiences, we note that intentional consideration of the salient aspects of a problem linked to structuredness, and complexity may be difficult to wrestle with during problem development. While many researchers describe the importance and difficulty of problem development and provide methods to support that development [30], [31], there is an apparent dearth of research on how dimensions of structuredness and complexity might be operationalized. Further, there is evidence to suggest that differentiating problem difficulty through complexity and structuredness dimensions may not be feasible or reliable [32].

Thus, reflective methods that support holistic evaluation and discussion of problem complexity and structuredness may be more fruitful. In our experience, realizing how ill-structure and complexity might be resolved requires a careful reflection on the problem. As alluded to previously, such reflection can be supported by hierarchy analysis.

Theory as Methods

The previous section provides the theoretical background on each of the items in our methodological toolkit. In the present section, we provide guidelines for constructing concept maps and learning hierarchies representing specific problems. Some of the recommendations offered in this section are speculative, offering what we consider useful tips for instructors, while others reflect ideas that have emerged from studies in progress by our research team.

Guidelines for constructing concept maps

During the design of a concept map, an educator is tasked with representing the problem statement in a standard format and the specific forms of the various knowledge types required to engage the problem. We have detailed guidelines for constructing concept maps elsewhere [5], [6], but cover the basic ideas here.

The concept map, with its topmost row of items under the initial question, "how do I solve problem x?" (see Figure 1), prompts the designer to consider and produce the items involved in solving the problem. On the left side of the concept map, "diagram" and "problem statement" represent the context and information content of the problem. Additionally, the "problem statement" specifies what artifacts students will be tasked with producing ("deliverables") which one might consider as an output of engaging the problem. This section tasks the designer with the actual problem that is responded to in the deliverable as well as the information students will produce that the designer considers a valid response to this problem. On the right side of the concept map, the knowledge required to solve a problem, distinguished by the four types described earlier, constitutes the final four items in this topmost row. Here, an educator must specifically think through the domain, conceptual, structural, and procedural knowledge required to solve the problem.

Educators might find it valuable to engage in concept mapping in an iterative manner. We envision that once an educator designs a problem, generating a concept map will help reveal the variety of components involved in a problem on both tangible (i.e., deliverables) and cognitive (i.e., knowledge distinguished by types) dimensions. In turn, this tool importantly provides the instructor with invaluable information that might be useful during problem facilitation, which we discuss later. As a final stage in this iterative process, we envision concept mapping might support reflective activities after a problem has been implemented into the PBL classroom. Iterative is the character of many educators' instructional approaches, and oftentimes one's reflection of a particular teaching experience prompts subsequent iteration on one's teaching materials. In the case of concept mapping, we view the tool as being useful for situations where an educator might wish to revise items that were a part of their initial concept map. Ultimately, the concept map offers a systematic way to make explicit problem components that might otherwise be opaque, and engaging in this activity in an iterative manner can help educators grapple with implementing PBL into the engineering classroom.

Guidelines for constructing a learning hierarchy

Construction of a learning hierarchy follows the nine-step process described in [20] resulting in a diagram like Figure 2. Starting from the highest-level task (reflecting higher-level learning outcomes), hierarchy construction works backwards, identifying each prerequisite task (learning outcome) until the lowest level task is reached. By beginning at the intended outcome, the instructor can identify the skills or information their students will need to successfully meet the learning outcome.

Additionally, we incorporated Bloom's Taxonomy [33] in the development of descriptions for each task represented in the learning hierarchy. As each task relates to a specific learning outcome in the problem, the corresponding action verbs were selected for each task after identifying the most appropriate level of Bloom's Taxonomy.

The learning hierarchy represents the way in which an expert *might* progress through solving the problem and can thus provide insight into areas where student understanding may need to be further enhanced before moving forward. We stress the provisional character of learning hierarchies here: because of the complexity inherent in PBL problems, it is likely that learners will diverge from the path the problem designer originally envisioned as mapped out in the learning hierarchy. Drawing on our experience and initial outcomes from a research study in progress, we have observed that the implementation of a learning hierarchy can assist in the visualization of ill-structured and complex problem elements in addition to the prerequisite skills students need so they are able to navigate these more challenging aspects of the problem. That is, the hierarchy analysis provides a reflective tool for answering the questions: 1) What makes this problem complex and how is that complexity resolved? and 2) What makes this problem ill-structured and how is that ill-structuredness resolved? With learning hierarchies, we envision educators might engage in reflective, iterative, and community-sharing activities similar to those described in terms of concept mapping. Ultimately, learning hierarchies have the potential to both support educators' design of a problem and encourage student understanding of a problem.

