Concept maps lead to better problem statements: An empirical study measuring the effects of priming students to think in systems

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ABSTRACT

Challenges associated with the design and construction of the built environment are complex. Students need training to help them deal with this complexity and to help them explore and reframe problems early during project planning and design. Concept maps provide a visual representation of complex information and the relationships between this information. The research presented in this paper tested whether priming students to think in systems by asking them to draw concept maps changes how they construct problem statements. In total, 40 engineering students participated in the study. Half were asked to draw a concept map before constructing a problem statement about how to improve mobility systems around campus. The cognitive effort (i.e., time and words) students spent on the task and the number of unique system elements included in their problem statement were measured. Students that received the concept mapping intervention spent significantly more time thinking about the problem, developed longer problem statements, and included more unique elements of systems. These findings suggest using concept mapping can aid students' conceptualization of complex problems.

INTRODUCTION

Designing and constructing the built environment is a complex process. It requires an understanding of the relationships between technical and social systems (Lund, 2020). To deal with this complexity, those who design and construct the built environment often follow a reductionist approach. Reductionists subdivide complexity into individual components and focus on a subset of variables (Beckerman, 2000). The tools designers and constructors use to develop the built environment tend to reinforce reductionism. For example, rating systems like Leadership in Energy and Environmental Design (LEED) guide stakeholders to think about individual parts using a checklist of options (Azhar et al., 2011). LEED draws criticism for over simplifying, even neglecting, the potential emergent benefits of a more holistic systems approach.

The complexity of problems associated with the built environment do not fit neatly into a checklist. Traditional project delivery processes, like design-bid-build, can further reinforce a reductionist approach that uniformly progresses from conceptual design to schematic design to final drawings through construction (Beckerman, 2000). This linear approach to design and construction of the built environment tends to favor spending more time thinking about the solution than the underlying problems. For instance, request for proposals that prescribe a solution (e.g., provide a roadway design to expand the highway from three to four lanes) asks for the technical details with little room for creative reframing of the problem statement (e.g., provide a solution that reduces traffic congestion). This is an issue because the problem and solution space co-evolve in an iterative cycle (Dorst & Cross, 2001; Maher & Poon, 1996; Schön, 1983). Relatively new, and still evolving, contractual approaches for project delivery, like integrated project delivery, address these issues by including more people and expanded perspectives early at the design table to conceptualize the problem. Public-private partnerships also tend to help provide opportunity to reframe the problem by moving from delivering a solution to a service.

Education for complex design and construction of the built environment

Engineering education must reflect the complexity that is inherent to challenges associated with the built environment and also help teach students new methods to expand and explore the early phases of problem identification during project planning and design (Jowitt, 2020; Lund, 2020). Negative and long-lasting consequences can occur when not enough emphasis is placed on exploring and reframing the problem. For example, stormwater engineers tend to approach stormwater as a problem about capturing and diverting water without fully considering the larger social and ecological systems that interact with the system (Birk, 2017; Brown & Farrelly, 2009; Earles et al., 2009; US EPA, 2015). To address stormwater in Onondaga County, NY, engineers designed a conventional stormwater holding tank facility. Their facility required the eviction of 45 families from their homes (Flynn et al., 2014). Only after the facility was built and failed to address the sources of bacteria in the watershed did the engineers reconsider and expand the problem to include the social implications of their design. With an expanded problem frame, they developed new green infrastructure solutions that had a profound positive effect on the community, increasing property values and saving the city nearly $20 million in additional grey infrastructure upgrades (Flynn & Davidson, 2017). In this example, adjusting the problem frame to include more complex systems (technical and social) led to a better engineered solution.

Many tools and methods exist to help students handle this type of complexity during design and are increasingly being integrated into the classroom (Dym et al., 2005; Zancul et al., 2017). Concept mapping is one approach with proven success in helping teach students to consider stakeholders and systems interaction (Watson et al., 2016; J. Novak, 1998). Concept mapping is a graphical tool to organize and represent concepts and relationships related to multiple systems (Novak, 1980). This process of graphically representing the connections between complex system components can help enable unique retrieval paths for new concepts and information (O'Donnell et al., 2002). Expanding and redefining initial problems can have critical effect on the types of solutions that are developed (Asimow, 1962; Schön & Wiggins, 1992).

