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# Characterizing Engineering Design Activities Using Jonassen's Design Theory of Problem Solving*

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This paper describes the development and implementation of a survey instrument, based on Jonassen's design theory of problem solving, which characterizes educational design activities. The motivation behind this work is to determine the effectiveness of authentic problem solving activities – called Engineering Design Days – implemented in the University of Waterloo's 14 engineering programs. The instrument is a guided survey given to instructors which captures an activity's problem variation and representation. The survey was developed through a number of iterations, with refinements addressing observed shortcomings in the collected data. Its application is demonstrated with a case study of one design activity that was offered to first year software engineering students. The survey captures many of the elements of Jonassen's design theory of problem solving as they pertain to educational design activities. Future work will focus on applying the instrument to additional educational design activities, which may inform future evolutions to the survey.

**Keywords:** instructional design; design; research to practice; problem solving

## 1. Introduction

Engineering educators routinely create new instructional activities, ranging from weekly problem sets to open-ended term-long design projects. What they may not realize is the full extent of decisions that they are implicitly making in this instructional design activity, everything from the way instructions are provided to students, to the size of teams, to the way deliverables are evaluated. Indeed, Atman et al. [1], observed exactly this phenomenon in a series of studies conducted in the mid-2000's. In interviews with engineering educators, they found that some struggled to identify specific examples of decisions made with respect to teaching. When justifying their decisions, resource constraints were given as a common rationale, however many stated that they based their decisions on the outcomes from prior, related decisions, with Atman et al. commenting: "this feature of their rationale reminds us of the historically situated character of teaching decisions [1, p. 98]". Clearly then, a tool that can help instructors recognize the broad range of possible decisions that are available when developing an activity may have a beneficial impact on teaching.

One example where a need to systematically catalogue a multitude of instructional decision points has emerged is in the development and improvement of Engineering Design Days ("Design Days") at the University of Waterloo. Design Days are curricular hackathon-like events where engineering students complete a design challenge over a period of two days [2]. In the last five years, offerings of Design Days have been developed, and implemented in each of the institution's 14 engineering programs. While the various Design Days all have the overarching goal of improving student problem solving and design skills, each is unique in the specifics of what it aims to achieve. Given the scope and diversity of the activities – a large number of Design Days activities varying significantly on many attributes – the development of a standard method for assessing them was not feasible. Instead, it became clear that a first step in this endeavor should be the development of a "common language" to characterize each activity along a common set of dimensions, detailing the decisions made by instructors in developing these activities. By making the available decisions explicit, instructors can identify possible choices when planning and improving design activities, with the goal of achieving the learning outcomes of their particular design activity. So how, then, can these decisions be characterized?

According to a useful framework by David Jonassen [3], student problem-solving outcomes are a function of both characteristics of the problem itself (its nature and how it is presented to the learner) and intrinsic attributes of the learner, from demographics, to experience, to cognitive characteristics. The focus of this work is on the former, which comprises aspects of the problem-solving situation that are in the purview of the instructor: problem variation and representation. This paper describes the operationalization of


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Jonassen's framework into a practical tool that can be used by instructors to identify various decision points involved in designing a design activity for students. The rest of the paper is organized as follows. After providing some background on Jonassen's typology, we then detail the process by which the framework was operationalized into a guided survey tool, which was used by 17 instructors to characterize 14 different Design Days (including two offerings of the same activity to different communities of students). This paper highlights one of these Design Day activities – the "spaceship activity", offered to Software Engineering students – to demonstrate the tool's application and usefulness. Finally, we conclude with a discussion of our next steps and future research directions that have emerged as a result of the development of this survey tool.