Representative Examples

In this section, two representative examples from two different faculty teaching different courses at different institutions are presented. Both are authors and have been directly involved in this research, with varying levels of experience using these methods. Alongside the concept map and hierarchy analysis artifacts, brief descriptions from those faculty are provided, with a focus on ideas or observations that stemmed from the creation and discussion of these artifacts.

Intro to aerospace engineering – Parachute selection problem

The concept map for a parachute selection problem (Appendix I) is shown in Figure 1. This problem is designed for second-year aerospace engineering students, which students work on over a three-week period. The problem statement provides information about the rocket's apogee altitude, information about the drogue parachute used to slow the rocket for payload deployment, the altitude of the payload deployment, and the payload's weight. Students are also provided with requirements specifying maximum kinetic energy at landing, maximum recovery area, and maximum descent time. These requirements come from the NASA Student Launch Competition from which this problem was derived. Students are tasked with selecting a parachute for the payload that meet these requirements and were given the name of a common supplier used by other student teams.

Students are expected to either already have the *conceptual knowledge* (e.g., basic understanding of forces like drag acting on the payload as it descends) or to acquire conceptual knowledge (e.g., parachute attributes) from engagement with the problem. They are not explicitly taught about these concepts. *Domain knowledge* for this problem is related to performance attributes of available parachutes (e.g., coefficient of drag, weight, packing volume) and specifying selection criteria and their individual importance when framing the decision problem. Domain knowledge for each parachute is acquired through review of the parachute supplier options. Domain knowledge related to selection criteria and weights is developed through group discussions with the instructor and deliberation with teammates that incorporates their preferences and values within the context of the problem requirements.

Students' *structural knowledge* is developed through problem engagement as well, where they are responsible for identifying and/or developing equations of motion for different phases of flight (projectile motion, decelerating flight, flight at terminal velocity). This requires that they leverage their conceptual knowledge of force interactions acting on the payload at various times. Though this problem is situated in an aerospace engineering, all but one aspect of *procedural knowledge* focus on the act of making a decision (a selection). Because most engineering students have not been introduced to formal methods for decision-making, this was a topic for explicit instruction by the instructor during the class.

