2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering Education for 130 Years
Paper ID #38817

A comparison of shared mental model measurement techniques used in undergraduate engineering contexts: A systematic review

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A comparison of shared mental model measurement techniques used in undergraduate engineering design contexts: a systematic review approach

Abstract

Design courses and experiences in undergraduate engineering contexts are common at many universities. There is a significant amount of research aimed at understanding how to best support students working in teams in these complex problem-solving environments. Research teams use a variety of methods for measuring both behavioral and cognitive elements of effective teamwork behaviors. One approach is to examine the shared mental models – organized knowledge structures – that students create as they work through design problems. This literature review provides a short synthesis and comparison of the techniques that have been previously used to measure mental models in undergraduate design contexts. We identified and reviewed a set of 13 articles to draw insight and summarize how these measurement techniques have been implemented. In general, our findings aligned with previously published literature. We provide commentary comparing these techniques and explain why these results are helpful to engineering educators who teach design in their classroom.

1. Introduction

Teamwork is used in undergraduate engineering classrooms to prepare graduates for the engineering design problems they will face that cannot be handled by a single person (Wolfinbarger, 2022). As a team generates solutions to problems, they develop various mental models related to the team itself and the work they must complete. A mental model is an organized knowledge structure which allows an individual to interact with their environment (Mohammed et al., 2010; Mathieu et al., 2000; Beddoes, 2020.) At the team level, individual mental models contribute to the team's shared mental model – the organized knowledge structure that allows the team to interact with their environment. These shared mental models play an important role in the success of the team (Mohammed et al., 2010). Prior research has identified and synthesized characteristics of two types of shared mental models, which are broadly categorized as a teamwork (or team) mental model or a taskwork mental model (Mohammed et al., 2010). Teamwork mental models include knowledge structures of the interpersonal interaction requirements and skills of team members (Mohammed et al., 2010). Taskwork mental models are knowledge structures associated with work goals and performance requirements. High quality mental models that are shared across team members have been found to positively contribute to the success of the team (Kim, 2019).

Given the utility of having a shared mental model within a team, a considerable body of research has been devoted to understanding this concept (see Mohammed et al., 2010 for a comprehensive overview). One of the most important, but challenging, elements of this research has been the development of methods to measure shared mental models. In this case, we define measurement to include a process of first eliciting the mental model (i.e., what is the content) from the individual or team, then interpreting the elicitation to generate the model itself (i.e., how that content is structured) and finally determining any insights that might be derived from the model. For example, in Badke-Schaub et al. (2007), in an evaluation of the concept of mental models for research with design teams, the authors identify three mental model measurement techniques that have been used previously: relatedness judgments of concepts, concept mapping, and observations. However, the inherent richness of a design team's social interactions present challenges that require a multidimensional approach (Milovanovic et al., 2022), meaning that a single technique may not be sufficient for understanding the detailed structure of mental models in these contexts.

To that end, this article will employ a systematic review approach to compare the techniques that have been used to measure team mental models in undergraduate engineering contexts. Another systematic review article by Kim (2019) explores a similar topic though the focus was on explaining the characteristics that contribute to development of mental models, factors that influence team performance and, briefly, how mental models can be measured. Kim (2019) significantly contributes to the growing consensus on the applicability of mental models in design contexts, however we note that there has been little targeted emphasis on the techniques used for eliciting shared mental models from students and generating insights from those shared mental models in engineering education contexts. As such, the remainder of the paper is organized as follows. In the next section, we provide a brief overview of the mental model literature. We then provide a description of the search strategy, exclusion criteria, and resulting set of publications. The results are then discussed to highlight the various measurement techniques and the contexts in which they are used. Our findings, and the discussion that follows in the final section, will be impactful for future research on mental models. Ultimately, we hope that this paper will inform how we might create targeted pedagogical strategies that help students identify the benefits of shared mental models.

2. Background

2.1 Shared Mental Models: Teamwork and Taskwork

In team settings, individuals first create their own mental models and a shared mental model becomes the extent to which those individual mental models are consistent among team members (Mathieu et al., 2005). These shared mental models are likely unique in different teams and contexts. That is, the shared mental model held with one team may not be the same as the shared mental model held by another team. In practice, individual teams can also hold multiple mental models simultaneously – one (shared) model of their task work, and one (shared) model of their teamwork.