## 2. Background

In his paper *Toward a Design Theory of Problem Solving* [3] and book *Learning to Solve Problems* [4], David Jonassen presents a framework for characterizing problems in general – and design problems in particular. In his view, a problem-solving situation comprises the choice of problem (and its characteristics), how it is represented to the solver, and the pertinent characteristics of the problem-solver (see Fig. 1). A problem varies on a number of characteristics. These include structuredness (the degree to which the problem has elements that are unknown), complexity (the number of issues/variables in the problem and the nature of interactions between them), domain specificity (the degree to which cognitive strategies related to a discipline are required to solve the problem), and context [4]. A problem's representation is composed of the level of information provided to the problem solver and the fidelity of that representation, that is, what information is withheld or provided to the problem solver and how authentic the environment is. With these structural elements of the problem in mind, Jonassen [3] proposed a typology of problem types that range from logical problems at one end of the spectrum to design problems and dilemmas at the other extreme. While this paper will focus on design problems, it is worth remembering that "higher" (i.e., more ill-structured/complex) types of problems often require a solver to employ skills from the "lower" types (e.g., *design* problems often require the use of *diagnosis-solution*, *trouble-shooting*, and *decision-making* skills).

From the perspective of the solver, problem-solving skills are a function of domain and structural knowledge, familiarity with problem type, affect and conation, epistemological beliefs, and metacognition. The tool described in this paper will focus predominantly on the elements that are under the control of the instructor (nature of the problems assigned and how they are presented to the learner), but it is important to keep the characteristics of the problem-solver in mind. For example, the ability of the problem-solver to handle a problem's complexity depends on their familiarity with the problem type, among other things, familiarity counters complexity. Instructors also have control over a number of factors that can increase (or decrease) student motivation to solve a problem.

Jonassen's works have been extensively cited in the engineering education literature, with a number of publications applying his definition and characteristics of design problems to their own work. For example, Akinci-Ceylan et al. [5] use Jonassen's framework to include relevant aspects of ill-structured problems in a study assessing problem solving processes used by different groups including students, practicing engineers, and faculty members. In work similar to our own, Houdeshell [6] uses Jonassen's description of structuredness to create an instrument capable of providing a variety of stakeholders, including researchers, professors and instructional designers, the ability to quantify the level of structuredness present in their problems. Ramírez et al. [7] use Jonassen's problem solving taxonomy to develop three different problem-solving learning environments for an introductory food engineering course. The research focused on providing formative evaluation metrics for the course, and the three problems (troubleshooting/diagnosis, design, decision-making/strategic perfor-

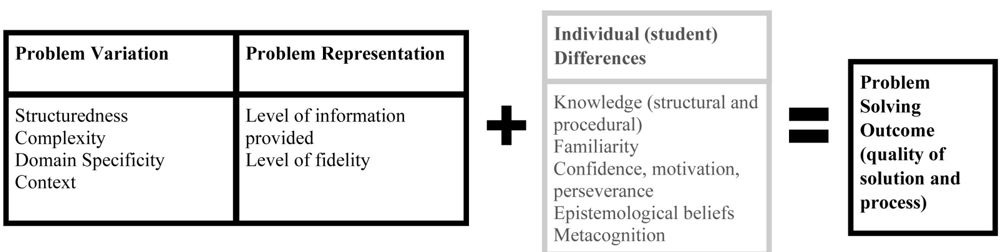


**Fig. 1.** Model of problem-solving adapted from Jonassen.

mance) were developed based on the characteristics described by Jonassen. More recently, Olewnik et al. [8] used Jonassen's problem solving typology to define what a good open-ended engineering problem looks like. Although the results focus solely on case analysis problems, the authors argue for increased development of problems with design characteristics (or other problem types), as exposure to these problem types might influence the metacognitive processes of problem solvers. The survey tool presented in this paper expands on these past efforts by attempting to capture all elements of problem variation and representation for design problems (as opposed to a single factor, like structuredness).

Other accounts of how problem-solving environments are structured and used in educational settings also exist. For example, Hung [9] explains that the differences between learning environments – which range from lecture-based problem-solving activities to pure problem-based learning (PBL) – are due to the amount of structure and self-directed learning present in the activity. In the case of lecture-based problem-solving activities there is more structure and instructor-led learning, while more ill-structured and self-directed learning is associated with pure PBL. In summary, while there are other frameworks that can describe differences in problem-solving environments, only Jonassen's framework seems to provide the necessary tools to capture differences between the different Design Days activities – all of which represent discipline-specific, open-ended, and ill-structured *design* problems.