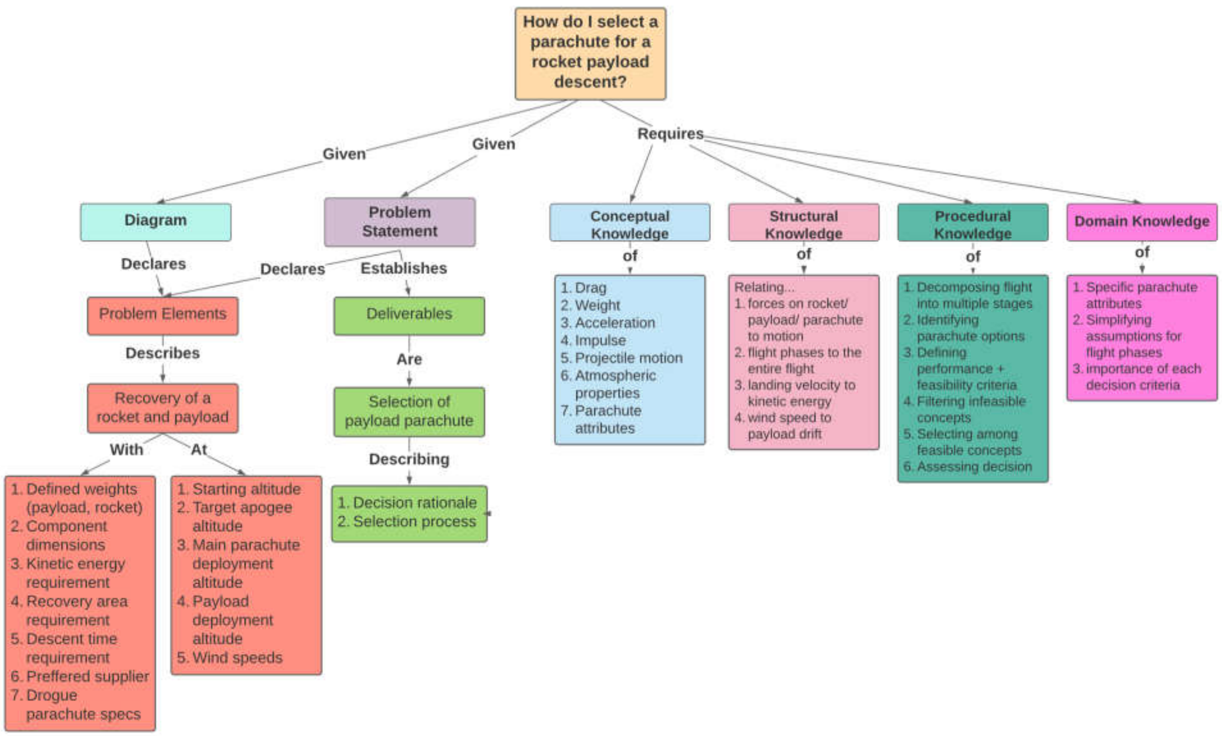

Figure 1. Concept map for parachute selection problem (Appendix I)

The learning hierarchy developed by the instructor is shown in Figure 2. The dual-nature of this problem reflecting two problem types [1] – engineering (case) analysis and selection – is captured in the learning hierarchy. Navigating the lower-right side of the hierarchy shows where students leverage their conceptual and structural knowledge to formulate and conduct their analyses. Navigating the lower-left side of the hierarchy shows where students leverage their procedural and domain knowledge in identifying the assessment criteria, goals and constraints, and the priority of their goals. These two branches are then combined such that the parachute options can be ranked, and the best option can be selected.

We draw attention to the blue and orange highlighted boxes, associated with ill-structuredness and complexity, respectively. Lack of structure in the problem reflects key elements necessary to frame the problem. In this case, students have agency over what parachute options to consider, which performance measures to treat as goals (e.g., minimize descent time) and which to treat as constraints (e.g., do not exceed maximum kinetic energy), and the individual importance of those goals. Thus, students must develop their own subjective framing of the selection problem to resolve the ill-structuredness of the problem.

