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System Modeling: An Exploratory Study Of Engineering Students' Conceptual Knowledge And Problem-Solving Skills

Ademola Amida

SYSTEM MODELING: AN EXPLORATORY STUDY OF ENGINEERING STUDENTS' CONCEPTUAL KNOWLEDGE AND PROBLEM-SOLVING SKILLS

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Ademola Amida
Bachelor of Engineering, HAMK University of Applied Science, 2013
Master of Science, University of North Dakota, 2016

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Name: Ademola Amida

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This document, submitted in partial fulfillment of the requirements for the degree from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

DocuSigned by:

Dr. Woei Hung

DocuSigned by:
Gail C. Ingwalson

Dr. Gail Ingwalson

DocuSigned by:
Robert Stupnisky

Dr. Robert Stupnisky

DocuSigned by:
Yun Ji

Dr. Yun Ji

This document is being submitted by the appointed advisory committee as having met all the requirements of the School of Graduate Studies at the University of North Dakota and is hereby approved.

DocuSigned by:
Chris Nelson

Chris Nelson
Dean of the School of Graduate Studies

7/21/2021

Date

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Ademola Amida
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ABSTRACT

System modeling (SM) instructional strategy, an application of system thinking (ST), can be used as an instructional approach to help students develop SM skills and deepen their understanding of subject matter (Hung, 2009). Mechanical engineering students have difficulty applying gained knowledge in real-world contexts and are reportedly underprepared for workplace challenges (Kirkpatrick et al., 2011; Warsame, 2017). This study explored the efficacy of system modeling (SM) instructional strategy in a mechanical engineering course. Specifically, the study sought to understand students' perceptions and experiences with the use of system modeling in enhancing their conceptual knowledge and problem-solving skills.

This study employed a qualitative inquiry approach to understand engineering students' experience and perceptions of the use of system modeling. A purposeful sampling technique was utilized to recruit mechanical engineering students to participate in the study. Semi-structured interviews and students' artifacts including problem solving survey and causal modeling diagrams, were used to explore and gain an in-depth understanding of students' experiences with the use of system modeling (SM) instructional approach.

The findings indicated promising effects of the SM approach on students' learning outcomes. Seven major themes emerged from the in-depth interviews conducted to gain insights into students' experiences. These themes included: problem diagnosis, interconnection and interdependency, linearity, external representation of causal relationship, wholeness and decision making, organize problem-solving approach, and systematic and forward-thinking process. Students' artifacts and data presented in this study supported their positive experiences using the

SM approach. The problem solving inventory PSI survey responses indicated that most of the participants believed the SM approach affected their perceived problem-solving skills, especially their approach-avoidance style. Furthermore, the model diagram analysis suggested that all participants showed moderate system thinking skills after the SM instructional strategy.

This current study provides insight and understanding about SM instructional strategy effectiveness and how it can help enhance student learning outcomes. Exploring the impact of SM on student learning experiences is important not only because it could provide alternative instruction to the traditional methods, but also to inform instructors of its potential benefit of undergraduate education instruction. Furthermore, the current study could serve as a guide for instructors on how to implement the SM instructional strategy in a mechanical engineering curriculum.

CHAPTER I

INTRODUCTION

Over the past decades, higher educational institutions have encountered a paradigm shift from traditional teacher-centered instruction to a learner-centered approach (Huba & Freed, 2000). Learner-centered instruction is rooted in the constructivist philosophy in which learners actively construct their own knowledge (Driscoll, 2002; Jonassen, 1991; Merrill, 1991; Schunk, 2012). In the learner-centered paradigm, learning is facilitated by creating an active learning environment, thereby fostering skills like problem-solving and critical thinking skills (Huba & Freed, 2000; Merriam & Bierema, 2013). Essentially, the focus is on the students and their learning needs and outcomes (Brown, 2003). However, creating an enabling environment that promotes these skills requires choosing appropriate instructional approaches and the design of suitable activities to meet students' learning needs (Nilson, 2013).

Despite the shift to the learner-centered approach, research suggests that most engineering instruction remains largely unchanged (Mills & Treagust, 2003; Felder, 2012). For instance, Brunhaver et al. (2017) reported that most engineering programs still use the traditional teacher-centered instruction, which may not effectively promote conceptual knowledge and problem-solving skills among engineering graduates (Kollöffel & de Jong, 2013; Robinson-Bryant, 2018; Vergara, et al., 2009). This could be because traditional instruction provides students linear and structured problems (textbook problems) that require only a single right solution (Sheppard et al., 2009). This instructional method may not facilitate integration of knowledge and lead to learning concepts in isolation with little or no context (Linn & Hsi, 2000;

Hopper & Stave, 2008). For instance, Buch and Bucciarelli (2015) argued that most engineering concepts and principles are taught without providing adequate context to help prepare students for real world problem solving. These ways of teaching do not align with the engineering workplace's needs, resulting in frustration for employers (Felder, 2012). Besides, the traditional approach contradicts contemporary constructivist philosophy that encourages active learning and knowledge construction (Bradforth et al., 2015). Consequently, there is a need for engineering educators to reconsider their teaching practices, align learning needs, and implement teaching strategies that will encourage knowledge construction, foster active learning and develop students' higher-level skills.

Mechanical engineering education require the same instructional improvements as the other engineering discipline. For example, Ow and Kanan (2015) reported that mechanical engineering curriculums do not align with the workplace needs. This gap was highlighted in an American Society of Mechanical Engineers (ASME) study that examined the expectations and levels of preparedness of new mechanical engineering graduates from the industrial employers' perspective (Kirkpatrick et al., 2011). Kirkpatrick and colleagues reported that some employers believed that the mechanical engineering profession can help address 21st century challenges; however, most believed that recent graduates lack higher order skills like problem solving skills, application knowledge, and critical thinking skills.

To address instructional problems, the systems modeling (SM) instructional strategy may provide a means to remedy the issue. SM, an application of system thinking, can be used as an instructional approach to help learners develop SM skill as well as deepen their understanding of subject under study (Hung, 2009). This is because SM enables learners to visualize and represent abstract concepts and understand the interrelationships within the concepts and mechanism of a phenomenon, with a holistic perspective (Bahill & Gissing, 1998; Hmelo-Silver et al., 2017). This system thinking perspective allows learners to develop and restructure their mental models (Greene & Papalambros, 2016; Hung, 2009). Thus, SM has the potential to provide instructional scaffolding that enables learners to visualize and represent relationships and interdependencies between units and the entire system.

System Thinking and Modeling

Theoretical Foundations

The theoretical basis of system modeling (SM) is the general system theory (GST). According to von Bertalanffy (1950), the "general system theory is a general science of wholeness… the whole is more than the sum of its parts" (p. 142). This definition suggests that the property of a system does not result from the sum of its parts. Rather, Ackoff (2004) claimed that the system properties are the product of its interacting parts. Similarly, a system was defined as "a set of interacting units or elements that form an integrated whole intended to perform some functions" (Skyttner, 2001, p. 53). This definition highlights that the interaction of parts within a system results in the behavior of that system. On this basis, system thinking can be said to be a way of thinking that conceptualizes a phenomenon from a holistic world view while also considering the interconnection between its parts (Capra, 1996; O'Connor & McDermott, 1997). It is important to note that as the parts of a system interact, its functions and existence remain unchanged (O'Connor & McDermott, 1997).

Systems modeling is a visual representation approach based on general systems theory. According to Jonassen (2000), "a model is a conceptual representation of something, described verbally, visually, or quantitatively" (p. 138). It comprises of elements, their interactions, and operational rules used to represent the behavior of a system (Jonassen, 2004). A model depicts the properties, conceptualization, constraints, and underlying assumptions of a real-world phenomenon (Morge, Narayan, & Tagliarini, 2019). System modeling SM is a cognitive tool that can be used to represent the complexity of a system and its interrelated parts (Hung, 2009; Jonassen, 2000). SM can encourage causal reasoning in dynamic systems (Jonassen, 2004).

System Thinking and Modeling – Characteristics

SM is the practical application of system thinking and has the following characteristics: wholeness, external visual representation, interrelationships, and non-linearity (Capra, 1996; Hung, 2009; Sweeney & Sterman, 2000; Verhoeff et al., 2018).