A teamwork mental model is the shared understanding of the roles, responsibilities, and skills of team members as well as interpersonal interaction requirements (Mathieu et al., 2000; Mohammed et al., 2010). In the design work context, Stempfle & Badke-Schaub (2002) describe elements of the teamwork model to include planning, analyzing, evaluating, deciding, and controlling (or summarizing) elements of the team's process. These steps are mediated through basic thinking operations. This model is developed over time and is an important element in the success of the team.

A task mental model is the shared understanding of the work goals, the process for how to achieve those goals, performance requirements, and design constraints. Stempfle & Badke-Schaub (2002) describe elements of the task model to include goal clarification, solution generation, analysis of solution space, evaluation of solution space, decision making and controlled implementation. The task mental model, like a design frame, is a way for designers to identify a particular pattern of relationships that can be used to create desired outcomes (Dorst, 2015). Like teamwork mental models, task mental models change over time via social interaction, as individual members impose their own experiences on the collective understanding of the problem (Hey et al., 2007).

Shared mental models for teamwork have, generally, been discussed in the context of command-and-control or military teams, where the tasks are structured, roles are clearly differentiated, and coordinated patterns of interdependence are specified (Mohammed & Dumville, 2001). In undergraduate engineering contexts, like capstone design projects, problems are more complex and less constrained (Howe et al., 2017). Given the complexity of design contexts compared to the more structured contexts found in the current shared mental model literature, it is not yet clear if the measurement techniques used in those studies are useful. Moreover, though we might expect the findings to carry over into the design context, it is not clear if results and findings related to shared mental models found in more structured problem settings will have the same characteristics compared to a more complex problem-solving environment.

2.2 Engineering Design Problems and Teamwork

Design problems are ill-structured and complex (Jonassen, 2000). These problems may have a wide range of conflicting technical issues and no obvious solutions (ABET, n.d). Engineering design is one response to the complexity of these problems, which uses an iterative, creative decision-making process to devise an engineering solution (i.e., a system, component, or process) that will influence the problem to a more desired state (ABET, n.d.; CEAB, 2021). These problems have elements that are significantly interdependent, which requires effort from the design team to coordinate their actions and decision making necessary for solution development (Hyman, 2003). This process involves identifying opportunities; defining constraints; generating, testing, and refining novel solutions; and implementing the solution in the world. Throughout this process engineering designers should engage with diverse groups of stakeholders to ensure that they are meeting the needs of those most affected by the problem (ABET; CEAB, 2021). The complexity of engineering design problems requires sophisticated levels of collaboration (Marra et al., 2016), indicating that teamwork is an essential element of the engineering design process. However, to complete these tasks, the teams must be able to operate effectively; teams require shared mental models of their teamwork and taskwork to do this effectively.

Teamwork experiences that occur in the classroom have been shown to promote active learning, when students work in small teams in cornerstone and capstone design courses (Johnson et al., 1998; Dringenberg & Purzer, 2018). Teams, as opposed to individuals, must not only deal with the design task itself but also direct part of their activity to creating useful team structures and organization processes. As one might imagine creating a shared understanding of these team structures is not straightforward. The degree of sharedness of individual mental models leads to better performance though that degree depends on the specific task, the composition of the team, and the organization of teamwork (Bierhals et al., 2007). Importantly, more diverse teams may face a trade-off between their ability to be creative in their design. Novel solution creation often needs diverse sets of ideas, though increased diversity can reflect divergence in shared mental models (Cash et al., 2017). For example, in terms of taskwork mental models, an ergonomist and electrical engineer may have difficulty in developing a device because one is concerned with how the device feels while the other is concerned with how it is going to work (Kleinsmann & Valkenberg, 2008). While this prior research agrees that students find collaborative settings both challenging (e.g., managing diverse perspectives) and rewarding (e.g., increased levels of self-esteem), a more thorough understanding of the variation in how students experience and conceptualize effective collaboration is needed to design effective learning environments (Dringenberg & Purzer, 2018).

Understanding the role that shared mental models (these organized knowledge structures) play in the success of a team is essential to determining this variation in how students experience collaboration during their design activities. However, to be able to understand their role, we first need to be able to measure them in existing design contexts. We wish to make it clear that, though many types of mental models can and do exist, we are interested in understanding the intricacies of the measurement techniques that are used for both task and teamwork shared mental models.