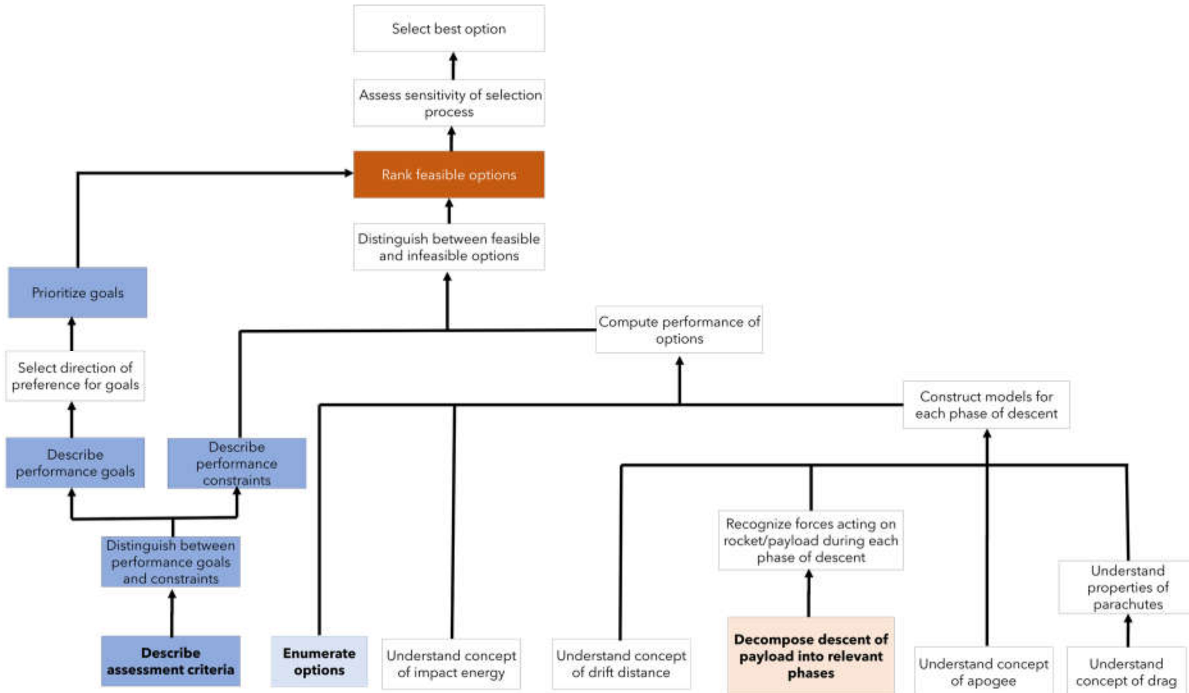

Figure 2. Learning hierarchy for parachute selection problem (Appendix I)

Complexity is reflected in two problem elements, modeling the descent of payload and ranking of the feasible options. To resolve complexity in modeling payload descent, there is a need to first decompose that descent into multiple phases and identify/develop a model appropriate for each phase. This is followed by synthesizing models for each phase of descent to predict the performance of individual parachute options.

Resolving complexity related to feasible options requires that problem solvers bring together results from performance models and their framing of the selection problem such that a final decision can be made. A ranking system must be implemented, which could be as an involved as a voting procedure with group deliberation or a more prescriptive multi-attribute utility calculation [34].

Machine design – Bicycle crank assembly problem

Figure 3 shows the concept map generated for a bicycle crank system redesign problem (Appendix II). This problem occurs in a third-year machine design course. As this map suggests, students must utilize the new, *domain knowledge* they are acquiring in the Machine Design course (such as how to evaluate and consider the design of shafts, bearings, and gears) while leveraging *conceptual knowledge* acquired in previous courses (e.g., manufacturing processes) to solve the problem. Acquisition of this domain knowledge is achieved through explicit instruction from the instructor.

Using this foundational knowledge, students are expected to develop and apply various *procedural knowledge* (e.g., explore design modifications) facilitated by the instructor. Acquisition of this knowledge is enabled by engagement with the problem, rather than through explicit and directed instruction. Further, students are challenged to grow their structural knowledge by performing related analyses and finding necessary connections between their domain and conceptual knowledge to redesign the crank system and meet the weight reduction goal.