Wholeness Instead of Isolated Parts. System theorists propose that the system properties emerge from the wholeness of the system rather than its isolated parts. This is a deviation from the traditional mechanistic analysis perspective that emphasizes understanding based on individual parts. For instance, in the traditional approach a problem-solver breaks down the system and examines its parts in isolation to understand the problem. The understanding of the parts can then be used to deduce the understanding of the whole system (Ackoff, 2000). In contrast, system thinkers focus on understanding the underlying causal structure of the system as a whole instead of breaking it down to its parts. In fact, Capra (1996) argued that essential properties of a system are lost when it is broken down to its constituent parts. Hence, a system can only be completely understood from a holistic perspective.

Interrelationship and Interdependency. System thinkers consider systems as having interrelationships and interdependencies within its parts. System thinkers view the world as having interconnected parts forming a network of things rather than isolated parts (Capra, 1996). The network of interrelationships within a system determines the emergent properties of that system (Hung, 2009). In other words, the property of a system is the product of its interacting parts and its causal relationships (Ackoff, 2004). Essentially, system thinkers suggest that the parts in a system do not have independent effects on the whole but that its effect in a system are interdependent (Ackoff, 2000).

Non-Linearity. In the traditional mechanistic approach, relationships that exist between parts of a system are considered linear and hierarchical. On the contrary, in system thinking the relationship between parts and whole is non-linear and non-hierarchical forming a network of causal-relationships (Capra, 1996). This implies that the effect of one variable can have multiple non-linear and various nature of effects on the other parts of the system (Hung, 2009). This is because all of the parts of the system are interconnected and interlinked.

External Representation. Systems can be modeled using external visual representation to show the causal relationships and the behavior of the system (Jonassen, 2000). External representations can be used to depict and describe the structure, operations, and underlying causal relationships that exist within a system. When system thinkers construct external representations, they are able to conceptualize the systems behavior as well as internalize and externalize their understanding of the system (Hung, 2009). These external representations can be paper and pencil diagrams or simulations.

System Modeling and Thinking – Tools

To understand a complex system, it is important to consider the wholeness of the system and the interrelationship between its parts. System researchers have long argued that a system's behavior is characterized by the interactions between its parts (Ackoff, 2004; Capra, 1996). The properties resulted from the interaction are known as 'emergent' system properties (Sweeney & Sterman, 2000). Complex system properties or dynamics can be modeled to show system behavior and the interrelationship between its parts. These properties can be modeled using system modeling/thinking tools like behavior over time graphs, causal loops/feedback diagrams (reinforcing loop, balancing loop), and stock/flow maps (Hopper & Stave 2008; Sterman, 2002; Sweeney & Sterman, 2000).

Behavior over time graphs (BOT) show the basic trend of the behavior of systems on a time graph. The BOT can help students visualize the changes occurring within the system over a period of time (Waters Foundation, 2008a). The BOT modeling/thinking tools allow students to find patterns or trends in a system's behavior over time rather than experiencing isolated events (Gillmeister, 2017).

The causal loops diagram (CLD), also known as a feedback loop diagram, can represent cause-effect relationships within a system. Unlike the linear causal diagram, the CLD shows not only the direction but also the nature of the effect of each part on other parts as well as the system (Plate, 2010). The interactions of the parts of a system can positively or negatively influence the system (Sweeney & Sterman, 2000). CLD can either be reinforcing or balancing loops within a system (Hung, 2009). Reinforcing loops are loops that depict a positive relationship between two variables, while balancing loops show negative relationship between two variables. The BOT and CLD capture the relationships that exist within a system. One drawback in using a CLD is that it cannot be used to make predictions on a system behavior (Jonassen, 2000).

The stock-flow map is another tool that can be used to visually represent changes and relationships in a system. It highlights a system's underlying physical organization (Sterman, 2000). The stock-flow map is comprised of stocks, flows, converters, and connectors (Arnold & Wade, 2015; Hopper & Stave, 2008; Jonassen, 2000). Stocks are like a reservoir of resources in a system (can be physical e.g., water or abstract e.g., feeling) that changes in quantity over time

(Arnold & Wade, 2015). Flows affect the inflow and outflow in a system, causing changes in the stock (Gillmeister, 2017). Converters influence the flow in a system and convert inflow to outflow, while connectors are lines that show the direction of flow in a system (Gillmeister, 2017; Jonassen, 2000).

The aforementioned SM tools could help students better conceptualize the subject under study. For instance, the stock-flow map may enable students to visualize the cause and effect relationships between multiple variables in a system. Students can see how an increase or decrease in one variable can affect the other variables. This visual experience can help students make accurate inferences about the behavior of the system and validate their internal model. Similarly, the BOT is a great tool for students to understand the pattern of behavior of the system over time and CLD is a helpful tool to capture the relationships that exist within a system. These learning tools could enable students to understand complex systems by considering the wholeness of the system and the interrelationship between its parts.

System Modeling and Factual Knowledge

Factual knowledge, also known as declarative knowledge, is the basic knowledge of content elements in the discipline, including facts, definitions, and terminologies (Anderson & Bloom, 2001; Krathwohl, 2002). When students can recall facts, the definition of terms, they are said to have gained factual knowledge. Factual knowledge is the term mostly used when assessing students' content mastery. Cognitive researchers suggest that mastery of factual information in a particular domain is important before higher-order learning like critical thinking and problem solving (Willingham, 2009; Roediger, McDaniel, & Brown, 2014). Essentially, factual knowledge can promote conceptual knowledge and ultimately enhance students' problem-solving skills (Huba & Freed, 2000).

Factual knowledge is an important dimension of knowledge in engineering education (Hoffmann, 2008). For instance, Frise et al. (2003) claimed that engineering students must master factual information with practical knowledge to attain professional knowledge needed in engineering workplaces. Factual knowledge in engineering involves students mastering engineering terminologies, concepts, formulas, equations, and algorithms.

Research suggests that representation tools, like SM, may reduce abstraction by helping students visualize abstract concepts, thereby promoting factual knowledge (Uttal & O'Doherty, 2008). In SM, students demonstrate factual knowledge by correctly recognizing, recalling, defining system parts, and recognizing interrelationships between the parts. Hopper and Stave (2008) argued that recognizing parts and their interconnections are the basic level of system thinking. Hence, SM could help students gain better factual knowledge than traditional instruction, promote retrieval of factual information, help organize the facts, and show the interrelationships between the concepts to promote more meaningful learning.

System Modeling and Enhancing Conceptual Knowledge

Conceptual knowledge is the 'knowledge of concepts' (Rittle-Johnson, Siegler, & Alibali, 2001). It is "an understanding of the essential parts and cause-effect relationships that exist within a system" (Guenther, 1998, p. 289). Guenther's definition suggests that conceptual knowledge is not just about memorizing concept and formulas, but that it also involves understanding concepts and the interrelationships between its parts (Davis, 2013). In other words, conceptual knowledge is knowledge-rich in interconnections (Hiebert, 2013).

Canobi (2009) described conceptual knowledge as understanding "the structure of the problem domain" (p. 132). This definition indicates that conceptual knowledge is important knowledge in understanding the problem domain, which can be explained by the underlying structure and interrelationships of the system under examination. These interrelationships are linked to the system's behavior and dynamic properties (Hung & Jonassen, 2006).

Indeed, in problem-solving students need to construct their conceptual knowledge in the problem domain (Lucangeli, Tressoldi, & Cendron, 1998). This will help them to define the problem and identify important aspects of it, thereby promoting problem space construction (Rittle- Johnson, 2006; Hung, 2009). A problem that is defined well can facilitate students' problem-solving process.

System Modeling and Application Knowledge

Application knowledge is the knowledge required to apply or use a procedure or content knowledge in a specific context (Krathwohl, 2002). When students are able to apply or use the knowledge learned in class to solve a given problem, they are said to have gained application knowledge. Teaching students factual knowledge alone does not guarantee that they will be able to apply the knowledge. While faculty members expect students to apply or use their knowledge to solve problems, in most cases, students do not know how to apply their knowledge because they have not been taught (Bankel et al., 2005).