3. Method

Using this background as a foundation, we have identified a unique opportunity to investigate mental models more thoroughly in engineering student contexts and, more specifically, to understand the mental model measurement techniques that have been previously used. This work follows a systematic review process (Page et al., 2020), to identify and compare the techniques that have been used to measure mental models in undergraduate engineering design contexts. Guidelines for reporting systematic reviews encourage the use of a flow chart (see Figure 1 below) to demonstrate how articles were selected for inclusion.

As we are interested in understanding what techniques have been used to measure mental models in undergraduate engineering contexts, we conducted searches in four databases (Scopus, Web of Science, Compendex, and ERIC) using the following search string (or some variation depending on the database):

("*mental model*" OR "*cognitive model*") AND (*student* OR *undergrad*) AND (*engineer** OR *design*) AND (*team*)

In total, 159 records were returned of which 43 were removed because they were duplicates. Nine of the records were removed because they were entire conference proceedings rather than individual articles. The remaining records were then screened based on the abstracts and title. In this phase, we removed articles that did not match our inclusion criteria which were as follows:

- IC1 – Context included solving or working on an engineering or design problem
- IC2 – Include a measurement of a mental model
- IC3 – Context included working in an undergraduate team
- IC4 – Record was either a peer-reviewed journal article or conference paper

Using these criteria, we eliminated a total of 69 articles resulting in a total of 38 records that were sought for retrieval. Two of the 38 articles could not be found using our institutional library services and other search techniques. Therefore, 36 articles were read in their entirety, again looking for articles that matched our inclusion criteria. In total, 13 records (6 journal articles, 7 conference papers) were included in our review. Each of these 13 records was read in its entirety again and analyzed by the first author. We sought out information relevant to the measurement techniques and other contextual information relevant to our purpose (i.e., descriptions of the design task, team composition, etc.). The findings of our review are discussed in detail in the next section.