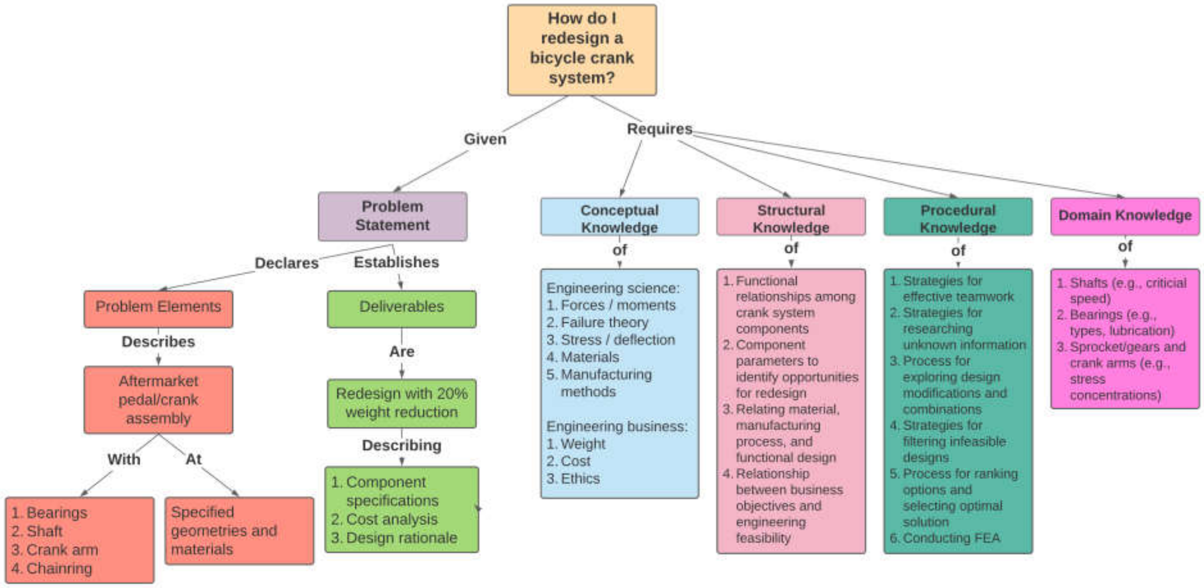

Figure 3. Concept map for bicycle crank assembly problem (Appendix II)

As shown in the learning hierarchy of Figure 4, students should begin their work on this problem by considering and ensuring they understand how the mechanical system works at a fundamental level. Once this is understood, they can begin to break down the system for more detailed consideration at a component level. Like the previous problem, issues related to ill-structuredness are in blue boxes, and complexity in orange.

For example, ill-structuredness is reflected in the need to understand how forces from riding a bicycle are transferred to the pedal-crank assembly. Additionally, how each component is redesigned to meet the system weight reduction target is at the discretion of the problem solver, fostering application and development of conceptual and domain knowledge to resolve the ill-structuredness. The integration of ethics is also an ill-structured aspect of the problem, especially since meeting the 20% weight reduction is a stretch goal, which the instructor is aware of but the students are not. In resolving ill-structured aspects present and emergent in the problem, students necessarily participate in actions that constitute problem framing.

Like the previous problem, resolving complexity is reflected in actions of decomposing the pedal-crank system into individual components that can be analyzed as part of the redesign process. Eventually, complexity is further resolved in synthesizing changes to individual components to understand the impact at the system level. Procedural and structural knowledge are necessarily developed and engaged to resolve these elements of complexity.