Mechanical engineers need to use their specialized knowledge in multiple contexts, including dynamic systems and processes. The first phase of gaining application knowledge requires students to learn abstract concepts, formulas, principles, or equations, and then apply that knowledge to solve a given problem in a different situation (Eggen & Kauchak, 2003). Jonassen (1999) recommended that in promoting application knowledge, educators should present instructions to encourage students to connect with instructional content in a meaningful way. SM instructional strategy has the potential to help students contextualize and depict the inter-causal relationships among concepts, thereby promoting meaningful learning. Hence, instructors seeking to improve the ability of mechanical engineering students may benefit from implementing learner-centered instructional approach like SM.

System Modeling and Developing Problem Solving Skills

A problem consists of the given state, the goal state, and the obstacle between the given and the goal state (Mayer, 1989). Problem-solving is a crucial skill for today's engineering graduates. Hung et al. (2008) defined problem-solving as "a process of understanding the discrepancy between current and goal states of a problem…" (p. 486). This discrepancy (also known as the gap) is the problem space (Newell & Simon, 1972) that is explored during the process of problem-solving (Hung, 2009). Hence, solving a problem involves finding the path within the problem space, starting from the current state, and ending in the goal state (Jonassen, 2004).

Problem-solving skills is an essential skillset for mechanical engineering students (Kirkpatrick et al., 2011). According to Hmelo-Silver (2004), "problem-solving skills is being able to define what the problem actually is, especially with ill-structure problems" (p. 253). Researchers suggest that the first step in problem-solving is to identify the problem and then construct the problem space (Jonassen, 2004; Newell & Simon, 1972; Reimann & Chi, 1989). The problem space construction includes identifying the key components of the problem like the current state and goal state, problem variables, and inter-casual relationships among the elements (Newell & Simon, 1972; Reimann & Chi, 1989). System thinking can help problem solvers better understand the underlying mechanism of the problem, thereby promoting their understanding of the inter-causal relationship (Hung, 2009). Thus, SM instructional strategies have the potential to help students develop these problem-solving skills, especially the step of defining the problem and problem space, which is essentially what system modeling does.

Mechanical Engineering Education

Mechanical engineering is one of the earliest engineering disciplines. It is "the branch of engineering dealing with the design, construction, operation, and maintenance of machine" (Dixit, Hazarika, & Davim, 2017, p. 4). Mechanical engineers contribute enormously to our daily lives by providing support services such as transportation and power generation system. Indeed, mechanical engineers are at the forefront of industry providing essential life-supporting services and pioneering innovations in environmental sustainability.

Mechanical engineering is the discipline of engineering that has the largest undergraduate enrollment among all engineering degrees (Roy, 2019; Yoder, 2015). Mechanical engineers apply scientific knowledge in designing, constructing, and maintaining processes and systems. Despite this large enrollment, research suggests that mechanical engineering graduates lack essential workplace skills such as problem-solving, application knowledge, and critical thinking to succeed (Kirkpatrick et al., 2011; Warsame, 2017). Hence, it is important to investigate instructional strategies that could help promote these essential skills.

Purpose of the Study

The purpose of this study is to explore the efficacy of system modeling (SM) instructional strategy in a mechanical engineering course. Specifically, the study sought to understand students' perceptions and experiences with the use of system modeling in enhancing their learning outcomes. The study focuses on learning outcomes such as factual, application, and conceptual knowledge, as well as students' self-perception of problem-solving and system thinking skills.

Research Questions

1. What are students' perceived efficacy of the use of SM instructional approach?
2. How do students describe their experience with SM instructional strategy in relation to their factual, conceptual, and application knowledge?
3. What perceptions do students have regarding the use of SM instructional approach in relation to problem-solving and system thinking skills?

Significance of the Study

This study contributed to the research on the implementation of system modeling instructional strategies in mechanical engineering. Specifically, this study provided insight and understanding of SM instructional strategy effectiveness in enhancing students' competence (i.e., factual, conceptual, & application knowledge) and promoting problem-solving skills as well as system thinking skills in mechanical engineering courses. Determining the impact of SM on students' learning experiences is important not only because it could provide alternative instruction to the traditional methods, but also inform instructors of the potential benefit of undergraduate education instruction. Furthermore, the current study could serve as an example for instructors on how to implement the SM instructional strategy in a mechanical engineering curriculum.

Definition of Terms

Active learning: is a type of instruction that promotes active engagement in the learning process through collaborative activities, thereby fostering the construction of knowledge and meaningful learning (Mintzes & Walter, 2020).

Application knowledge: is the knowledge required to apply or use a procedure or content knowledge in a specific context (Krathwohl, 2002).

Behavior over time graphs (BOT): are visual representations of the basic trend of systems' behavior on a time graph. The BOT can help visualize the changes occurring within the system over a period of time (Waters Foundation, 2008a).

Causal loops diagram (CLD): are diagrams that can be used to represent cause-effect relationships within a system.

Conceptual knowledge: is the 'knowledge of concepts' (Rittle-Johnson et al., 2001). It involves understanding concepts and the interconnections between the concepts (Davis, 2013).

Constructivism: is a philosophical view of the world that perceives reality as multiple and constantly changing based on individual experience. Constructivists postulate that learning involves the active construction of meaning from a unique individual perspective (Merriam & Bierema, 2013; Schunk, 2012).

External representation: is an external visual or other form of depiction of an individual's internal mental model of a concept, schema, or system, which describes the structure, operations, and underlying mechanism of the system (Hung, 2009; Jonassen, 2000).

Factual knowledge: is the basic knowledge of foundational elements in the discipline, including facts, definitions, and terminologies. It is also known as declarative knowledge.

Mental models: are "deeply ingrained assumptions, generalizations, or even pictures or images that influence how we understand the world and how we take action" (Senger, 2006, p. 8). Mental models are belief structures that represent a simplified conceptualization of an individual's understanding of a system (Monat & Gannon, 2015).

Non-Linearity: is a term used to describe non-linear and non-hierarchical relationships between parts and the whole. A non-linear relationship means that "a given variable in a system causes effect on one or more variables, and these variables consequently produce effects on their related variables" (Hung, 2009, p. 9).

Stock-flow map: is a tool that can be used to represent changes and relationships among variables within a system visually, thereby highlighting the system's underlying physical organization (Sterman, 2000).

System thinking ST: is a way of thinking that conceptualizes a phenomenon from a holistic world view while also considering the interconnection between its parts (Capra, 1996).

System modeling SM: is "a process of systemically conceptualizing and constructing a representation of a given system, phenomenon, or problem under study" (Hung, 2009, p. 1). Systems modeling is the application of system thinking.

CHAPTER II

REVIEW OF THE LITERATURE

The following chapter describes the literature review on system thinking (ST) and system modeling (SM). Specifically, the review examines the historical evolution of ST and SM, its definition, and theoretical foundations. The chapter also describes the characteristics of SM as an active learning, holistic instructional approach, as well as the tools used in its implementation. This chapter also reviewed literature on the impact of SM on students learning outcomes such as conceptual and application knowledge, as well as problem-solving and ST skills. Examples of SM implementation in engineering education and research in related areas like chemistry, mathematics, biology, and physics are discussed.

Mechanical Engineering Education: Issues and Need for Practical Competencies

Engineering education is a field of study that emphasizes the technical expertise, application of scientific principles, and practical knowledge (Crawley et al., 2007; Tan, 2014). Mechanical engineering, specifically, deals with the application of scientific knowledge and engineering concepts in designing, constructing, and maintaining processes and systems (Dixit, Hazarika, & Davim, 2017). These principles and concepts serve as the foundation for developing higher-order learning like problem-solving, critical, and system thinking (Willingham, 2009; Roediger, McDaniel, & Brown, 2014). This foundation becomes the building block of knowledge and learning in the engineering field. Hence, mechanical engineering education needs to promote the development of foundational knowledge and practical competencies in college graduates to prepare them for a successful career.

The literature, though, reported that most engineering graduates are not well prepared for workplace challenges (Warsame, 2017). In fact, research suggests there is a knowledge gap between mechanical engineering graduate competencies and industry needs. For instance, the American Society of Mechanical Engineers (ASME) conducted a study in which surveys were administered to more than 1,000 industrial employers. The survey assesses employers' perspectives on the level of preparedness of recent mechanical engineering graduates (Kirkpatrick et al., 2011). The researchers reported that most employers believed that new graduates lack essential workplace skills including problem solving, application knowledge, and critical thinking skills. While this may seem shocking, other researchers have reported similar concerns with engineering graduates (Buch & Bucciarelli, 2015; Falconer, 2016; Felder, 2012).