Concept mapping as an educational tool has previously centered around its use for measuring students' ability to think in systems (Watson et al., 2016). Much research has focused on how to develop concept mapping as an assessment tool (Watson et al., 2016; Brandstädter et al., 2012). The traditional scoring method counts the number of concepts, cross-links, and the level of hierarchies (Nguyen & Bosch, 2012). The purpose of the research presented in this paper is to measure how concept mapping can help students explore the problem space of engineering design problems about the built environment. Concept mapping may help expand the scope of systems that students considered and help students create new knowledge and relationships between these systems. In turn, it could improve how they define complex problems.

RESEARCH QUESTIONS

Priming involves introducing new material before a future task or problem occurs (Herr, 1986) and can mentally prepare students for an upcoming event (Liao & MacDonald, 2018). Here, we explored whether priming students with concept maps improves how students' construct a complex engineering problem. The specific research question was what is the effect of priming students with concept maps on engineering problem framing? To explore the effect of concept mapping on problem framing, this study focused on the cognitive effort applied to constructing the problem (i.e., time and word count) and (2) the exploration of the various elements of the problem space (i.e., the number of systems mentioned).

METHODS

Experiment design

Engineering students (n = 40, age = 22.13 ± 2.93 years) at Virginia Tech were recruited to participate in the study. Students were majoring in civil engineering, environmental engineering, industrial systems engineering, mechanical engineering, and construction engineering and management. The pool of participants included both undergraduate and graduate students. All students were compensated with a $30 Amazon gift card for their participation in the study. All components of the study were reviewed and approved by Virginia Tech's Institutional Review Board.

Participants were asked to frame an engineering design problem by setting requirements for the improvement of mobility on campus. Students were randomly assigned to one of two cohorts. The intervention cohort (n = 20) was primed to think in systems using concept mapping prior to receiving the engineering design problem task. Students in the intervention group were shown a four-minute introductory video about concept maps, which explained how to create hierarchies and crosslinks between concepts. After watching the video, they were asked to create a concept map breaking down the American education system. The purpose of this first concept map activity was to let participants practice how to use concept maps. Participants were allowed to ask questions about the process to construct a concept map during this first activity.

The next step asked the intervention group to create a concept map illustrating all of the mobility systems on campus. Prior research emphasized that the priming intervention should be specific and pertinent to the scenario of the problem-solving task (Alexander, 2016). Students were given no time constraints to develop their concept maps. On average, students spent 8.9 minutes developing their concept maps. The control group (n = 20) had no priming intervention and started the engineering problem statement task directly. The task was as follows:

"Virginia Tech has hired you as a consultant. Mobility on campus needs to be redesigned and your role is to provide a document containing everything you think that could be improved. Please be as descriptive and elaborate as you can when explaining your ideas and how they would impact mobility on campus."

The task was meant to provide some direction for defining mobility problems on campus without limiting the types of problems defined. Open-ended problems with a relatively large problem-solution space, with many categories of potential problems and solutions, tend to increase stimulation effects (Nijstad et al., 2002). This was the premise used for selecting the mobility systems topic for the problem framing task. Students responded to the prompt by writing the problems they identified with pen and paper. No time limit was given to students.

Data analysis

The study measured the effect of priming with concept mapping on (1) cognitive effort spent on the problem framing task and on (2) the participants effectiveness in framing the problem. To measure cognitive effort, time spent on the task and word counts of writing their response were used as metrics. Examples in the literature from economics and computer science highlight that word count and the amount of time spent positively correlated with cognitive effort (Chen et al., 2010; Vieira, 2016). The time students spent considering the task and writing their response was recorded by the research team. Students' hand written responses were transcribed into electronic text files, which allowed the research team to count the number of words. A *t*-test was used to compare differences between the intervention and control groups. Cohen's *d* was also calculated to measure the effect size between the average time spent and average number of words written between groups. For the case of different standard deviations, a Glass's *delta* was also calculated to describe the effect size.

To identify participants' effectiveness in framing the problem, the number of design problem systems (i.e., elements and stakeholders) were identified to assess the variety in participants' system identification. Variety in ideas is one measure of effectiveness in engineering design (Shah et al., 2003). One member of the research team read through all of the responses and developed an emergent code book of the mobility system elements that were mentioned by each student. An example is "Mobility on and around campus can be improved in many important ways to improve the flow of people through campus whether they be *driving*, *taking public transport*, riding a wheeled device such as a *skateboard*, *scooter*, or *bike*, *walking*, or even *taking an elevator*." The elements coded are italicized. According to Shah et al. (2003), the variety of systems discovered relates to the extent of problem-solution space explored. A *t*-test was used to compare the number of elements identified between the groups.