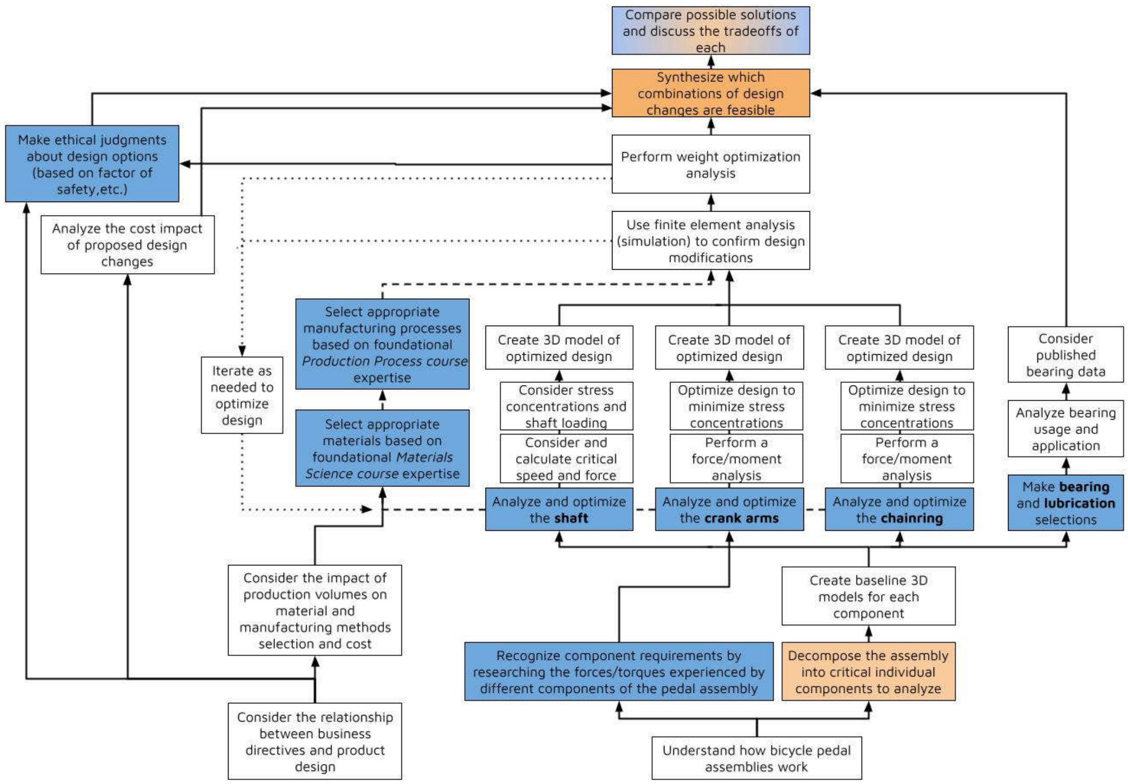

Figure 4. Learning hierarchy for bicycle crank assembly problem (Appendix II)

Discussion and conclusion

This paper introduced a methodological toolkit aimed to address challenges associated with designing and facilitating PBL. By integrating problem characteristics, knowledge types, and guidelines for reflection, the toolkit aims to support educators in creating more effective and engaging PBL environments. We envision a collaborative future where educators share their toolkit-derived resources, experiences, and reflections in a community dedicated to integrating PBL into engineering education.

Using these tools as part of our research has helped us to make explicit and foreground the types of knowledge relevant to a problem, as well as the ways in which characteristics of complexity and ill-structuredness are made salient and resolvable. This has enabled meaningful insights may help us in discovering common and uncommon forms of these characteristics. For instance, as observed in the representative examples, complexity is linked to decomposing and (re-)synthesizing across interfaces. This concept is analogous to work in complex systems engineering, where working across interfaces is an important strategy and requires a good understanding of structural knowledge. Similarly, both problems help to explicate specific ways in which problem solvers also participate in problem framing to resolve ill-structuredness. Continuing to explore problems with others to identify strategies for the resolution of complexity and ill-structuredness is an area for continued work that may inform PBL facilitation.

With concept maps and learning hierarchies, identifying the knowledge, tasks, and deliverables involved in problem engagement enables educators to effectively think through how these items might be handled during facilitation. For example, consider a concept map that identifies both knowledge students have covered in a previous course, as well as knowledge that is completely new to students, yet instrumental in engaging a problem. The educator in this situation might plan facilitation activities that shift focus away from previously covered knowledge in order to make room to introduce this new content. Depending on the scope of this content, the educator might decide to didactically cover new material, introduce supplementary materials (such as textbooks or internet resources), or devise novel strategies for scaffolding content into the facilitation phase. These considerations might in turn be further informed by the learning hierarchy analysis which importantly reveals the structuredness and complexity dimensions of a problem. In this way, an educator might create a plan to resolve ill-structuredness and complexity of a problem through facilitation to a level he or she sees fit in terms of where the problem is sequenced within the course. The concept map and learning hierarchy are intended to support this process.

We feel that our toolkit presents a few opportunities for future exploration. First, we hope this toolkit offers a starting point for thinking about assessment in PBL learning environments. Specifically, the learning hierarchy reveals items that problem designers might view as instrumental in terms of assessing student performance. Potentially, an educator might consider each of these items an individual learning outcome, and in this way the learning hierarchy might be leveraged as a tool to connect map the tasks required to solve a problem with an instrument to assess how successfully students attended to these tasks. We plan to explore this potential use for the learning hierarchy in future work.

Another related opportunity for further study is to explore the amount of time it might take to implement this toolkit into problem design and reflection. As a result, we hope to explore how educators might feasibly utilize this toolkit given the constraints of designing a problem amidst busy schedules. Designing problems in PBL is both time- and labor-intensive; we hope that the pedagogical insights this toolkit can provide justifies the work and time involved in using it.

The ultimate goal of this work is to make PBL a more accessible and attractive educational approach for engineering educators. By lowering the barriers to entry and encouraging a culture of collaboration and sharing among educators, our team believes this toolkit has the potential to significantly impact the way PBL is perceived and utilized. We hope this shift towards a more communal and reflective practice in PBL design and implementation will lead to more dynamic, engaging, and effective learning environments that are better suited to meet the challenges of 21st-century education.