Several factors might be responsible for the gap between theories learned in the classroom and industrial practices. Some of these factors may include the types of instruction used in engineering classes (Buch & Bucciarelli, 2015) and the lack of practice experience needed to help recent graduate transition to professional engineers (Warsame, 2017). Moreover, the passive nature of instruction creates discrepancies between engineering classes and the active application-based workplace environments (Palmquist, 2007 cited in Yadav et al., 2011). As a result, engineering education has become abstract to learners compared to workplace practices (Bankel et al., 2005). This knowledge gap means that college graduates are underprepared and lack essential competencies to succeed in their careers (Felder, 2012; Sheppard et al., 2009).

The literature identified mechanical engineering competencies as: (1) acquiring specialized content knowledge, (2) gaining the ability to apply knowledge, (3) solving real world problems, and (4) developing system thinking skills (ABET Criteria for Accrediting Engineering Programs, 2018; Passow & Passow, 2017). Undergraduate engineering educators need to design instructions to help mechanical engineers develop these essential competencies to prepare them for a successful career. Clearly, as mentioned earlier, there is a competence gap between mechanical engineering education and industrial needs. So, the question is, what instructional strategies could be implemented to bridge this gap?

Researchers have suggested that an active learning approach might help students develop these essential competencies (Falconer, 2016; Hung & Amida, 2020). System modeling (SM) instructional strategy is an example of active learning instruction that may help alleviate the issues discussed earlier. Implementing SM instructional strategies in the curriculum has the potential to promote engineering competencies of gaining factual knowledge, acquiring the ability to apply knowledge, and enhancing problem-solving and system thinking skills. The following section discusses the origin and foundations of system thinking and system modeling.

System Thinking and System Modeling – Historical Evolution

From Reductionism to Holistic

Generally, when we desire to understand how something works, our first instinct is to take it apart and break it down to its constituent parts and study the parts in isolation. This inquiry method, also known as analysis, is fundamental in modern scientific methods that emphasize observations and experiments to understand the phenomenon around us (Ackoff, 2000). This scientific method is grounded in the reductionism paradigm (Chan & Chia, 2003). The reductionists believe that breaking down parts of a system into constituent parts conceptually and physically can aid understanding of its function and operation (Fardet & Rock, 2014).

However, this mechanistic paradigm views the world as a machine with no consideration for its environment (Ackoff, 2000). For instance, the mechanists believe that the world works like a clock – very orderly and linear, and that one can understand how it works by studying each individual part. This perspective of reality was the foundation of the industrial revolution. Unlike the mechanistic perspective, the holistic view emphasizes the relationship between whole and parts, and causal relationship, as well as the interaction with the environment (Ackoff, 2000; Frank, 2002).

Analytic and Systemic Approach of Inquiry

The mechanistic inquiry is grounded in the analysis approach, which involves breaking down a system to gain an understanding of its function. On the contrary, systemic thinking involves not merely putting things together but also considering the effects of the individual parts on the whole. Ackoff (2000) highlighted the difference between the analysis and systemic approach of inquiry as follows:

- In traditional analysis, the broken-down parts are examined in isolation, thereby reducing the focus of the inquirer, while systemic thinking expands the scope of inquiry.
- The analysis approach focuses on revealing the structure of a system and how it works, whereas systemic approach focuses on revealing the function and why the system function the way it does.
- The analysis approach helps describe a system, while systemic thinking helps explain a system.

The Nature of a System – What is a System?

According to Skyttner (2001), a system is "a set of interacting units or elements that form an integrated whole intended to perform some functions" (p. 53). Von Bertalanffy (1950, p. 143) defined a system as a "complex of interacting elements". Ackoff (2000) stipulates that a system must have these three conditions:

1) The behavior of each element has an effect on the behavior of the whole, 2) The behavior of the elements and their effects on the whole are interdependent, and 3) However subgroups of the elements are formed, each has an effect on the behavior of the whole and none has an independent effect on it (p. 221).

Hence, the basic properties of a system emerge from the interaction of its parts and not from the property of its individual parts. This interaction is known as ‘emergent’ system properties (Sweeney & Sterman, 2000). Systems are non-linear entities with multiple cause-effect relationships among its parts. Systems are everywhere around us. For instance, humans are biological systems called an organism and containing organs like the heart, brain, lungs, and each of which can affect human behavior.

System Thinking and System Modeling

System thinking (ST) is defined as “the ability to see the world as a complex system, in which we understand that you cannot just do one thing and that everything is connected to everything else” (Sterman, 1989, p. 4). ST involves viewing the world as an “integrated whole,” and the behavior of the whole cannot be reduced to its constituent parts (Capra, 1996, p. 36). In solving a problem, system thinkers conceptualize the phenomenon from a holistic perspective, considering not only the interactions between the parts and with the whole, but also with its environment (Ackoff, 2000).

Jonassen (2000) defines a model as “a conceptual representation of something, described verbally, visually, or quantitatively” (p. 138). The conceptual representation of a model comprises of parts of a system and their interactions as well as the operational rules governing the behavior of that system (Jonassen, 2004). According to Morge et al. (2019), a model shows the fundamental assumptions of a system, its properties, conceptions, and constraints.

System modeling is "a process of systemically conceptualizing and constructing a representation of a given system, phenomenon, or problem under study" (Hung, 2009, p. 1). SM can be considered as a cognitive tool that depicts the interrelated parts of a system and its complexity, thereby enabling causal reasoning in complex systems (Jonassen, 2000). Unlike the mechanical analytic methods, SM encourages students to think holistically, thereby promoting a deeper understanding of the system under examination (Hung, 2009). SM is the practical application of system thinking.

Theoretical Framework

General System Theory

The origin of system thinking could be traced to the early twentieth century (Verhoeff et al., 2018). Most commentators credited its origin to organismic biologists, such as Ludwig von Bertalanffy, who felt dissatisfied with the reductionist interpretation of reality regarding the general phenomenon in organisms (Ison, 2008). Because of his dissatisfaction, von Bertalanffy (1950) proposed the general system theory (GST), which emphasizes "a general science of wholeness…" (p. 142). The GST is the theoretical basis of system thinking. It proposes a holistic perspective of understanding the world. In fact, systems or entities cannot be understood completely by only considering the parts of the system, as von Bertalanffy argued "the whole is more than the sum of its parts" (p. 142). Ackoff (2004) further explained that the system properties are the product of the interactions between its parts.

von Bertalanffy's work inspired other researchers and gave rise to research areas such as cybernetic systems (Ashby, 1961; Wiener, 1948), dynamic systems (Forrester, 1968; Sterman, 2000), and operational research (Churchman, Ackoff, & Arnoff, 1957). All these different interdisciplinary perspectives of the GST contributed to the development of the contemporary system thinking approach (Ison, 2008). For instance, one of the important contributions of cyberneticists was the distinction between the physical structure and the organization of a system (Capra, 1996).

Constructivism

Constructivism is a philosophical view of the world that perceives reality as multiple and constantly changing based on individual experience. Constructivists believe that knowledge is internally constructed and unique to individuals (Merriam & Bierema, 2013). Learning, according to the constructivist perspective, involves the active construction of meaning based on learners' prior and new knowledge (Schunk, 2012). Some of the assumptions of constructivism include: learning is constructed and situated in context; individuals are active learners; meaning of reality is personal; individuals learn in different ways; learning is an interactive process between the learner and the environment; and learning assessment should be integrated in learning task (Driscoll, 2002; Merrill, 1991; Schunk, 2012). Several instructional strategies like problem-based learning (Hung & Amida, 2020), collaborative learning (Roschelle & Teasley, 1995), and active learning are rooted in constructivist philosophy. These instructional approaches are problem-driven instructions anchored in real-life context (environment) to foster learners' engagement and active learning (Hung & Amida, 2020).