## 3. Development of Survey Tool

The development of the tool was conducted over three phases. In the *first phase*, we conducted hour-long semi-structured interviews with four instructors that had previously developed and implemented Design Days activities. These interviews were guided by a series of questions that sought to understand various components of the activities including the problem itself, domain relevance, and characteristics of the students who participated [10]. The semi-structured nature of the interviews also allowed for other aspects of the problems to emerge, which had not been included in the prepared questions. Findings from these interviews formed the basis for creating the first iteration of a survey as a tool to characterize a Design Days activity. The aims of developing this survey were to reduce the effort of data collection for a large number (14) of additional Design Days, and to limit the subjectivity of that data collection and subsequent analysis. The survey questions were then further validated using a think-aloud protocol with a fifth Design Days instructor, resulting in further refinement to the instrument.

With some confidence in the survey tool's ability to capture key characteristics of a Design Days activity, the survey was distributed to 4 Design Days instructors from the fall 2019 semester, effectively beginning *phase two* of the development. An important refinement to the tool that occurred at this stage was the addition of questions to the survey about the number and source of success criteria, as well as how these success criteria were incentivized, to better capture problem structuredness. Further, a question related to the number of dimensions that exist aside from the technical elements (e.g., sustainability, costs, efficiency) was included in later offerings of the survey to capture an important aspect of problem complexity. These questions were added after a review of the survey instrument and its ability to capture elements of Jonassen's theory.

The survey was further evaluated in *phase three.* In computer-assisted interviews the facilitators (typically 1–2 members of the research team) guided study participants (Design Days instructors) in answering the survey questions. At the conclusion of the survey, instructors were prompted to think about how completing the survey might influence the refinement and/or creation of future Design Days activities. Interviews were recorded and transcribed. This phase of the study served both as a qualitative evaluation of the survey and as an opportunity for instructors to participate in a guided reflection of their process designing instructional engineering design activities. The computer-assisted interviews allowed the research team to understand how instructors interacted with and felt about the survey, as well as ensured that a response was recorded for each Design Days activity.

## 4. Case Study

In order to demonstrate the application and usefulness of the survey instrument, we present a case study of one Design Days activity – the Software Engineering (SE) activity, described in detail in [11]. This activity was chosen because it was one of only two activities with a response from more than one instructor related to the activity. In the activity, first year software engineering students worked in large teams of 16 (divided into four smaller sub-teams of 4 students each) to program the simulation of an autonomous spaceship capable of navigating three progressively more difficult sections of interstellar space developed in a real-time video game engine. The purpose of the activity is to help students learn about teamwork, use software version control as they iterate during the design process, and practice prototyping and testing. Students need to prioritize design goals, as the task is too large and complex to be completed in the time given.

The survey tool was administered to two instructors involved in the SE activity's conception and facilitation. The following sections describe the questions in each of the problem variation and representation sub-categories and our interpretation of the instructors' responses to those questions.

### 4.1 Problem Variation

As introduced in section 2, Jonassen [3] describes problem variation as a function of structuredness, complexity, domain specificity, and context.

#### 4.1.1 Structuredness

An ill-structured engineering problem is described as having "*conflicting goals, multiple solution methods, non-engineering success standards and constraints, unanticipated problems, collaborative activity streams, and multiple forms of problem representation* [4, p. 7]. Table 1 presents the four questions used to assess the structuredness of the activity, the breakdown of the instructor responses, and our interpretation of the results. These questions capture much of Jonassen's definition of an ill-structured problem, with some notable omissions: the presence of non-engineering success standards was included with complexity (presented in Section 4.1.2), and the presence of multiple forms of problem representation was left out because existing Design Days activities are predominantly for first year students, and so have relatively simple problem representations.

Both instructors agreed that the problem had more than one solution; for example, students could implement complex algorithms to improve their spaceship's effectiveness and speed.

Success criteria can be defined as the metrics used to evaluate student design process and/or products; these metrics are usually provided in the instructions – though some Design Days activities provide no success criteria for the design task. The SE instructors indicated that the performance of the final product was not measured as a success criterion, in part because most groups would be unable to produce a fully functional autonomous ship. Instead, student success in the activity was evaluated by examining the approach each student took, specifically, the amount each team member contributed to the code for the spaceship and their level of interaction with the version control software (Git) used in the activity. In addition, open and ambiguous success criteria (e.g., create something *useful* for the client) make the activity more ill-structured.

