Operationalizing Jonassen's Design Theory of Problem Solving: An instrument to characterize educational design activities

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1. Introduction

Problem-solving lies at the core of the engineering discipline. The Canadian Engineering Accreditation Board (CEAB) requires graduates of engineering undergraduate programs to demonstrate the ability to identify, analyze, investigate, and design solutions to complex engineering problems [1]. In order to ensure that these skills are developed in engineering programs, we must both regularly expose students to engineering design problems and effectively measure if positive outcomes have been achieved.

For the last four years, the University of Waterloo has been developing a series of Engineering Design Days (Design Days). These are two-day, discipline-specific design sprint activities that provide a mechanism for introducing students to open-ended and ill-structured problems. More background on Design Days and examples of their implementations in various disciplines are provided in [2]. We are currently engaged in a large project that seeks to evaluate how the Design Days contribute to advancing engineering students' design problem solving skills. A crucial aspect of this larger project, which is the focus of this ***work in progress*** paper, is to develop a tool to characterize the design problems at the center of Design Days. The aim is to support instructors developing new Design Days activities or evaluating and improving existing ones.

A useful framework for characterizing problems in general - and design problems in particular - is provided by David Jonassen in his paper *Toward a Design Theory of Problem Solving* [3] and book *Learning to Solve Problems* [4]. It describes the ability to problem solve as a function of the nature of the problem, the way the problem is represented to the learner, and individual differences among problem solvers [3]. When applied to an educational context, the first two factors - the nature of the problem and its representation to the learner - are decisions that are in the domain of the instructor.

A problem's nature (or variation) is characterized by its structuredness, complexity, and domain specificity [3]. Ill-structured problems have multiple solutions that can be reached in a variety of ways and require the integration of several domains to create meaningful solutions [4]. Problem complexity is associated with how many, how clearly and how reliably components are represented in the problem space [3]. The final element of problem variation is domain specificity - problem solving is embedded in contexts and is thus dependant on the nature of those contexts [4].

Importantly for the education context, it is the responsibility of instructional designers to select which information they present to the problem solver, withholding or providing relevant information necessary to solve the problem [3]. Jonassen referred to this attribute as problem representation. Problem solvers are required to discern which information from their context is relevant to their pursuit of finding a solution to a problem [3].

2. Objective

The objective of this first, qualitative stage of our research has been to characterize the design problems presented in the Design Days activities. The aim is to understand the differences in problem variation and representation from the perspective of the instructors who designed the activities. By doing this, we will be better able to understand and contextualize the problems used in Design Day activities, which will in turn help with further investigations of student problem solving outcomes. This study can also be useful in elucidating the types of decisions instructional designers can make when implementing new educational initiatives (see Atman et al. [5], section 3.2, for a discussion of instructor decision-making).

3. Method

This stage of the study is being conducted as case study research, with Design Days instructors as the participants and Jonassen's theory as the lens to interpret each case. To simplify the complex data collection necessary to describe a Design Days activity, the authors sought to build a survey that can be easily distributed to instructors across Engineering. To better understand the metrics that are important to describe a Design Days activity, development of the tool began with semi-structured interviews with four instructors that had developed and overseen previous Design Days activities in Mechanical, Nanotechnology, Civil, and Environmental and Geological Engineering. The interviews were guided by a series of questions that probed instructors to describe the design problem, its relevance to the domain and relationship to other courses, how it was structured and presented to students, and the characteristics of the students and their experience in the activity. 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. Each interview was approximately 1 hour in length, and was attended by 2-3 members of the research team, all of which took detailed notes of the questions and answers. The interviews were also audio-recorded.

The questions that were asked in the interviews (both those prepared and those that naturally emerged during the interview) and the range of instructors' answers to those questions formed the basis for creating a comprehensive survey, as a tool to characterize a Design Days activity. The survey questions were then further validated using a think-aloud protocol with a fifth Design Days instructor, resulting in some changes to the instrument. With some confidence in the survey tool's ability to capture the important and meaningful characteristics of a Design Days activity, the survey was distributed to all Design Days instructors from the fall 2019 semester. Table 1 summarizes most of the survey questions and maps those questions to Jonassen's framework. The questions that are not included in Table 1 are collecting background information for the researchers, and data relating to future stages of this research project. Some elements of the chart use the same language that Jonassen uses, however some new categories were developed.

4. Pilot survey results

The survey was piloted in fall 2019 with four instructors developing and overseeing two separate Design Days - Mechatronics Engineering (MTE) and Architectural Engineering (AE). MTE students were tasked with designing and building a tele-operated 3 degree-of-freedom robotic arm in an event called "Tron Days" (for more information on Tron days see [6]). AE students designed and constructed full-scale furniture using mixed materials (for more information on AE days see [7]).