Figure 1 shows this study's theoretical framework identifying the connections between general system theory and constructivism. Specifically, system thinking shares some similarities with constructivism. For instance, one of the underlying characteristics of ST is the emphasis on the interactions between the parts and whole in a system as well as the interaction with the environment (Ackoff, 2000). Likewise, in the constructivist approach, there is an emphasis on interaction with the environment as the learners try to make sense of it. Sensemaking is an important aspect of system thinking. It is the process of understanding a system (Clark & Clark, 1977) and creating a mental model (Gentner & Stevens, 2014). In other words, it is important for system thinkers to use their understanding and mental model of the system to construct visual representations of the problem (Hung, 2009). This practice is at the core of constructivist philosophy in which problem solvers construct their own reality (understanding of the problem) based on their internal representation (Jonassen, 1991).

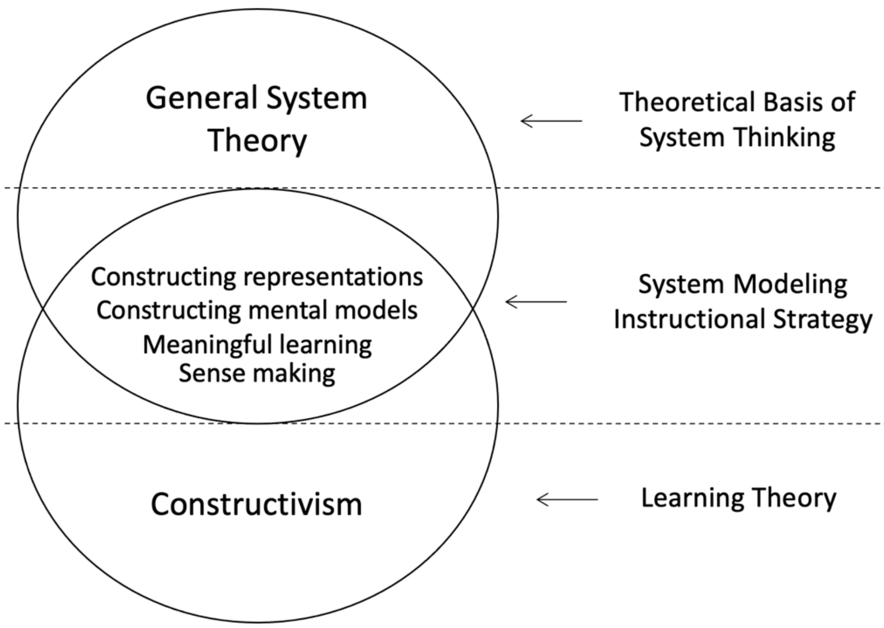


Figure 1. Theoretical Framework. This figure shows intersections between general system theory and constructivism.

The Elements of System Modeling (SM)

Models are important for how we see and think about the world. Meadows (2008) described model nicely in her book titled *Thinking about Systems*. She stated that:

1. Everything we think we know about the world is a model. Every word and every language is a model. All maps and statistics, books, and databases, equations and

computer programs are models. So are the ways I picture the world in my head–my *mental* models. None of these is or ever will be the *real* world.

2. Our models usually have a strong congruence with the world. That is why we are such a successful species in the biosphere. Especially complex and sophisticated are the mental models we develop from direct, intimate experience of nature, people, and organizations immediately around us.
3. However, and conversely, our models fall far short of representing the world in fully. That is why we make mistakes and why we are regularly surprised. In our heads, we can keep track of only a few variables at one time. We often draw illogical conclusions from accurate assumptions, or logical conclusions from inaccurate assumptions. Most of us, for instance, are surprised by the amount of growth an exponential process can generate. Few of us can intuit how to damp oscillations in a complex system.

(Meadows, 2008, p. 86-87)

One of the most prevailing thoughts in system thinking is that no model is perfect, that is no model is a precise representation of the system it claims to show (Sterman, 2002). This is partly because during the process of conceptualizing and constructing a model (abstraction), some parts of the system are hidden and others considered more relevant are revealed (Ramage & Shipp, 2012). Think about a map for example, it represents a picture or model of a place or landscape, but it is not the actual area. The incomplete nature of models may also be explained by the fact that systems are like 'black boxes' and all that can be seen are the inputs and outputs (Meadows, 2008). Hence, models are only representations of reality but not reality in itself.

So, the question is – why should we be interested in models when they are not a precise representation of reality? In system thinking, models are intended to be a *picture* of reality. They are representations that are meant to inform the thinking and decision-making process (Ramage & Shipp, 2012). To put it differently, models are thinking tools that can help people construct knowledge, make decisions, and solve problems (Pidd, 1997).

System Modeling – A Cognitive Tool

System modeling (SM) is the application of system thinking (ST). SM is a cognitive tool that can be used to conceptualize and construct an external representation of a system (Hung, 2009). External representation, also known as visualization, is "the mental outcome of a visual display that depicts an object or event" (Rapp & Kurby, 2008). SM uses external representations to depict the operation of the system. These external visual representations reveal the underlying causal relationships in a system. The construction of external representation not only allow system thinkers to conceptualize the properties of the systems but also enable them to externalize their understanding of the system (Hung, 2009). The creation of an external representation of the system has three benefits (Hung, 2009). First, it enables students to externally visualize the system, thereby reducing the level of abstraction (non-concrete nature) in the system. Second, it promotes the intra-personal validation of the system. Last, it can help students communicate their understanding of the system and gain feedback.

System Modeling – A Representation of Mental Models

According to Senger (2006), mental models are "deeply ingrained assumptions, generalizations, or even pictures or images that influence how we understand the world and how we take action" (p. 8). Mental models are belief structures that represent a simplified conceptualization of an individual's understanding of a system (Monat & Gannon, 2015). Mental models evolve and change as people interact with the system and gain more understanding of the structure and properties of the system (Norman, 1983). Indeed, an individual's mental model is an iterative cognitive process (Capra, 1996).

In system modeling, an accurate mental model of a system and its parts should represent the system structure, behavior, and functions (Arnold & Wade, 2017). A novice student's mental model of a system tends to be less accurate and complete than an expert's mental model, which could partly explain the inefficiency and ineffectiveness of novices' problem-solving process. Mental models can be improved to more accurately reflect the system under examination by using mapping techniques that will be discussed later in this review of the literature (Doyle, 1997).

System Modeling – A Reflection of the System Thinking Characteristics

Wholeness. This suggests that systems should be understood as a whole instead of as individual parts. The mechanistic analysis method of problem-solving involves breaking down the system to understand the problem by examining separate parts to understand their behavior in isolation, and then combining the understanding of the parts into an understanding of the whole (Ackoff, 2000). This approach is the foundation of inquiry in the mechanistic philosophical world view. Unlike the mechanistic method, system thinking employs a more holistic approach. The system approach focuses on understanding the underlying structure and framework of the system as a whole rather than breaking it down to its parts. In fact, Capra (1996) suggested that once a system is divided into its constituent parts, the essential properties of the whole will no longer exist. Essentially, the elements in a system do not have independent effects on the whole (Ackoff, 2000), like, for instance, an automobile, which is a mechanical system that is used to move from point A to B. The different parts of the automobile work together to make the car function. However, if the individual parts of the car are taken apart, it can no longer function as an automobile.

Ackoff outlined the three steps of the system thinking approach in regards to wholeness. These steps include:

> (1) "Identify a containing whole (system) of which the thing to be explained is a part, (2) "explain the behavior or properties of the containing whole", (3) "then explain the behavior or properties of the thing to be explained in terms of its role(s) or function(s) within its containing whole" (p. 222).

Interrelationship and Interdependency. According to Capra (1996) the system thinking approach is to "see the world not as a collection of isolated objects, but as a network of phenomena that are fundamentally interconnected and interdependent" (p. 7). This perspective suggests that nature is a web of relationships that are linked and interdependent. The interdependence and interrelationship that exists between the multiple parts of a system are fundamental for its operations (Hung, 2009). These characteristics of a system make the different parts function together as a whole. In other words, the properties of a system are the product of its characteristic parts and the causal relationships with itself and the whole (Hung, 2009). Hence, interrelationships among the parts of a system emerge into the systemic structures of the system, influencing its behavior (Senge, 2006).