Although it was possible for students to create their own success criteria for this activity, responses about this element of structuredness were not consistent among the two instructors, as one indicated that the students did create their own success criteria, while the other did not. This might mean there is a potential problem with the way the survey question is phrased, or possibly the instructors "sampled" different teams of students when making their observations (there were 125 students participating). This will need to be investigated more moving forwards.

#### 4.1.2 Complexity

Complexity is defined by the number of functions or variables that are involved in the problem as well as the connectivity between them. This includes the relationship two components of a problem have to one another, and how stable that connection is over time. More complex problems, like *design* problems, typically take place in a more dynamic environment. In the case of Design Day activities, these components are related to the tools and materials that are available to students, the number of dimensions involved and how much prior knowledge is required to solve the problem. Stability of relationships over time was omitted from our survey due to the short duration of the activities under study (2 days long). Table 2 presents the SE instructors' responses to questions related to the complexity of the problem and our interpretation of those responses.

Instructors indicated that students were using many tools that were very unfamiliar to them, including programming languages and version control software. In addition, the activity had multiple

**Table 1.** Structuredness of the SE activity

| Question | Instructor (I) responses | Researchers' comments |
|---|---|---|
| Did the problem have more than one solution? | I1: Yes<br>I2: Yes | The problem has more than one solution |
| What success criteria were given to students in the instructions?<br>How are success criteria defined? | I1: Participation, process<br>I2: Participation, process | Success criteria are open and ambiguous. They have few to no conflicting criteria. |
| Did students create their own success criteria? | I1: Yes<br>I2: No | Disagreement about whether students created their own criteria |

**Table 2.** Complexity of the SE activity

| Question | Instructor (I) responses | Researchers' comments |
|---|---|---|
| How familiar would the average student be with the tools/materials they are required to use in the activity? | I1: Not familiar at all<br>I2: Not familiar at all | Students were not familiar at all with the materials |
| Are there multiple dimensions to the problem aside from the technical ones? | I1: Yes<br>I2: Yes | There was a significant social element related to the problem |
| Do students need to use knowledge/skills from other concurrent courses? If so, how many? | I1: Yes, one<br>I2: No | Disagreement over the amount of knowledge from concurrent courses |
| Do students need to use knowledge/skills from prior courses? | I1: Yes<br>I2: Yes | Students required knowledge from prior courses |

dimensions in addition to the technical one, including a social element, may have required students to use knowledge from one of their concurrent courses, and relied on students' prior programming experience from high school, which is required for admission to the software engineering program at the University of Waterloo. Complexity appears to be captured well by our survey; future work will focus on validating these questions once additional data have been collected.

### *4.1.3 Domain Specificity*

Problem solving activities are situated and are therefore dependent on the nature of the context or domain [3]. When an activity can be solved by students in other disciplines, it indicates that the knowledge from that domain is not a requirement for successful completion of the activity. Instructors can select a problem that is so entrenched in a domain, that only those students who have knowledge from that context would be able to create a solution. Our survey measures domain specificity by asking instructors three questions about students in other disciplines, effectively assessing whether students in disciplines progressively further from software engineering can solve the problem, as presented in Table 3.

The instructor responses indicate that this activity utilized a highly domain specific problem. This was likely due to the high computer programming effort it required. It should be noted that domain specificity decisions like these ones are likely influenced by when the activity takes place in the curriculum. For example, an activity that takes place during the first day of classes, where students have little formal training in the domain will look quite different from an activity designed for third year students who are much more familiar with domain concepts and methods. The SE activity is somewhat anomalous among other Design Days activities studied, most of which are delivered to first year students, in that it is highly domain specific even though it occurs very early in the program (in the first semester of first year) because students are required to have taken a programming course before they are admitted to the program. These questions present some issues for activities which take place very early in students' university careers, as instructors tended to focus on the fact that students have not learned much university-level knowledge, and so concluded the activity was not domain specific. Moving forwards, these questions may need to be adjusted to address this concern.