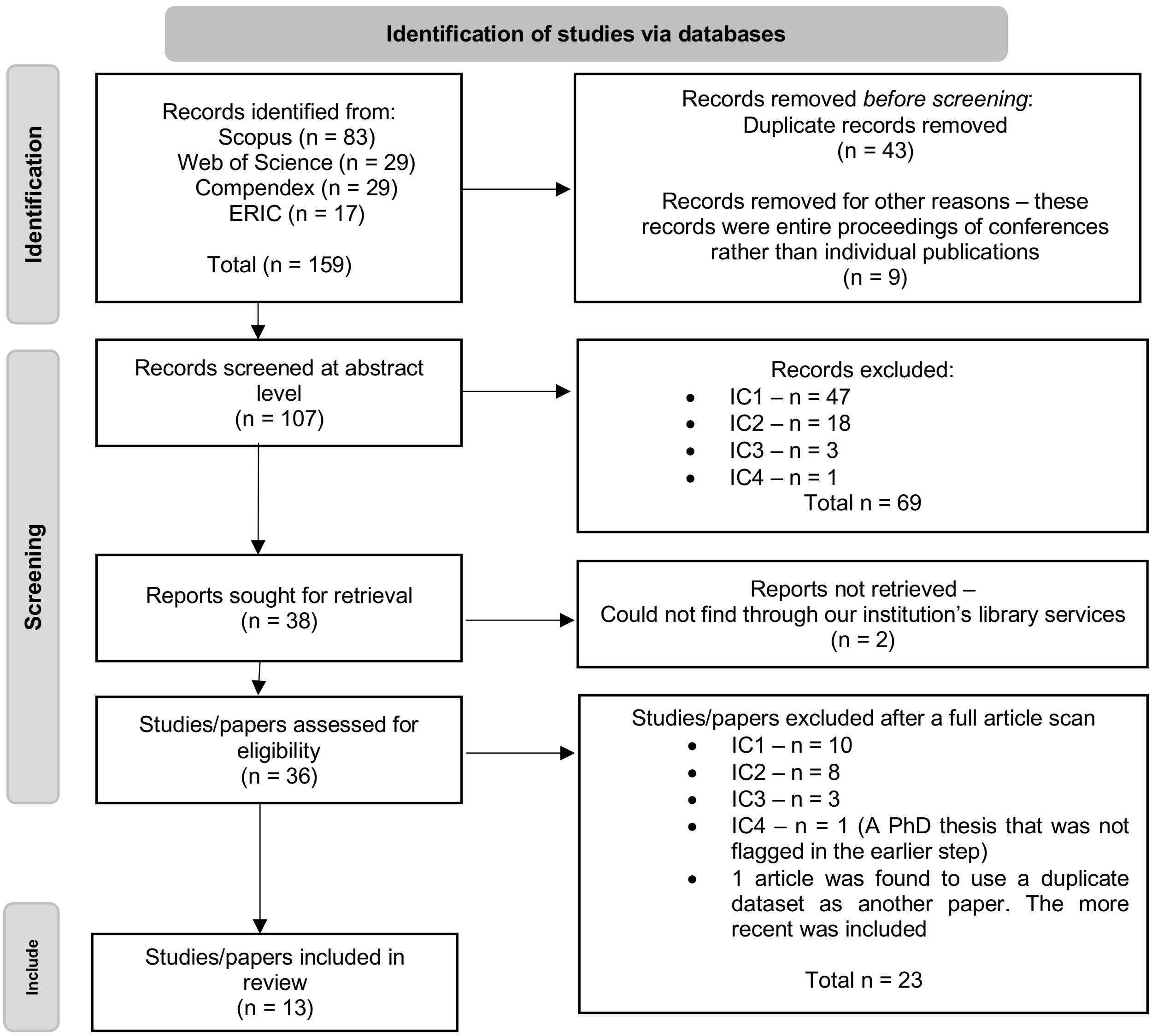

Figure 1: PRISMA Statement for Identification of Mental Model Measurement Techniques in Undergraduate Engineering Contexts

4. Results

The 13 records that met all our inclusion criteria, were published between 2004 and 2021, indicating that this has been a relevant area of research for several years. Table 1 below summarizes the findings from our analysis of each article.

Each article included undergraduate (and sometimes graduate) students working on an engineering design problem in teams of varying sizes. We focused on understanding the context of each paper, the technique(s) used to elicit the mental model ("Elicitation Process") from the teams and then the process used by the research team or the students themselves to generate a representation of that mental model ("Model Generation Process"). The design contexts in which students were working were different and included topics related to issues with transportation in snow (Helm et al., 2017), designing low-income housing (Quinones et al. 2009), or designing a new desk lamp (Muller et al., 2009).

The elicitation processes – meaning the way in which the authors of each article took out the information that would create the mental model – was unique, though they can be broadly categorized as having a significant visual element (e.g., Pathfinder Networks in Braunschweig & Seaman (2014)), being derived from text(s) that were either generated by the students themselves (e.g., in the form of reflective writing found in Sochacka et al. (2020)) or observations of designing (e.g., audio recordings found in Quinones et al. (2009)). Depending on the context of the study, the elicitation technique that was used could also act as the generation process of the mental model – meaning the way in which authors interpreted or translated the knowledge to give it structure. In other words, some studies used a measurement technique that required a limited amount (or none) of interpretation by the research team to represent the model. This was often the case with the more visual forms of representation (e.g., Bailey et al., 2021).

Table 1: Reviewed papers including the context, elicitation, and model generation process

Author (Year)	**Title**	**Context**	**Elicitation process**	**Model Generation process**
Bailey et al. (2021)	Interdisciplinary Team-Based Learning: An Integrated Opportunity Recognition and Evaluation Model for Teaching Business, Engineering and Design Students	Participants were junior and senior undergraduate students from a variety of engineering disciplines. Students worked in teams of 4-6 people to identify and propose an entrepreneurial project (e.g., a sustainable home)	Concept maps were used as a way for students to elicit, codify and share their individual discipline specific mental models. Venn Diagrams were used as a way for students to visually represent the logical relationships between discipline specific mental models. Prototypes were used as a way for students to elicit and share the mental model of the discipline specific approach to opportunity evaluation. Students created multi-criteria decision matrices to represent the logical relationships between evaluation criteria.	Concepts maps act as the generated model of the groups. Venn Diagrams act as the generated mental model of an interdisciplinary understanding of the problem. Prototypes act as the generated mental model as they are concrete representations that enable assessment. Multi-criteria decision matrices act as the generated shared interdisciplinary team mental model.
Braunschweig & Seaman (2014)	Measuring shared understanding in software project teams using pathfinder networks	Participants were undergraduate computer science students. Participants worked on a semester long design project.	Teams submit requirements and design documents 8 weeks into the project. Then students complete a relatedness survey based on concepts they generated that is passed to a pathfinder network software. The authors also conducted group interviews.	The authors selected concepts using document analysis from the documents text, tables, and diagrams. These concepts were visualized as Pathfinder Networks and analyzed in R. Group interviews were transcribed and coded using an open coding approach.
DeFranco & Neill (2009)	Improving learning outcomes using cognitive models in systems design	Participants were novice computer science students as well as graduate software engineering students. Participants worked in groups of 3-4 people to develop a supermarket simulation.	Participants submitted a Problem Understanding Document and a Solution Plan Document.	The Problem Understanding document was assessed by two independent judges using a rubric. The rubric outlines what the judges were to look for the inclusion of simulation elements. The Solution Plan document was also assessed the same two judges using a rubric. The rubric outlines that the document should contain details of the plans, subgoals, and schedules.