Non-Linearity. This characteristic of ST suggests that systems are non-linear. Non-linearity means that the effects in a system are not proportional to its cause (Sterman, 2002, p. 22). This implies that a cause may not necessarily be directly linked to a single effect in a non-linear system. This is unlike the mechanistic view of reality that emphasizes a hierarchical and linear cause-effect relationship. In the systemic approach, relationships are considered as web-like networks that are non-linear (Capra, 1996).

Practically, non-linear relationships mean that "a given variable in a system causes effect on one or more variables, and these variables consequently produce effects on their related variables" (Hung, 2009, p. 9). The effect of one variable will have multiple non-linear effects since all the parts of the system are interconnected and interlinked. Thus, system thinkers, as von Bertalanffy claimed, view systems as non-linear forming chains of causal links. These causal links are cyclic in nature and are called causal/feedback loops. Causal loops are cyclic representations that depict the underlying relationship pattern in a system (Capra, 1996). Causal loops are closed chains of causes and effects that reflect sequences of action and information flow in a system (Richardson, & Pugh III, 1997). It shows the organizational pattern of a system (Capra, 1996).

System Modeling Tools

According to Sterman (2000), "every model is a representation of a system – a group of functionally interrelated elements forming a complex whole" (p. 89). The model representation of a system must simplify the system, be understandable, and depict its interrelationships. Systems can be modeled using mapping tools to depict the causal relationships and the properties of the system (Jonassen, 2000). In SM instructional strategy, mapping tools can be used either to present information to students or as a cognitive tool in problem-solving. These mapping tools, also known as system modeling tools, include behavior over time (BOT) graphs, causal loops/feedback diagrams, and stock/flow maps (Hopper & Stave 2008; Sterman, 2002; Sweeney & Sterman, 2000).

Behavior Over Time Graph (BOT). The BOT is a graphical representation that shows the behavior of a system over a period of time. BOT graphs "help people focus on patterns of change over time rather than isolated events, leading to rich discussions on how and why something is changing" (Waters Foundation, 2008a). This visual tool aids in identifying trends and patterns (Gillmeister, 2017). This is because it enables students to visualize the increase or decrease occurring in the system over time instead of looking at a snapshot of the event.

In a BOT, the y-axis is often labeled as the variable being plotted and the x-axis is labeled with the time unit. The relationship between multiple variables of interest can be observed by plotting the variables on the same graph. Essentially, inferences drawn from the BOT graph can enable students to deeply understand the pattern of behavior of the system considering past behavioral patterns and possibly enable prediction of future occurrence.

Causal Loop Diagram (CLD). The CLD, also known as a feedback loop diagram, is a visual representation tool that can depict causal relationships within a system. It shows the nature and direction of the effects between variables and the system (Plate, 2010). The CLD displays the links and connections between variables and how changes in one variable affect the others. It also describes a web-like, non-linear, causal loops that exist within a system.

Causal loops can be either reinforcing or balancing loops (Hung, 2009). Causal loops can be graphically represented in a CLD. The connections in a CLD are designated by arrows connecting variables and indicating the effects between them. In the reinforcing loop diagrams, arrows labeled '+' or 's' indicate a positive relationship between variable A and variable B. This relationship is also known as a positive correlation (Hung, 2009). It implies that either variable A adds to variable B or A causes a change in B in the same direction. This means an increase in one will lead to an increase in the other, while a decrease in one results in a decrease in the other

(Kirkwood, 1998). Hence, reinforcing loops are loops that strengthen the initial change causing the change to continue in the same direction, thereby striving to keep the momentum in the system going (see Figure 2).

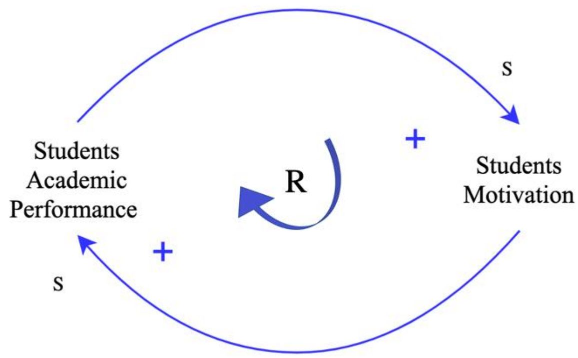


Figure 2. Reinforcing loop. This illustration shows the relationship between motivation & academic performance.

On the other hand, balancing loops are loops that resist the initial change in the opposite direction (negative). Unlike reinforcing loops, balancing loops strive to maintain an equilibrium and oppose changes in the system. Balancing loop diagrams have arrows labeled ‘o’ or ‘-’ indicating a negative relationship between variables A and variables B. This kind of relationship is also known as negative correlations (Hung, 2009). This means that either variables A subtract from variables B or A causes a change in B in the opposite direction – increase in one results in decrease in the other (Kirkwood, 1998).

Figure 3 shows an example of a balancing loop diagram. The subscripts in the causal diagram indicate the direction of the phenomenon, + means the same and - means the opposite. The figure shows that students’ exam performance is influenced positively by students’ study time and teaching improvements. However, a student’s low exam performance negatively influences instructor dissatisfaction.

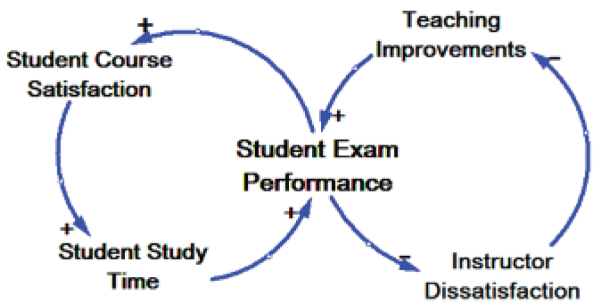


Figure 3. Balancing loop. This illustration shows the relationship between exam performance, satisfaction and teaching improvement (Adapted from Orgil, York, Mackellar, 2019).

Stock-Flow. This map is another system modeling tool that can depict the relationship that exists in a system (Arnold & Wade, 2015; Hopper & Stave, 2008). It describes the underlying physical organization that exists in a system (Sterman, 2000). The stock-flow map comprises of different elements like the stock, flow, connectors, and converters (Jonassen, 2000; See Figure 4). Stocks represent 'accumulation of something' or 'a reservoir of resources' in a system (Arnold & Wade, 2015). It is most denoted by nouns and can be physical (e.g., water, bathtub) or abstract (e.g., motivation, happiness). A flow influences the level of a stock in a system and it changes over time. A flow is represented by a verb and it affects the inflow and outflow in a stock (Gillmeister, 2017).

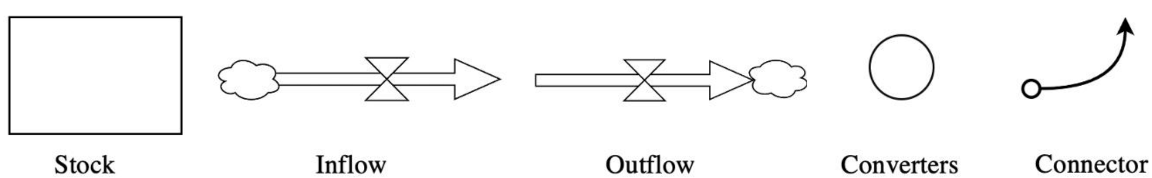


Figure 4. Stock-flow icons. This illustration shows the stock-flow map icons.

Also present in a stock-flow map are converters and connectors. Converters affect the flow in a system by providing information that influences the flow rate, thereby affecting the inflow (flow into the stock) and outflow (flow out of the stock). Connectors, on the other hand, are presented by lines showing the direction of flow in a system (Gillmeister, 2017; Jonassen, 2000). An example of a stock-flow is the bathtub (see Figure 5). The amount of water (stock) in the tub is affected by the rate of inflow and outflow of water. The faucet controls the inflow of water while the drain regulates the outflow. This example represents a simple stock-flow map with no feedback loop. Essentially, the stock-flow map helps students visualize how the stock changes over time, considering the rate of inflow and outflow in the system.