### *4.1.4 Context*

According to Jonassen, "*context affects the nature of the social interactions as well as cognitive processing*" [4, pg. 11]. Adapting this sub-category to the survey proved challenging, and it certainly overlaps with the sub-category of domain specificity; however, two questions were included in the survey to capture additional detail on problem context: how representative is the problem of real engineering practice in the domain, and whether there were any external partners involved in the activity (e.g., industry clients), as shown in Table 4. The two instructors' responses indicated that the problem was very realistic to what students might expect to see in industry but there were no external partners in the activity. This sub-category may need to be revisited as the researchers' understanding of this

**Table 3.** Domain specificity of the SE activity

| Question | Instructor (I) responses | Researchers' comments |
|---|---|---|
| What percentage of students in another **engineering** discipline could successfully solve the problem? | I1: 20%<br>I2: 50% | Two factors may explain the large difference in how the first question was answered: how the instructors perceive the activity, and how the instructors perceive the capabilities of students in other engineering disciplines. |
| What percentage of students in another **STEM** discipline could successfully solve the problem? | I1: 3%<br>I2: 10 % | |
| What percentage of students in a **non-STEM** (arts/humanities) discipline could successfully solve the problem? | I1: 0%<br>I2: 0% | |

**Table 4.** Context of the SE activity

| Question | Instructor (I) responses | Researchers' comments |
|---|---|---|
| Compared to a problem students at this level could expect to see in industry (for example, on co-op) how realistic is your problem? | I1: Very realistic<br>I2: Very realistic | The problem is very realistic |
| Were there any external partners involved in the activity? | I1: No<br>I2: No | There were no external partners involved |

component of problem variation improves with additional study.

*4.2 Problem Representation*

Jonassen [3] describes problem representation as the decisions that are made by the instructional designer with regards to how the problem is *presented* to problem solvers. Problem representation is related to the particular contexts in which the problem is embedded, and the constraints imposed by the context [4, pg. 146]. In an educational setting, it is the responsibility of the instructional designer to construct the problem space for the learner, which in an ill-structured problem-solving environment is typically done with scaffolded supports for students.

*4.2.1 Scaffolding*

One critical aspect of the problem representation is the level of scaffolding – information, clues, or prompts that create the problem space for the learner [3]. This information can include learning objectives, instructions, feedback, assigned deliverables, and the kind of assistance that is available to students as they solve the problem.

In our survey, scaffolding was assessed through a number of questions, as presented in Table 5. First, given the role that instructions play in scaffolding for the activity, the survey asked instructors when students received the instructions, and in what format. Second, we asked the instructors what deliverables were integrated into their activity (including any that take place before the activity officially begins) and how they built on one another. The timing of instructions and presence or absence of deliverables before the activity begins, contribute to student preparedness for the activity. Third, we asked about the amount (and method) of feedback provided on each deliverable/checkpoint, as this also contributes to how the problem is represented to the solver. Feedback for deliverables of various Design Days activities included: verbal, written, observation, and questioning. For the SE activity in particular, the instructors indicated that there were three deliverables with feedback, and the responses from the instructors identified that students would not be able to progress to the next step (coding their spaceship) without completing the previous step (installing appropriate software or reading documentation). Although there was a final demonstration of the product created by each large group, the final product was not evaluated for completeness or efficacy. One final element of scaffolding is identifying who is available to help students. These could include instructors, teaching assistants, graduate students, co-op students and other staff. Their presence allows students to access domain specific knowledge from content experts. As such, increasing the number of available mentors increases the scaffolding of the activity. This section of the survey is data-rich, and it requires significant effort to extract and summarize the information provided by instructors. Moving forwards, efforts to streamline data collection of activity scaffolding will ease the use of this instrument.

*4.2.2 Extrinsic Motivators*

As a part of the context around the activity, one element of problem representation that is not discussed explicitly in Jonassen's framework is how instructors extrinsically motivate their students.