Table 1: Reviewed papers including the context, elicitation, and model generation process (cont.)

Dulipovici & Robillard (2004)	Cognitive aspects in a project-based course in software engineering	Participants were undergraduate software engineering students Participants worked in teams of 3-4 and were tasked with the development of a Web-based meeting management system.	A time recording tool was used to measure the effort spent on each activity or artifact produced.	The authors created five codes related to the types of artifacts the team spent time on (4 technical codes, 1 project management code). The authors linked the time records to their own codes to obtain percentages of time spent on each artifact/activity.
Flus & Hurst (2020)	The emergence of the project manager role in student design teams: A mixed-methods exploratory study	Participants were students enrolled in an interdisciplinary program as well as fourth year engineering students from a variety of disciplines. Participants worked on 8-month long design projects, each with a different context.	The study with the interdisciplinary students used semi-structured interviews with rotating team members. The study with engineering students used survey response.	The interview questions aimed to elicit how teams were managing their projects and evaluating the success of those management techniques. The survey asked questions related to the nature of project management within each team (i.e., when a PM was assigned, how a decision was made about PM, etc.).
Helm et al. (2017)	The idea mapping board: A tool for assessing design concepts and visualizing a team's use of the design space	Participants were engineering undergraduates. Participants worked in groups of two and used the Idea Mapping Board to assess ideas they generated for a design problem focused on new solutions for transporting a person in the snow.	The Idea Mapping Board is used as the representation of the solution space across two-dimensions as well as individual reflections. Additional data collected included sketches and written descriptions of design concepts.	The Idea Mapping Board is used as the representation of the solution space across two-dimensions as well as individual reflections.
Ifenthaler et al. (2014)	Exploring learning how to learn in team-based engineering education	Participants were undergraduate and graduate students from a variety of disciplines. Participants worked in groups of 2-4 students to provide an answer to a courses "Question for the Semester". Limited details on the Question for the Semester were provided in the article.	Individual mental models were elicited from 350-word written responses. Shared mental models were measured in a similar way with additional measurements from a survey.	The paragraphs were analyzed using an automated knowledge visualization and assessment tool which creates an association net between concepts. Individual association nets act as the mental model that was generated. Individual responses were aggregated into a shared knowledge representation using common knowledge that individual participants shared.

Table 1: Reviewed papers including the context, elicitation, and model generation process (cont.)