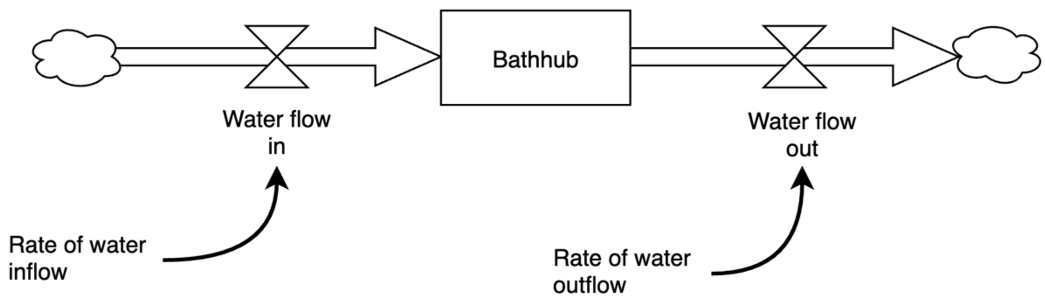


Figure 5. Stock-flow map. This illustration shows a stock-flow map of bathtub water (Adapted from Sterman, 2000).

System Modeling as an Instructional Strategy

System modeling (SM) is an instructional strategy that have been utilized in various disciplines especially in management and decision making (Ackoff, 2000; Sterman, 2000). For instance, Sedlacko et al. (2014) used participatory system modeling involving causal loop diagrams to facilitate the understanding of issues in sustainable consumption among policy and decision-makers. The researchers reported that causal loops provided a means for managing complex systems thinking and facilitated the systematic understanding of the issues. This included helping the participants to understand the underlying structural cause of the problem and to make inferences on the possible consequences. Sedlacko and colleagues also claimed that the modeling activities helped participants to reorganize their mental model and promoted a shared knowledge experience. Other studies used system modeling in understanding management issues (e.g., Hare, Letcher, & Jakeman, 2003; Pahl□Wostl & Hare, 2004).

The SM approach has also been used as a cognitive tool to facilitate students' learning outcomes such as system thinking skills. For instance, Hmelo-Silver et al. (2017) examined the effect of conceptual representation intervention (a modeling tool) on students' causal reasoning (system thinking) in science. Hmelo-Silver and colleagues used the Components-Mechanisms-Phenomena (CMP) conceptual representations to help learners understand ecological patterns, generate plausible mechanisms, explore the parts, and interact in the ecosystem. Students created models based on their understanding of the ecosystem. The models drawn were coded based on the CMP criteria, considering ecological system component identification, interrelationships between the parts, and the whole. The researchers reported that the intervention enabled the learners to examine the parts of the ecosystem and how the individual parts interconnect and work together to form the ecosystem. Thus, the intervention significantly promoted students' system thinking skills. Likewise, other studies reported significant increase in students' system thinking skills (Hung, 2008; Plate, 2010; Tripto et al., 2017).

SM instructional strategy use tools such as causal loops and stock-flow maps to improve students' mental models (Doyle, 1997). As identified earlier, the mental model is an important factor in the accurate representation of a system (Arnold & Wade, 2017). When students use SM tools, they are able to depict their internal representation and understanding of the system in an external environment, something Hung (2009) referred to as externalization. Externalization enables students to: (a) identify and represent causal relationships (Jonassen, 2000); (b) visualize the underlying structure of the system; and (c) internally and externally validate their mental model (Hung, 2009). These benefits of SM could enhance mechanical engineering students learning outcomes. The following section discusses mechanical engineering education and how SM instructional strategies could be implemented.

Mechanical Engineering Education: How Engineers Use of Knowledge

Mechanical engineering is "the branch of engineering dealing with the design, construction, operation, and maintenance of machine" (Dixit, Hazarika, & Davim, 2017, p. 4). Mechanical engineers apply scientific knowledge (e.g., mathematics, chemistry, and physics) in designing, constructing, and maintaining processes and systems. It is an applied science that involves applying theories, principles, and concepts to solve problems. Mechanical engineering education incorporates principles and concepts from physics and mathematics (Dixit, Hazarika, & Davim, 2017). These principles and concepts do not only provide a foundation for higher-level learning; they are central to applying knowledge in real-world situations.

The use of knowledge in mechanical engineering is highly application-based. For instance, mechanical engineering experts apply their technical knowledge and concepts to solve problems in a real-world context. While this process might appear intuitive to experts, it requires a highly complex cognitive process. The cognitive process involves making connections between concepts and real practical applications. This is an important step in knowledge integration and application. Unlike novice problem solvers, experts have developed a multifaceted conceptual understanding of the content domain (Anderson & Schönborn, 2008) and have constructed a mental model of the problem-solving process. Hence, for students to acquire similar competencies like the experts, they need to gain skills like specialized content knowledge, knowledge application, problem-solving skills, and system thinking skills (ABET Criteria for Accrediting Engineering Programs, 2018; Passow & Passow, 2017). These learning outcomes are discussed below.

Despite the importance of mechanical engineering, educational researchers have expressed similar concerns attributed to engineering education in terms of its ineffectiveness in meeting modern engineers' needs. For instance, Kirkpatrick et al. (2011) stated that most employers reported that recent graduates are not well prepared for workplace challenges. Other researchers (Buch & Bucciarelli, 2015; Falconer, 2016; Felder, 2012) shared similar concerns.

Mechanical Engineering Education: Learning Outcomes and Gaps

Factual Knowledge

Factual knowledge, also called declarative knowledge, is the basic information of content elements such as facts, concepts, definitions, terminologies, mathematical symbols, and vocabularies used in the discipline (Anderson & Bloom, 2001; Krathwohl, 2002). Mechanical engineering students need to master terms and concepts like stress, work, energy, power, and force, as well as principles like fluid mechanics and thermodynamic principles. This basic knowledge forms the foundation essential in developing higher-order learning and complex thinking skills like problem-solving and critical thinking (Willingham, 2009; Roediger et al., 2014). Essentially, factual knowledge can support students' conceptual understanding and, therefore, bolster their application knowledge and problem-solving skills (Huba & Freed, 2000).

It is important for engineering education to promote factual knowledge (Hoffmann, 2008). According to Frise et al. (2003), students must acquire factual and application knowledge to meet engineering workplace skill requirements. This is not just important for students to understand technical terminologies used by mechanical engineering experts, but also to help them translate theories into practice (Warsame, 2017). Moreover, understanding mechanical engineering phenomena such as heat transfer requires students to have factual knowledge of terms and concepts like conduction, heat exchange, and thermal energy. In other words, without concrete prior knowledge about these terms, students may find it difficult to understand the topic of heat transfer.

While engineering students could memorize basic engineering terminologies and concepts, Bankel et al. (2005) revealed that most could not apply their knowledge in a real-world context. This might be because most of these facts are presented to students with little or no situational context, thereby failing to establish the relevance of the content (Buch & Bucciarelli, 2015). As a result, students' knowledge exists in isolation and the concepts learned are disconnected in the memory (Anderson & Schönborn, 2008), thus making it difficult or even impossible to use during application. Indeed, knowledge in the memory remains inactive until students know how to meaningfully connect and apply them (Anderson & Schönborn, 2008).

Furthermore, prior researchers suggest that students have difficulty grasping new abstract information that is not effectively related to their prior knowledge or experience (Williams & Cavallo, 1995; Felder et al., 2000). Abstract concepts are unseen, invisible concepts that cannot be directly observed by students. For example, thermodynamics, a core topic in engineering, comprises concepts like temperature, heat, energy, and pressure that are often considered abstract and, therefore, difficult for students to understand (Kamble & Tembe, 2013). In fact, a number of studies have reported that students have difficulty understanding thermodynamics (Clark, Thompson, & Mountcastle, 2014; Turns et al., 2013).

Conceptual Knowledge

Conceptual knowledge has been described as the 'knowledge of concepts' (Byrnes & Wasik, 1991; Rittle-Johnson, Siegler, & Alibali, 2001). It is not just memorizing or understanding concepts and facts; it is also the "understanding of the essential parts and cause-effect relationships that exist within a system" (Guenther, 1998, p. 289). The relationship aspect of conceptual understanding was emphasized in Hiebert's writing. Hiebert (2013) stated that "conceptual knowledge is characterized most clearly as knowledge-rich in relationships. It can be thought of as a connected web of knowledge, a network in which the linking relationships are as prominent as the discrete pieces of information" (p. 3-4). These definitions clearly emphasize that conceptual knowledge involves understanding concepts and the interconnections between the concepts (Davis, 2013; Rittle-Johnson & Schneider, 2015).