**Table 5.** Scaffolding for the SE activity

| Question | Instructor (I) responses | Researchers' comments |
|---|---|---|
| When are students provided the detailed instructions? | I1: Provided on the day of<br>I2: Provided on the day of | Students were provided information on the day of the activity |
| Were there checkpoints/deliverables before the event began? | I1: No<br>I2: No | Students were not required to prepare in advance |
| For each deliverable, was feedback provided? If so, how? | I1: Verbally, final demonstration<br>I2: Verbally, final demonstration | Feedback was provided on all three deliverables over two days |
| Do deliverables during the activity build on prior submissions? | I1: Yes<br>I2: Yes | Deliverables build on prior submissions |
| Who was available to assist students during the activity? | I1: Instructors, TA's, Co-op students<br>I2: Instructors, TA's, Co-op students | Help was available to students when required |

**Table 6.** Extrinsic motivators of the SE activity

| Question | Instructor (I) responses | Researchers' comments and value assignment |
|---|---|---|
| Does the activity appear in at least one syllabus in the term? | I1: Yes<br>I2: Yes | Activity appeared in at least one course syllabus |
| Were prizes given to students? | I1: No<br>I2: No | No prizes were given to students |
| How many courses included grades for the activity? | I1: 1<br>I2: 1 | The activity was worth grades in a single course, as opposed to no courses, or many courses |
| Were grades a bonus for students or required? | I1: Required<br>I2: Required | The grades were a required component of the course |

The presence of extrinsic motivators can alter students' intrinsic motivation during a learning activity, and can impact their affect, persistence, and level of interest in the activity [12], and so was included in our survey. As instructors are in control over the rewards for a given activity, as well as structural elements like the level of competition in the activity, it was important to capture this element of the activity design. Table 6 provides a summary of the instructors' responses to questions on how they extrinsically motivated their students during their activity.

We asked the instructors if the activity was built into the syllabus and if it was worth grades for students. The SE activity is included in a course syllabus, allocating only a small percentage of the final course grade to the outcome of the activity. Other methods of motivation can include awards, prizes, and friendly competition among groups; in the SE activity, no awards or prizes were used; while the final demonstration could have added some level of competition among students, this was not directly observed in the instructor responses. Some caution is needed in the case of friendly competition in an activity, as the competitive portion of an activity can discourage some students, suggesting that instructors should be careful to provide inclusive and diverse ways of motivating their students [12]. These questions capture the variety of rewards which instructors can apply to a learning activity, but do not capture the student perspective. Going forwards, these questions will need validation once student perspectives on design days are captured.

#### *4.2.3 Level of Fidelity*

In engineering design projects, designers almost never work alone [13]; as such, the amount and nature of required teamwork is a significant contributor to an engineering design problem's fidelity. Our survey asked the SE instructors how many students were in each group, if those groups were assigned, whether those students had worked together in the past, and if there was any expectation that those students would be working together again later in the term. Table 7 provides an overview of the instructor responses to questions on how much teamwork is required for the students to successfully complete the activity.

We expected that larger teams would create a more challenging environment because of the increased level of coordination required between team members. In the case of the SE activity, students were separated into large groups of 16. In each of these large groups, 4 subgroups existed, each responsible for a different element of the final design. These 4 subgroups needed to communicate and collaborate with each other in order to successfully complete the activity, significantly increasing the level of required teamwork on the students.

Familiarity with group members also influences the level of teamwork necessary to solve the problem. In the case of the SE activity, students had not explicitly worked together before, resulting in a high level of social complexity involved in the activity. The survey asked instructors if their students would be working on future tasks together because it was assumed that the feeling of developing, and then preserving, a strong working relationship with their group members would be more important in such a case. This too would increase the level of teamwork demand necessary for successful completion of the activity.

**Table 7.** Level of fidelity for the SE activity

| Question | Instructor (I) responses | Researchers' comments and value assignment |
|---|---|---|
| How many students were in a group? | I1: 16<br>I2: 16 | Groups were larger than 6, as opposed to working individually, in groups of 2–3, or in groups of 4–5 students |
| Have the students worked together in the same group on a previous task? | I1: No<br>I2: No | Students were unfamiliar with their group |
| Will the students be placed into the same group for future tasks? | I1: No<br>I2: Unsure | Students will not be intentionally working together in the future |

We recognize some of the measurements related to the sub-category of *fidelity*, in the way Jonassen describes, are not measured by the survey. This is partly a result of the similarity between different Design Days implementations. Specifically, Design Days activities are all heavily time constrained and the social pressures are not as authentic as real engineering design practice. Moving forwards, we intend to add additional questions to the survey relating to the level of fidelity of the tools/equipment/supplies that students use to create prototypes of their designs during the activity. For example, it is important to capture the difference in complexity of implementation between an activity that uses cardboard versus aluminum extrusions as the building material.