Muller et al. (2009)	The Explication of Implicit Team Knowledge and Its Supporting Effect on Team Processes and Technical Innovations An Action Regulation Perspective on Team Reflexivity	Participants were graduate or undergraduate engineering students. Participants worked in teams of 3 to design a concept for a desk lamp with an area of adjustment of five degrees of freedom.	Team members completed an exercise using the Repertory Grid Technique for action-guiding elements. This process facilitates explication of group level knowledge. Video recordings were taken and analyzed.	Inductive qualitative content analysis identified six categories related to important action-guiding elements generated by the participants.
Quinones et al. (2009)	Bridging the gap: discovering mental models in globally collaborative contexts	Participants were undergraduate engineering students in different disciplines. Participants were grouped into three different teams and were asked to work on a design project in an international context	Detailed observations of the groups' meetings, transcripts from interviews with participants, weekly journal entries, survey responses	Notes from the observations, interviews and journal entries were compiled and grouped into categories reflecting the types of problems a team encountered.
Sochacka et al. (2020)	A qualitative study of how mental models impact engineering students' engagement with empathic communication exercises	Participants were sophomore mechanical engineering students. Participants completed four empathy modules included encountering others with genuineness, self-awareness/emotional regulation, affective responding, and mode switching.	Empathy module reflections	Empathy module reflections were analyzed used an inductive thematic analysis approach to identify elements of both team (e.g., affective sharing) and task (e.g., listening to stakeholders) mental models.
Walters et al. (2017)	Fostering systems thinking within engineers without borders student teams using group model building	Participants were undergraduate and graduate students involved in the Engineers Without Borders program. Participants worked in small groups on a Group Model Building assignment related to a water building project in Peru.	Individuals created their own pre-workshop diagram with factors, links, and feedback loops. Then the team aggregated the sub-factors they created individually into a group defined causal-loop diagram. A pre- and post-survey were also used to identify shifts in mental models.	The responses to the individual pre- and post-workshop models as well as the aggregate causal loop diagrams were used as representations of the mental models. The individual models were compared to the group model based on number of factors, connections, and loops.

Table 1: Reviewed papers including the context, elicitation, and model generation process (cont.)

Zeiler (2016)	Competencies beyond Engineering: a Mental Model of Conceptual Building Design	Participants were engineering students from a variety of disciplines. Participants worked in teams of 4 to design a nearly Zero Energy Building in a single semester.	Individual morphological charts generated by the participants were used as representations of the mental models. These charts were later discussed and combined into a shared morphological chart.	Individual morphological charts generated by the participants were used as representations of the mental models. These charts were later discussed and combined into a shared morphological chart.
Zemke (2016)	Developing a coding framework to analyze student-to-student reasoning based on mental models theory	Participants were mechanical engineering students. Participants worked in teams of 3-4 students to design a machine that would flip poker chips individually from one stack to another.	A recording and transcript were gathered from the teams reviewing the prototypes.	Transcripts were segmented and coded using a theory of mental models. Codes identified statements that were possible, iconic, and true characteristics of mental models according to Johnson-Laird's theory.

5. Discussion

Mental model measurement techniques are not consistent, likely due to the context-dependent nature of mental models (Mohammed et al., 2010). Results from the analysis confirm this finding as well, as our selected set of articles uses diverse implementations of mental model measurement techniques (i.e., elicitation and generation processes). In the following sections we will use the findings to draw some comparisons between the various techniques and their utility in measuring mental models. In general, we notice that the mental model measurement techniques have one of two general structures, which have also been described in Mohammed et al. (2010): single process where both the content and structure of the model are generated simultaneously or dual process where the content and structure of the model are retrieved at two separate times, usually by two distinct sets of people. In the case where the measurement took place in two parts, there was usually an element of translation between some artefact (e.g., a reflection or course document) and the generated mental model. We will comment on the usefulness of these two approaches in the following sections.

5.1 *Measurement is a single process (What and How together)*

Four of the articles reported using measurement techniques in which both the structure and content of the mental model was reported at the same time. These techniques are visual in nature, allowing multiple participants to include their own subjective interpretation of the task at the same time. These techniques ask students to create a visual representation of a situation that serves as a representation of their mental model. In Helm et al. (2017), authors report that the Idea Mapping Board technique used was a useful tool for visualizing and assessing ideas as well as understanding how the design space was explored (Helm et al., 2017). This tool is meant to help teams visualize the design space as they form a taskwork mental model. In this case, the idea mapping board is a dynamic visualization of this shared mental model. Similarly, the four elicitation techniques used in the Bailey et al. (2021) article allowed the students to elicit, codify and share their mental models over time. These visualizations also allow for integration of knowledge, evaluation, and assessment (Bailey et al., 2021).

In Walters et al. (2017), using both the individual and aggregate (i.e., the shared mental model) causal loop diagrams created by the students the authors were able to assess any shifts in the shared mental models related to sub-factors of the project as well as the student's ability to use systems. In this case, the causal loop diagram – which is the generated mental model – had several interesting metrics that could be associated with it (e.g., # of factors, # of connections, observable loops). These could then be used to draw insight about the team's shared mental model (Walters et al., 2017). Similarly, the morphological charts used in the Zeiler (2016) article, allowed the author to comment on the effectiveness of creating functions and sub solutions first at the individual level and then later at the shared mental model level. Using this technique allowed for comparison between individual and team morphological charts to assess the sharedness of the team's taskwork mental model (Zeiler, 2016).