Table 1: A categorization of the survey questions

Survey question / Category	Problem variation	Problem representation
Structuredness		
1. Did the problem have more than one solution?	✓	
Task complexity		
2. Do students need to use information/knowledge/skills from other concurrent course(s) in the term in order to successfully complete the task?	✓	
3. Please list the course/course topics students require to successfully complete the activity	✓	
4. What tools/materials were available for students?	✓	
5. Are students using equipment/tools/algorithms/building block that they have never seen before?	✓	
Domain specificity		
6. What percentage of students in other domains (at an equivalent academic level, e.g. first year) could solve this problem?	✓	
Nature of group work		
7. How many students were in a group?		✓
8. Did you assign the groups?		✓
9. Have the students worked in the same group on previous task?		✓
10. Will the students be placed in the same group for future tasks?		✓
Level of scaffolding		
11. Do deliverables during the activity build on prior submissions? (For instance, is the work performed early in the activity necessary for later deliverables?		✓
12. For each day: What was/were the checkpoint(s) or deliverable(s) that day?		✓
13. For each Deliverable: Was feedback provided to students that could be used during the event?		✓
14. Who was available to assist students during the activity?		✓
15. How were the students evaluated?		✓
Extrinsic motivation		
16. Does the activity appear in at least one course syllabus in the term?		✓
17. Approximately what percetange of students attended?		✓
18. Were prizes given to students during/after the activity?		✓
19. Were these grades a bonus for students, or required?		✓

Table 2 summarizes the survey results, aggregated by activity. For each activity, we describe the design problem according to problem variation and representation. We wanted to represent the aggregate data with a single descriptive word, in order to capture the elements of the activity at a glance. It is important to note that each of these categories are relative to these students participating in these particular activities. That is, the results of Table 2 would look completely different if expert designers or professional engineers were to complete these activities. The following sections outline how we generated Table 2.

Table 2: Aggregate survey results

Category / Design Day	MTE	AE
Problem Variation		
Structuredness	Ill-structured	Ill-structured
Task complexity	High	Low/medium
Domain specificity	STEM	General
Problem Representation		
Level of scaffolding	High	High
Extrinsic motivation	High	Low
Nature of group work	Low	Low/medium

4.1 Problem Variation

Problem variation refers to the nature of the problem that is being solved, irrespective of other external factors related to how the problem is presented. As determined by Jonassen, problem variation is a factor of its structuredness, complexity, and domain specificity.

Structuredness

This category was straightforward to describe. According to Jonassen's framework one element of ill-structuredness is the number of solutions available to the problem solver [3]. This attribute was captured by question 1 of the survey. The results of the survey indicate that both the MTE and AE problems have a significant number of solutions that students can develop, making both problems ill-structured.

Task complexity

In our survey, task complexity was captured in questions 2 to 5 by the number and nature of elements students would require to complete the activity. The survey results concluded that the number of elements, the familiarity with working tools and previous knowledge required to solve the problem presented to MTE students was greater than for AE students. MTE students were required to draw on a significant number of their courses to successfully solve the problem, where AE students were not. According to Jonassen, more complex problems are dynamic and require the solver to make connections between disciplines [3]. Instructors indicated that the MTE activity included a variety of materials that students would be unfamiliar with (Tetrix kits, pneumatic cylinders, pressure vessels, etc.). The AE students were working with common crafting material (cardboard, hot glue guns, measuring tapes, etc.) and were only faced with one material – Hydrostone (a fast-setting plaster) - with which they might have been unfamiliar. As such, the MTE activity has been characterized as more complex than the Design Day activity for AE.

Domain Specificity

The level of domain specificity was determined (through question 6) by identifying who would have the ability to solve the problem. The survey respondents indicated that the MTE problem presented to the students was entrenched enough in the discipline that only STEM students would be successful in solving this problem. However, the AE problem is far more generic, and could be solved by almost anyone. Aside from the materials that are used during the event, the task would only require general knowledge of furniture in order to develop a viable solution.

4.2 Problem Representation

Fundamentally, problem representation relates to how the problem is presented to the problem solver. We have interpreted and expanded on this definition to include the level of scaffolding that the instructor provides, the nature of the group setting in which the student must solve the problem, and extrinsic motivators (if any) provided by the instructor. These are distinct from problem variation in that they are elements of the problem-solving environment, and not the problem itself.