### *4.3 Other Findings*

It is evident that based on the survey responses highlighted in Sections 4.1.1 through 4.2.3, the way the SE activity was designed made it quite challenging for students: it was an ill-structured, complex, and highly domain and context-specific activity that had little scaffolding, while providing some extrinsic motivation for students and placing them in situations that required a lot of teamwork. It is important, therefore, to reflect on the impact such activity design had on students' design processes and outcomes, and whether the results warranted changes to the activity to improve effectiveness.

In addition to the questions listed in Tables 1 through 7, instructors were also asked to provide their observations on student engagement, the success of student designs, and any planned changes for future offerings of their activity. While instructor observations will obviously not describe the activity from the student perspective, they do provide some general insights into the success of the activity. Generally speaking, for an activity as logistically challenging as Design Days to justify continued offerings, students need to at least be engaged with the activity and experience some growth (whether that be in knowledge, skills, or affect). To that end, instructors were asked what percentage of students were consistently engaged during the activity, and what percentage of students successfully met all design objectives during the event. For the SE activity, there was disagreement between the instructors, with one saying 50% of students were engaged and 25% of students met all design objectives; while the other instructor said 90% of students were engaged and 100% met all design objectives. It is difficult to make any conclusions when there is such broad disagreement between instructors; however, at least one of them observed some issues with student engagement. Regarding student success, in this particular activity there was room for students to go above and beyond with their solutions, and it is possible that the first instructor was thinking of these extensions to the base solution when commenting that only 25% of students met all design objectives, while the other instructor was thinking more of a minimum viable product (that they felt all students were able to achieve).

The last series of questions on the survey were more reflective in nature, asking instructors to comment on any unintended learning outcomes from the activity, as well as what they would change for future offerings of the activity. In the case of the SE activity, the instructors commented that students were able to improve their programming skills, and their knowledge of advanced software algorithms. While the activity obviously required students to write code, improving these skills was not the primary learning outcome. One of the instructors also commented on the activities' social outcomes: it appeared that students were able to make new social connections with their classmates as a result of working together on the problem. When asked to reflect on what they would change in future offerings of the activity, the instructors were consistent in their view that students needed more initial information provided to students before starting the activity, more scaffolding during the activity, and/or more time to complete it. These reflections are in line with the findings from the survey: that the activity was ill-structured, complex, domain specific, and had low scaffolding, some motivators, and high teamwork complexity; and that perhaps students needed an easier problem representation to counter the very challenging problem variation. This change has been seen in later iterations of the spaceship activity, first offered to electrical and computer engineering students in spring 2020. In this case, significant changes to the level of scaffolding were provided, including a dedicated teaching team member assigned to each team of 16 who stayed in close contact throughout the activity, as well as significant improvements to the activity instructions, in order to combat the complexity and ill-structured nature of the problem.

## 5. Discussion

### *5.1 Main Outcomes and Findings*

This work was motivated by a desire to better evaluate the effectiveness of Design Days activities, and to better understand student outcomes as they relate to design and problem-solving. The first step on that journey was to have a common measuring stick for understanding the different Design Days activities as they were presented to students. Jonassen's framework [3] provided a solid foundation of concepts and language to describe problems and problem types; however, the framework lacked sufficient granularity to distinguish between similar activities like Design Days. The main contribution of this work, then, is in creating and refining an instrument that can provide additional granularity for design activities. We have demonstrated, using the SE spaceship activity, how we have adapted Jonassen's design theory of problem solving into a survey capable of describing problem variation and representation of engineering design activities. While this survey was not intended to evaluate the effectiveness of a Design Days activity (see [14–20] for more detail on evaluations of individual activities), insights derived from the survey data are consistent with instructor observation of the design activity itself (as discussed in section 4.3). In operationalizing problem variation and representation for engineering design problems, this work can help future researchers, instructors, and/or educational developers as they create, implement, and evaluate their educational design activities.