5.2 *Measurement is more than one process (What from one, How from other)*

Many of the articles (9) reviewed in the study used a measurement technique that first elicited the knowledge (e.g., what is in the mental model) followed by a process completed by members of the research team to determine the structure of that knowledge (e.g., how is it organized). The structure was generated using a broader set of techniques than the models that were measured in a single process. These included visualizations, in addition to the coding of transcripts or observations, and other statistical methods. For example, in Ifenthaler et al., (2014) individual paragraphs were analyzed using an automated knowledge visualization and assessment tool. The tools create an association net between concepts that are identified in the students' written reflections. These association nets can then be used to create a visual representation of the relationships between concepts. The process of creating the structure of the mental model, depicted using the association nets, was completed by the researchers not the students themselves. Similarly, in Braunschweig & Seaman (2014), the authors used pathfinder networks to determine the structure of concepts in the students' mental models after having collected a set of concepts from the team's design documents. Using this method allowed the authors to generate insight about the concepts that team members may (or may not) have had a shared understanding of. They state that concepts with low similarity scores (i.e., limited shared understanding) were either misunderstood by all members of a team or one team member had a mature understanding of the concept while others on the team did not, likely because of roles and responsibilities of team members (Braunschweig & Seaman, 2014).

Other papers included in our set used qualitative methods that included coding of some written or recorded artefact. To generalize, the written or recorded artefact provides the information relevant to what is included in the mental model. The coding process that follows, completed by the researchers and not the students themselves, provides a structure of that knowledge. For example, in Sochacka et al., (2020) the authors inductively thematically analyzed empathy module reflections which helped them identify elements of both team and task shared mental models. This type of method allowed the authors to comment on how preconceptions about engineering practice may lead to tensions with student effort to develop more sophisticated understandings of the role of engineering in society (Sochacka et al., 2020).

In Muller et al. (2009), the authors use an inductive qualitive content analysis approach to identify the action-guiding elements of the shared task mental model. These elements included working conditions, team climate, communication strategies and goals. Using this approach allowed the authors to conclude that the development of the shared task mental model seems to support overall team performance (Muller et al., 2009). In Zemke (2016), the authors take a more deductive approach, using a pre-determined coding scheme based on a theory of mental models for content analysis of transcripts. This allowed the authors to identify the structure of the students' reasoning process, which provides structure to the knowledge students have about how they might approach their problem. One interesting insight they provide is that the structures emerge whether the students seemed to be in full agreement or strong disagreement.

Finally, some measurement approaches used tools to conduct statistical analysis on data that was gathered using interviews and surveys. For example, a time recording tool used in Dulipovici & Robillard (2004) allowed the authors to measure the percentages of time spent discussing mental processes that the team shared included reading, discussing, thinking, browsing, training, and inspecting. Flus & Hurst (2020) used results from a survey to determine if a shared mental model of project management strategies (i.e., an element of teamwork mental models) was present among engineering-student teams. The survey results indicated that teams did not have a common understanding of how the teams were managing their projects (Flus & Hurst, 2020).

5.3 *Comparison of the two approaches*

The identification of these two general approaches for measuring mental models (i.e., single process or dual process) offers an opportunity for comparison between the two. In general, we noticed that the measurement processes where elicitation and generation (section 5.1) were completed at the same time were used exclusively for taskwork shared mental models. For example, in Helm et al. (2017) the authors were able to identify how students in their study structure their solution ideas in the design space, an element related specifically to their task. This might offer a unique opportunity for design instructors to implement this type of activity into their classrooms to ensure that the student teams have a shared understanding of their task. It may also be the case that these measurement techniques are more challenging to implement with the knowledge structures associated with teamwork mental models, and students' limited knowledge of teamwork concepts. That is, elements of teamwork (i.e., complex social relationships or conceptualizations of leadership) are not as easily visually represented compared to elements of taskwork. A study, like Flus & Hurst (2020), that used a survey and interview protocol might be more appropriate for determining the content and structure of a shared teamwork mental model, as they were able to identify instances of teams not having shared understanding of their project management strategies in a fourth-year capstone design course.