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Appendix I: Intro to Aerospace Engineering – Parachute Problem Statement

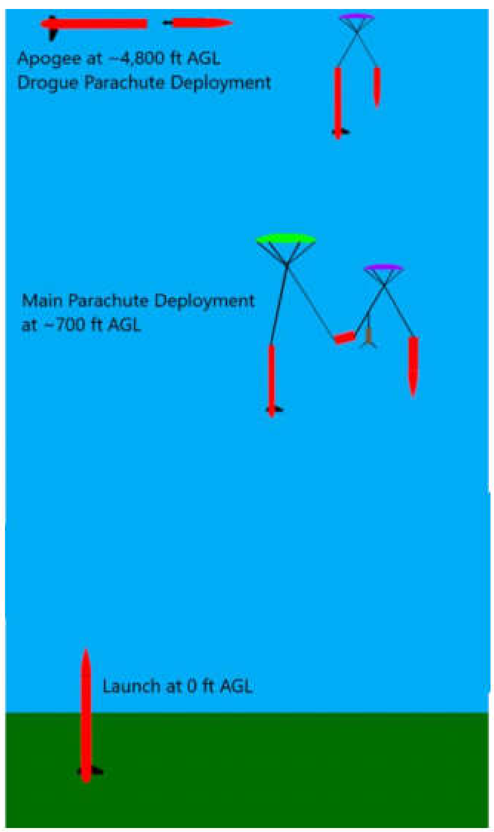
Your analysis on rocket motor engines helped the group ascertain that the engine they selected (F15-6) would not help the design reach the required apogee altitude. Changes were made to the rocket body and a different engine was subsequently chosen. During the sub-scale launch test, the group was able to reach the desired target altitude.

Work has continued on making the full-scale launch vehicle for competition. This rocket will carry a 9 lb payload to a target apogee of 4800 ft. The current design of the payload is 22 inches in length. It must be placed within the Upper Payload Bay which is currently designed to be 24 inches in length. The weight of the rocket at launch is approximately 48.5 lbs. It takes the rocket approximately 19 seconds to reach apogee.

At apogee, the rocket will be at 43.1 lbs. Pyrotechnic charges are then detonated to separate the components of the rocket body and allow the deployment of a drogue parachute. The team typically purchases their parachutes from Fruity Chutes (https://fruitychutes.com/). The Recovery Lead has already specified that an 18-inch Classic Elliptical parachute will be the drogue chute. Information on this parachute is here:

https://shop.fruitychutes.com/collections/classic-elliptical-12-to-60/products/18-elliptical-parachute-1-2-lb-20fps

At 700 feet above ground level (AGL), the forward pyrotechnic charge is triggered and the nosecone and payload bay are separated. This separation allows for the deployment of the main parachute and the deployment of the payload. This is shown in the following figure:



The payload immediately detaches from the main parachute harness and begins to free-fall. The payload will descent under a furled parachute in a Nomex deployment bag and is kept secured by a Jolly Logic Chute Release device (consisting of an altimeter and a latch). This device wraps around the furled parachute and deployment bag with an elastic band. At 300 ft above ground level, the Jolly Logic device will unlatch, allowing the parachute to unfurl. The payload continues to the ground and upon landing the payload parachute will be jettisoned.

Once on the ground, the team will send commands to the payload that control a camera. Multiple pictures will be taken and those images are then sent back to the team at the launch site.

Your task is selecting the parachute that will be used to control the descent of the payload. In documenting your choice, you must also explain the rationale and selection process used.

The following requirements from the NASA Student Launch Competition Handbook may influence aspects of your decision:

- Each independent section of the launch vehicle will have a maximum kinetic energy of 75 ft-lbf at landing.
- The recovery area will be limited to a 2,500 ft. radius from the launch pads.
- Descent time of the launch vehicle will be limited to 90 seconds (apogee to touch down).

They also require that teams calculate the drift for each section of the launch vehicle from the launch pad for five different cases: no wind, 5-mph wind, 10-mph wind, 15-mph wind, and 20-mph wind. The drift calculations should be performed with the assumption that apogee is reached directly above the launch pad.