The uniqueness of the systems mentioned was also measured. Tree maps were used to provide an illustration of the uniqueness of the systems identified by each group. Tree maps represent the uniqueness of each system (the size of the squares correlates with the number of times each system was mentioned) and the differences in number of systems identified (the quantity of squares in the map). In other words, a tree map with a high number of smalls squares accounts for a larger amount of the problem space explored and a higher uniqueness of the systems identified.

RESULTS

Priming students with concept maps helped them sustain cognitive effort when constructing their engineering problem statements

Students that received the concept map activity (i.e., intervention group) spent significantly ($t = 3.52$, $p = 0.0023$) more time on completing the problem framing task (M = 608.75 sec, SD = 237.43

sec) than students in the control group (M = 368.43 sec, SD = 243.11) (see Table 1). The number of words used in the problem framing task was also compared between the cohorts. Students in the intervention group wrote 76.3% more words (M = 201.50, SD = 102.60) than the students in the control group (M = 114.3, SD = 55.63) (see Table 2). The difference in the number of words was also statistically significant (t = 3.30, $p = 0.0038$) between the cohorts. The effect size for both metrics was large (Cohen's d > 0.8), even after controlling for the different standard deviations between groups using the Glass's delta.

Table 1. Time (sec) spent in the problem framing task

Group	Mean	Standard Deviation	*t*	*p*-value	Effect size (Cohen's d)	Glass's delta
Control	368.43	243.11	3.52	0.0023	1.00	0.99
Intervention	608.75	237.43				

Table 2. Number of words written in the problem framing task

Group	Mean	Standard Deviation	*t*	*p*-value	Effect size (Cohen's d)	Glass's delta
Control	114.30	55.63	3.30	0.0038	1.06	1.57
Intervention	201.50	102.60				

Priming students with concept maps extended the size of the problem space

Students primed with the concept mapping activity mentioned an average of 5 extra systems compared to the students in the control group (see Table 3). The effect size measure was large (Cohen's d > 1.12 and Glass's delta = 1.55). Participants in the intervention group explored a significantly larger problem space than participants in the control group (t = 3.94, $p < 0.001$).

Table 3. Number of systems mentioned in the problem framing task

Group	Mean	Standard Deviation	*t*	*p*-value	Effect size (Cohen's d)	Glass's delta
Control	7.75	3.29	3.94	8.90E-4	1.12	1.55
Intervention	12.85	5.55				

Further analysis of the uniqueness and frequency of systems identified in the problem statements reveals that the intervention group listed significantly more elements (non-human systems) than the control group (t=4.15, $p < 0.001$) with a large effect (Cohen's d > 0.8 and Glass's delta = 2.00). The elements identified by participants in each group are represented on the tree map in Figure 1 (intervention group) and Figure 2 (control group).

The intervention group mentioned a total of 81 different elements, while the control group mentioned 43. In total, 33 elements were common to both groups implying that 59% of the elements identified by participants in the intervention group were unique while only 23% of the elements mentioned by the control group were unique. The number of different stakeholders mentioned by the two groups did not differ significantly.