In the interviews that were conducted in phase 3 of this study, instructors were asked about the value of the survey in reflecting on their activity design(s), and whether it triggered any thoughts for future implementations. Generally speaking, most instructors who participated in this study didn't find the survey overly useful in identifying areas of improvement in their activities as they were already reflecting on their activity after each offering. This is likely due to a stronger background in engineering education and active-learning pedagogies in this community of instructors, as compared to a more typical engineering instructor. Indeed, many of the Design Days instructors have published one or more papers describing their activity designs with evaluations of their effectiveness. There were, however, two instructors who had not previously taken the time to extensively reflect on their activity. These instructors appreciated spending an hour systematically talking about their activity, and both identified some areas to change for the next offering. While a rigorous assessment of the value of this survey instrument as a reflective tool for instructors is outside the scope of this paper, this could be a promising area of research moving forward.

### *5.2 Limitations, Next Steps, and Future Research Opportunities*

As with any work, our methodology and findings are subject to limitations; nevertheless, we are excited about future avenues of inquiry based on this current research. The survey as implemented in phase 3 of this study captures many of the elements of Jonassen's theory, some more completely than others. However, as mentioned in the sections above on each sub-category, going forward, questions may need to be reworked, or additional questions added, to more completely capture the elements described by Jonassen (especially for structuredness, context, and level of scaffolding).

The first limitation we note is the subjectivity of responses from instructors, which can be due to a number of reasons. In the SE activity, where we have more than one response, it proved difficult to interpret an answer when there was broad disagreement between instructors. This may be a result of our own phrasing of questions, instructors observing different groups during the activity, or possibly even differences in instructors' levels of understanding as it relates to design instruction. For future offerings of the survey, it would be beneficial to subsequently show the results to the instructor after analysis is complete, to demonstrate where their activity sits, verify the accuracy of our categorization, and determine if it is aligned with their goals. Another limitation of instructor responses is that many of these activities took place 8–12 months before the survey was administered, and therefore participant recall about the activity cannot be as accurate as it would have been if the survey had been offered immediately after. Going forward, since the survey tool has now been built, the survey will be administered closer to the offering of the activity.

We are interested in investigating – more systemically – the correlations between the problem variation and representation, and student engagement and performance in the design activity. While there are many factors that contribute to student engagement – most notably, characteristics of the students themselves, which we did not investigate in this study – preliminary analysis of surveys completed for the other Design Days activities indicates that activities that are highly complex and ill-structured, with difficult problem representations (e.g., the spaceship activity), resulted in lower overall student engagement as reported by the instructors. While there is evidence of the impact of these activities on students, more work is needed to examine the interactions between activity design and student outcomes. Highly complex/ill-structured activities with difficult problem representations may be pushing students out of the "flow state" of maximum engagement into the anxiety realm: where they have too little skill to match the high challenge of the activity [21].

Finally, we are interested in further developing the survey to become a reflection tool for instructors. The tool can be used as an explicit reminder of the decisions that are in the control of the instructor, how they can be changed and how this will influence student outcomes as we have demonstrated above. Similarly, we wish to adapt our current survey tool to be more inclusive of and generalizable to other educational design activities. In its current form, the survey is designed to gather information on Design Days activities and may not be helpful in gathering information on educational activities that differ significantly in format. We hope to remove some of those contextual elements in order to make the survey useful to a more diverse set of activities.

## 6. Conclusion

This paper describes the implementation of a survey based on Jonassen's design theory of problem solving to characterize educational design activities. The development of the survey has required a number of iterations, with refinements addressing observed shortcomings in the collected data. Its application is demonstrated with a case study of one design activity that was offered to first year software engineering students.

The researchers have identified shortcomings with three of the sub-categories: structuredness, context, and scaffolding, which will require further refinements. Some of these can be attributed to ambiguities in Jonassen's theory, and some to our difficulties with applying the theory to our design activities. Future iterations of the survey tool will seek to overcome these shortcomings and improve the survey's ease of use. Lastly, the survey is opening the path for evaluation and improvement of our many educational design activities by providing a tool which can distinguish between similar activities.

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