Interestingly there were examples in each of the two technique categories that generated a visualization of the mental model. If we compare those two approaches, like pathfinder networks (Ifenthaler et al., 2014) or causal loop diagrams (Walters et al., 2017), we notice that they afford different kinds of analysis. That is, in the case of pathfinder networks, though the visualizations look like the causal loop diagrams found in Walters et al. (2017), it allows for more computational methods of analysis compared to the casual loop diagrams generated by the students. Depending on the nature of the research, a more computational approach to analysis might be preferred. However, using a measurement technique that both elicits and generates the model at the same time might produce a more accurate representation of the model, simply because there is less inference on the part of the researcher about what the structure of the mental model is. Having a researcher engage in discussion with the students to develop a deeper understanding of the model they represented and ensure student meaning is conveyed in their representation (instead of inferring meaning alone) may afford even more accurate measurement.

5.4 *Connection to the literature and classroom practice*

In the background section we mentioned that the design contexts that engineering undergraduate students work in are different than the command-and-control or military contexts which have been the contexts in which most of the literature has focused thus far. Though these contexts are quite different in nature, we notice that many of the same measurement techniques are used. We see similar measurement techniques emerging in the undergraduate engineering contexts (both concept mapping and qualitative methods are present), though with far less frequency given the limited number of articles that we were able to identify. Techniques such as card sorting (which are often seen in scoping activities in design, see Yilmaz and Daly (2016) for an example) were not prevalent in our findings. This may be because there is no presumption of a fixed set of concepts within the mental models that are being assessed; there is an acceptance that each team will define/understand their taskwork and teamwork differently.

Our results align with another recently published literature review on a similar topic by Kim (2019). Their review focused on understanding a broader set of elements related to mental models in engineering design contexts, but not specifically engineering education contexts. While none of the records that were included in our review were used in the Kim (2019) review, 6/25 articles used in their study conducted research with students as participants – the population focus of our literature review. Though the focus of their review was broader, they observed techniques (i.e., surveys and interviews, concept mapping, etc.) that align with the measurement techniques we found. As a result, this lends credibility to the potential utility of the measurement techniques we have identified, and posits an alignment between the engineering design classroom and engineering design in practice.

In the context of the undergraduate design classroom, a single process mental model measurement technique may afford design instructors a way to assess their student understanding of their team and task work. The visualization techniques we have found for taskwork models are tools often used in defining a design or solution space. Having students individually complete these representations and then share them with each other to compare what each has generated (as in Walter et. al. (2017)), will provide students an opportunity to self-assess the sharedness of their mental models, and by extension their understanding. Prompting these activities could stimulate conversation to ensure teams have a shared understanding of both what they are working on and how they are working on it that will prevent problems in the future.

We believe that this discussion indicates a larger research gap which is of interest to the engineering education community. This gap offers two rich areas for further inquiry. The first is to continue to draw from the methods and measurement techniques used in the more structured contexts to determine their utility in design education contexts. It may be the case that these measurement techniques can provide insight about how to help students generate shared mental models in design contexts. The second research area is to continue comparing findings from the previous literature with the findings from the design education contexts to determine if the characteristics of shared mental models are similar across disciplines. We anticipate that focused research in these two areas will be useful for engineering educators to continue improving their pedagogical techniques and mentorship of student design teams, as we will have a more thorough understanding, in this case at the cognitive level, of how students are experiencing their work in design contexts.

6. Conclusion

The inherent richness of design practice in undergraduate engineering contexts provides a unique opportunity to understand shared mental models in more detail. Of utmost importance to this endeavor is to be able to use the appropriate methods for measuring mental models in these contexts. This literature review has provided a short synthesis and comparison of the techniques that have been previously used. We identified and reviewed a set of 13 articles to draw insight and summarize how these measurement techniques have been implemented. In general, we found that the measurement techniques either had students provide both the content and structure of the mental model or had students provide the content which could then be processed in a way that allowed researchers to identify the structure. We have provided some commentary comparing these techniques highlighting some of the differences between a single combined elicitation and generation process and the dual process. We have also provided some suggestions for how knowledge of these elicitation techniques will be helpful in the context of the engineering classroom in which design is taught. Finally, we have provided evidence for how this review continues to build on previously published work, with hope to drive further interest in research projects that measure mental models. By doing this, we will continue to develop a more sophisticated understanding of how students are experiencing team-based design situations.

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