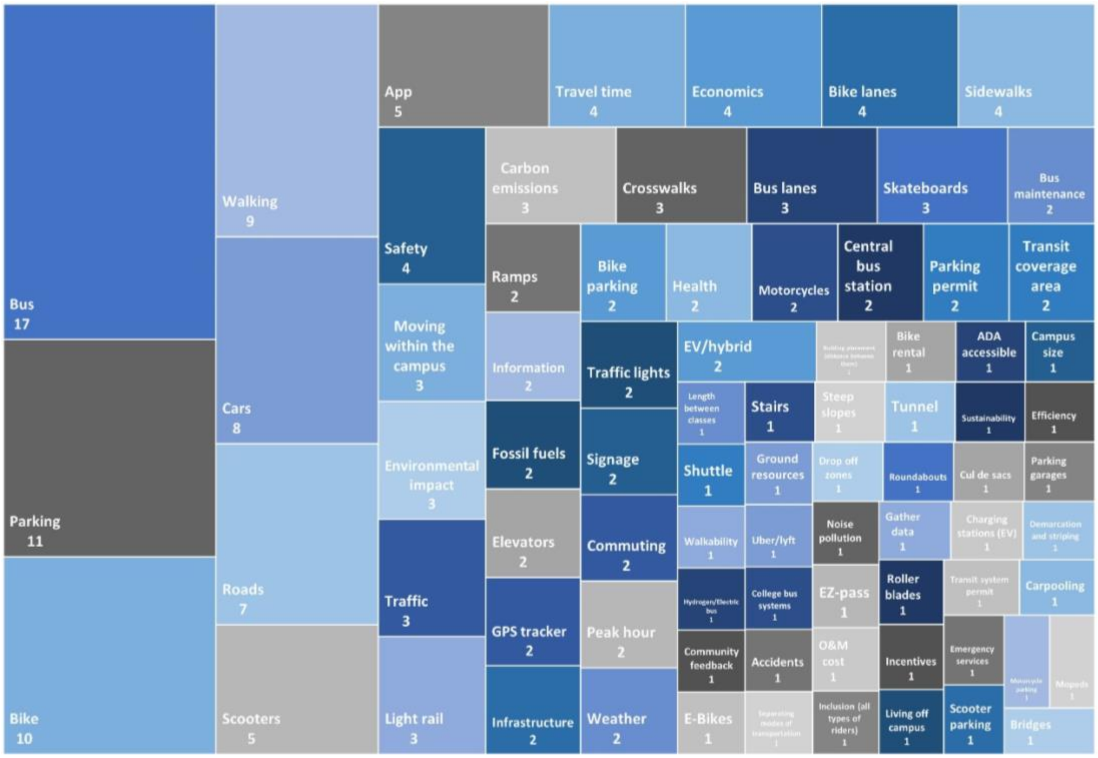

Figure 1. Elements of the mobility system identified in the problem framing task by participants in the intervention group. The number of times an element was mentioned appears in each box. The box size is related to the number of times an element was mentioned.

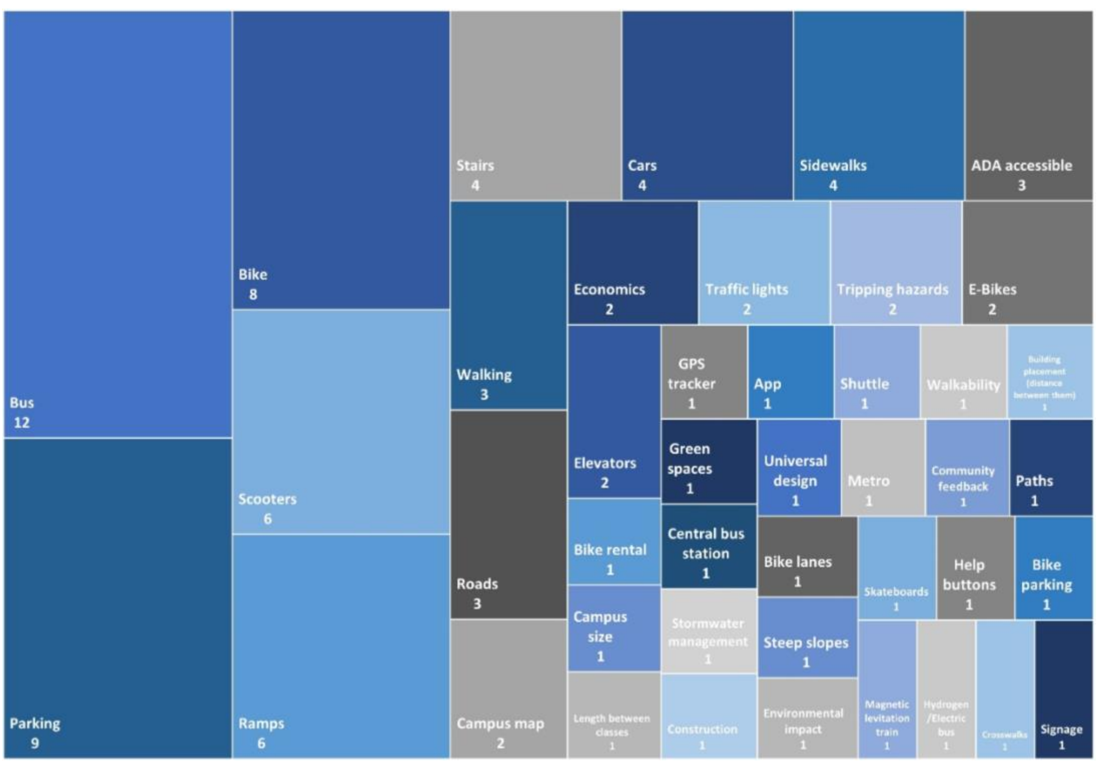

Figure 2. Elements of mobility systems identified in the problem framing task by participants in the control group.