__**Problem timeline and deliverables**__

- Multi lecture problem #2 pre-class reflection (due before class on 10/7)

- Checkpoint #1 (due by 11:55 pm eastern on 10/12)
  - One of your group members must submit a single PowerPoint deck to Moodle
  - This PowerPoint deck should include problem name and number, checkpoint number, date, names of students and an organized presentation of all artifacts (diagrams, sketches, models, calculations, etc.) that explain your solution process so far
  - Objective for this checkpoint: Describe the options that are available and evaluation criteria that you plan on using

- Checkpoint #2 (due by 11:55 pm eastern on 10/18)
  - One of your group members must submit a single PowerPoint deck to Moodle
  - Contents of the PowerPoint deck will build on your previous checkpoint submission
  - Objective for this checkpoint: Describe how you evaluate/score the options that you identified and conduct your evaluation

- Problem solution to Multi Lecture Problem #2 (due by 11:55 pm eastern on 10/25)
  - One of your group members must submit a single PowerPoint deck to Moodle
  - Contents of the PowerPoint deck will build on your previous checkpoint submission
  - Additional information to include is your final selection and an interpretation of your results
  - Also include a description of what each group member was responsible for

- Multi lecture problem #2 post-class reflection (due on 10/25)

Appendix II: Machine Design – Bicycle Crank Assembly Problem Statement

Note: This problem is used in a 3-credit Machine Design I course for third-year mechanical engineering students.
The course is taught with a PBL "hybrid" structure with content-specific lectures and activities half of the time and structured problem work the other half of the time. Within this structure, students were given approximately 1 month to solve the following problem (working in teams of three).

<u>Problem Statement:</u>
You are a mechanical design engineer tasked with optimizing an aftermarket pedal/crank assembly that is used to convert standard mechanical bicycles to bicycles with a gas-powered option. Basic details and dimensions of the major components in this assembly are included below (with respective pictures of those parts) for reference. The primary goal of this optimization is to reduce the overall weight of the assembly by 20%, but care should be taken to ensure that durability and efficiency are not compromised. This weight reduction is a non-negotiable from your management, as this optimized product is forecasted to be significant for the company's financial bottom line (with an estimated sales volume of 100,000 units).

Component Specifications and Requirements:

- **Bearings**: The pedal assembly should incorporate suitable bearings to reduce friction and ensure smooth rotation of the pedals. Select appropriate types of bearings, size, and determine their placement within the pedal assembly. Also, consider and select the appropriate lubrication for the bearing you select. (Note: The bearing selection will not have a significant impact on your weight optimization, so the focus here should be to select an appropriate bearing and lubrication strategy for this component.)
- **Shaft, Crank Arms, and Chainring**: Design the pedal axle shaft and crank arms to withstand forces exerted during pedaling. For the shaft specifically, consider the material, diameter, and length of the shaft, taking into account the mechanical properties, the load distribution, how connecting elements will be held in place, deflection, and critical speed. Ensure the chainring can withstand the torque it experiences to transfer motion from the pedal axle to the rear wheels.
- ***Material Selection:*** Consider the selection of materials for various components of the pedal assembly (e.g., crank arms, shafts, threaded fasteners) based on their mechanical properties, weight, cost-effectiveness, and compatibility with the bicycle's usage environment.
- ***Cost Analysis:*** Perform a basic cost analysis of the proposed design, considering the cost of each component (based on material and manufacturing cost) for both the original and proposed designs. While cost does not need to be reduced for this optimization, it should not increase. (Note: It is challenging to get accurate cost information for specific material and manufacturing processes since this is largely proprietary information, so feel free to consider this analysis from the perspective of anticipated cost increases/decreases from the initial design only).
- ***Ethics****:* Despite the fact that the company has a firm target for weight reduction and maintaining cost, it is your responsibility as an engineer to ensure that the product you make is safe for consumers. Please consider this in your analysis.

You will be given models for the original crank assembly components for reference. Your submission should include detailed drawings and specifications for a proposed, optimized pedal assembly along with a detailed rationale explaining your design choices (including but not limited to the categories requested above).