Level of scaffolding

The level of scaffolding is associated with how the problem is presented to the students, how many checkpoints are required, and how the students were provided feedback. These elements were investigated through questions 11 to 15 of the survey. In both Design Day cases, the activities are highly scaffolded. Students in both activities were required to submit in-progress designs of their solutions and were provided feedback on those partial solutions. In addition to the feedback at each checkpoint, students were able to ask instructors, TA's, technical staff, etc. questions throughout the activity in order to improve their design.

Extrinsic motivation
When someone does something for the purpose of obtaining some outcome, they are said to be extrinsically motivated [8]. In the context of the Design Days, students can be extrinsically motivated to succeed in the day's activities by course credit or prizes. The survey responses to questions 16 to 19 indicated that students participating in the MTE activity would be more extrinsically motivated than their AE peers, as the outcome of the activity is built into their course syllabus, offering course credit for participation.

Nature of group work
This category was the most complicated to narrow down to one label. We chose to compare the responses of questions 7 to 10 of the survey on a combined scale across three categories: team size (scale of 1-5), team development (scale of 4-1), and task interdependence (scale of 1-5). Larger teams (size extracted from question 7) created a more challenging environment (with a maximum score of 5), as there is an increased level of required coordination between team members for successful collaboration.

Team development, as described by Tuckman (1965), goes through four stages: forming, storming, norming, performing [9]. Each level of development was used as one level of the scale, based on which stage the team were expected to be in at the start of the Design Day activity. The stage was interpreted from survey questions 8 to 10. For example, it was assumed that if a team had been formed by the instructor and the students had not previously worked together, they were likely in the forming stage. The highest score was associated with forming and the lowest score with performing, as this would indicate the increased level of complexity associated with working in a group where members are less familiar with each other.

Finally, task interdependence is the extent to which individual team members rely on the knowledge, materials and support from other team members [10]. No questions on the survey directly mapped to this aspect of teamwork; as such the author most familiar with the development of the suite of Design Day activities used their judgement to assign a rating. The scores from these three scales were multiplied to provide one number which was placed on a scale divided into 5 categories: low, medium/low, medium, medium/high, and high. After tabulating the results from the three scales, we found that the MTE activity had a score of 24/100 and AE activity had a score 36/100, leading to the categorization of low and low/medium respectively.

5. Limitations and future work
We have shown that our survey can be used as an instrument to effectively characterize design activities, though there are some limitations. Our goal is to provide the most objective accounts of the Design Days activities as possible. Although we are gathering data from the entire population of instructors involved in the design of these activities, there is a limited number of

responses so any statistical analysis that would provide evidence for our claims would be difficult to carry out. It would also be desirable to test the generalizability of the survey instrument to capture problem variation and representation for other instructional activities targeting design skills, however this work has not yet taken place.

Upon critical examination of instructor responses, some questions (like question 6 in Table 1) have more variation in response than expected. Conceivably, instructors who designed and oversaw the implementation of the same activity should all have similar ideas for how the problem varies and is represented to the students. This was not found to be the case for some questions. This leads us to believe that there may be some problems (misunderstanding of questions, inappropriate response options, subjective wording, etc.) with the questions in the survey. Further refinement of the survey is needed to improve the inter-rater reliability of the instrument.

Another limitation is the number of questions used to measure specific characteristics of the problem variation and representation. As seen in Table 1, structuredness is only being measured by question 1. As described by Jonassen, structuredness is also related to the success criteria used for evaluating solutions [3]. In order to more comprehensively capture the structuredness of the problem, in the next iteration of the survey, new questions to capture how success criteria are defined for students will be included. Jonassen also states that ill-structuredness involves problem solvers making judgements about the problem (i.e. creating their own success criteria) [3]. As such question to address this element of structuredness will also be included. Similarly, one or more questions will need to be added to capture task interdependence in the group [10].

The survey instrument will continue to be offered to instructors of Design Days activities to expand our dataset and provide insight into ways it can be improved. This tool will lay a foundation for future investigations of the perspective of student problem solvers, a task that can be extremely complex when applied to large groups of students designing at the same time.

6. Conclusions

Using Jonassen's design theory of problem solving as a guide, we have developed a first iteration of a survey that captures and describes important problem-solving elements of an engineering design activity in an academic setting. The survey, and an expansion of Jonassen's framework that we have developed around it, provide a means to operationalize the problem variation and problem representation elements with additional descriptive granularity for design problems. The tool is of primary benefit to instructors who are implementing design activities (like Design Days) in the future, and represents an important first step in characterizing a design problem (and the environment in which it will be solved).

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