DISCUSSION

Priming students using concept maps significantly changed the amount of time, length, and systems they considered when framing their problem statements about how to improve mobility on campus. The effects were significant and large. These results offer new insight into the benefits of concept maps as a tool to support how students conceptualize problems. Concept maps can function as a tool for expanding the problem space by helping students identify more systems and their relationships.

The results are consistent with prior studies that suggest concept maps influence how students think (Hu et al., 2019). Concept mapping appears to work as a mental aid to sustain students' cognitive effort when constructing problem statements. Students primed with concept mapping extended the duration they considered the design problem and expanded the number of systems they included in their problem statements. One reason why concept maps may enable more time to consider the problem is it alleviates brain network complexities, creating more room for extended evaluation (Hu et al., 2019). Prior research found concept mapping compared to just writing concepts in a list required less coordination between memory systems (e.g. short-term memory, long-term memory, and working memory) (Hu et al., 2019). In other words, illustrating concepts and their connections required less neuro-cognitive effort than generating a similar list of concepts without showing their relationships. By externalizing the identification of systems within the problem, the cognitive effort could be put into expanding the number of ideas explored.

Using concept mapping as a primer may have made the future problem identification task cognitively easier to handle. Students primed with the concept mapping task were able to sustain focus on the problem framing task, which could be because the cognitive demand was not as great as for students who directly engaged in the problem framing task. Concept mapping appears to have helped students organize their thoughts and ideas. This likely helped reduce the complexity of the task and improved their ability to develop the problem statement.

Priming students with concept maps helped generate richer problem statements with more system elements. Students in the intervention group identified almost twice as many system elements as participants in the control group. More than half of the systems identified by students in the intervention group were unique to that group. The problem statements built by participants in the intervention group incorporate more diverse and unique systems, which could lead a more effectiveness in the generation of solutions (Shah et al., 2003).

Surprisingly, the priming intervention did not expand the number of stakeholders that students considered. This may be a result of a knowledge gap in the various stakeholders associated with mobility on campus. For example, in a study using concept maps to understand students understanding of sustainable development in engineering, Segalàs et al. (2012) pointed out that unlike professionals, students tend to omit social aspects of sustainable design. Teaching about stakeholder engagement through a process driven pedagogical framework would emphasize the interconnectedness between social, economic, and environmental objectives in engineering (Jowitt, 2020).

The implication of these findings for the engineering industry, if the same results are obtained with professional engineers, is concept mapping may help expand how problems are defined, which could benefit the types of solutions produced. Providing a broader perspective and motivating sustained cognitive effort to frame the problem space can improve the outcomes of projects like mobility systems that benefit society. Concept mapping is inexpensive to implement; it took less than 10 minutes and significantly influenced how students conceptualized the problem.

The study limitations relate to the participants and their familiarity with the mobility problem. The cohorts were engineering students, not professionals. While these results present the effects on students, the findings may also translate to professionals. Future research can begin to replicate these results with professionals and with a larger sample. Moreover, participants were familiar with the mobility systems on campus that were presented as the engineering problem. This might have influenced the outcome as it likely helped them retrieve prior experiences, make new connections, and develop detailed concept maps because problem framing is situated within the students experience (Gero, 1990; Schön, 1983). Future research could also begin to explore how concept mapping informs other types of problems and the variability within groups based on their prior experiences.

CONCLUSION

Engineering students intending for careers to design and construct the built environment must acquire skills to think in systems. Designing and constructing the built environment relies on the understanding on technical and social systems, hence stakeholders in the built environment need the ability to cognitively manage the complexity of these systems and the context they work within. Their ability to recognize the complete picture, varying points of view, and develop solutions beneficial for all stakeholders is critical for infrastructure systems to better adapt to changing environmental and social conditions (Lezak & Thibodeau, 2016). An increased focus on identifying the systems associated with the problem can help students to develop a richer understanding of the problems they will face in their careers, which can help lead to more creative and innovative solutions.

The research presented in this paper explored how students identify and construct problem statements associated with the built environment. It tested to what extent priming them to think in systems using concept mapping changed the way they constructed their problem statement. Concept maps are known to be useful tools for assessing systems thinking (Novak & Cañas, 2006; Watson et al., 2016). Priming students with a concept map significantly increased the effort spent on constructing their problem statements. Moreover, their problem statements were more diverse and unique compared to students who did not receive the concept mapping intervention.

Techniques like concept mapping that provide a graphical illustration of concepts and the relationships between them are useful in assisting students construct new knowledge and solve problems. The tool may also be useful to practitioners as well. Future research can begin to explore and look for ways to integrate similar exercises as concept mapping into the early project delivery stages when designing and constructing the built environment.

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