Canobi (2009) presented a slightly different description of conceptual knowledge. According to Canobi, conceptual knowledge "involves knowledge about the underlying unifying principles–the structure of the problem domain" (p. 132). Canobi's description of conceptual knowledge highlighted the underlying principles of the domain. This suggests that conceptual knowledge is an essential element that is not only about understanding the concepts but also about conceptualizing the underlying structure in a specific problem domain. Moreover, Crawley et al. (2007) argued that conceptual knowledge is more than just applying principles and concepts; rather, it involves a much 'deeper working knowledge' in a given domain.

Generally, students must be able to construct their conceptual knowledge in the problem domain to become effective problem solvers (Lucangeli, Tressoldi, & Cendron, 1998). For instance, mechanical engineering students need to identify and connect multiple concepts that is required to solve engineering questions. Making these connections will enable them to understand the concepts associated with the problem and their underlying relationships, thus promoting problem space construction (Rittle- Johnson, 2006). Problem space construction is a crucial component in problem-solving (Hung, 2009). Hence, it is important for mechanical engineering graduates to develop the conceptual connections between the classroom theories and practical applications (Warsame, 2017).

Researchers have reported students' difficulty in developing and applying conceptual understanding in mechanical engineering. For instance, Wattanakasiwich et al. (2013) used a conceptual tool to measure students' thermodynamics understanding. The researchers reported that students performed better on questions of heat and temperature, but fell short on thermodynamics questions. The researchers concluded that students have difficulty in conceptualizing and integrating thermodynamics concepts. Similarly, other researchers also reported students' difficulty in conceptual understanding in thermodynamics (Clark, Thompson, & Mountcastle, 2014; Turns et al., 2013).

This instructional difficulty might be linked to how students approach solving engineering questions. Most students tend to use the functional-reduction reasoning approach to solve complex engineering problems (Wattanakasiwich et al., 2013). This approach involves reducing multiple variables of interest to only two so that students can understand relationships using linear-causal reasoning (Rozier & Viennot 1991). The functional-reduction approach is similar to the reductionist perspective discussed earlier in which problem-solvers attempt to break down systems into parts in order to understand it. Clearly, this approach does not seem to be effective in solving conceptual problems.

Application Knowledge

Application knowledge is the knowledge required to apply or use a procedure or content knowledge in a specific context (Krathwohl, 2002). This kind of knowledge requires students to apply factual information learned in class to solve specific problems. Teaching students' factual knowledge alone does not guarantee that they will be able to apply the knowledge to solve problems. This is because students' ability to apply their knowledge to different contexts is not intuitive; it has to be learned. In fact, Bankel et al. (2005) indicated that most faculty expect students to be able to apply knowledge; however, students often cannot apply what they have learned (use their knowledge) because they have not been taught how to apply it.

Engineering education needs to promote students' application knowledge. This is because engineering practices emphasize theoretical concepts and practical application (Goodhew, 2010; Tan, 2014; Welch, 2007). Specifically, mechanical engineering education must prepare students to be able to apply specialized knowledge, principles, and theories in complex and dynamic real-life contexts (Kirkpatrick et al. 2011; Warsame, 2017). According to Eggen and Kauchak (2003), the first step for engineering students to acquire application knowledge is to gain factual information such as equations, terminologies, formulas, principles, and algorithms, and then learn how to apply the knowledge to solve problems. Other researchers, like Jonassen (1999), suggested that to promote application knowledge, instructions should be presented in ways to guide students to meaningfully connect the abstract content knowledge with the situations (where) and how the knowledge can be applied in real life. Meaningful, logical, and contextualized instructions could help students trigger prior knowledge and activate their pre-existing schema to help them connect, understand, and interpret the content (Schunk, 2012). Schemas are internal cognitive processing networks that help organize information into meaningful patterns (Rumelhart, 2017; Schunk, 2012).

Despite the importance of application knowledge, a number of studies reported that mechanical engineers are unable to apply their knowledge effectively. For instance, Wattanakasiwich et al. (2013) conducted a study on thermodynamics and reported that students had difficulty applying thermodynamics concepts to solve problems. Similarly, other researchers reported that students have issues with applying their knowledge (e.g., Dunlosky et al., 2013; Khoshaim & Aiadi, 2018). Students' inability to apply gained knowledge could be partly attributed to the manner in which instruction is delivered (Biggs, 1999). Khoshaim and Aiadi (2018) emphasized that students need to learn and apply concepts and principles in practical, real-world situations to gain application knowledge. Essentially, application knowledge is acquired through active engagement with the content and solving real-life problems.

Problem-solving Skills

A problem exists when there are an unknown entity and a need to find it (Jonassen, 2004). According to Mayer (1989), a problem consists of the given state, the goal state, and the obstacle between the given and the goal state. Problems vary by the kind of knowledge required to solve them, the context of the problem, the complexity, and its structure. For instance, problems can be well-structured or ill-structured. Well-structured problems (also known as 'textbook problems') are highly structured, linear, and non-complex, requiring only one right solution. In contrast, ill-structured problems, mostly compared with real-world problems, are non-linear, complex, and have multiple path solutions (Jonassen, 2004; Jonassen & Hung, 2008).

Problem-solving is the process of understanding the unknowns and gaps that exist between the present and the desired state (Hung et al., 2008). Jonassen (2004) argued that problem-solvers need to understand the problem and construct its problem space. The quality of the problem space will determine the effectiveness of the problem-solving process (Hung, 2009). Problem space construction involves identifying the problem scope and variables, current and goal state of the problem, and the inter-causal relationships between its elements (Mayer, 1989; Newell & Simon, 1972; Reimann & Chi, 1989). This process also enables problem solvers to develop mental models for the problem domain and external visualization (Hung, 2009).

Problem-solving is an important skill set for today's mechanical engineering graduates (Ismail et al., 2019; Yadav et al., 2010). In fact, the ABET Criterion (2016) stated that students learning outcomes include developing "an ability to identify, formulate, and solve engineering problems" (p. 3). Furthermore, mechanical engineering experts emphasized the development of problem-solving skills among students to prepare them for real-world problems (Kirkpatrick et al. 2011). Despite the importance of this skill, research suggests that students lack problem-solving skills in solving real-world problems (Khoshaim & Aiadi, 2018; Luo et al., 2015; Slavin, 2019). This problem may be linked to the students' inability to transfer concepts learned in class to solve real-world problems. Hence, to effectively solve real-world problems, mechanical engineering students need to be able to identify and define the problem and construct problem spaces during the problem-solving process.

Bridging the Gap: Why use SM for Mechanical Engineering Education?

As revealed, there is a gap between classroom theory and actual practice in mechanical engineering (Kirkpatrick et al. 2011; Warsame, 2017). Researchers have recommended active learning strategies (like SM) to help bridge this gap (Falconer, 2016; Hung & Amida, 2020; Manteufel, 2015; Wattanakasiwich et al., 2013). Indeed, SM instructional strategies might be particularly useful for facilitating mechanical engineering learning outcomes. This is because SM instructional strategy enables students to be engaged with the content and practice how to apply their knowledge to solve real-world problems. Notably, SM instructional strategy could help mechanical engineering students who are unlikely to use a single concept during problem-solving and to think systematically considering the relationships between relevant concepts during the problem-solving process. Hence, SM might help students develop a systemic approach to addressing problems.

SM and Promoting Factual knowledge

SM instruction strategy might help promote factual knowledge in mechanical engineering students. External visual representation could help students reduce the level of abstraction and visualize abstract concepts, thereby enhancing their factual knowledge (Uttal & O'Doherty, 2008). Students define the system and its parts during system modeling by identifying feedback in the system and recognizing the inter-causal relationships between the parts (Sweeney & Sterman, 2000). These active tasks enable students to demonstrate and consolidate their factual knowledge. By so doing, students can meaningfully organize their mental models such that they are easy for them to relate to and make necessary connections and establish the relevance of the content. Hence, SM has the potential to promote students' factual knowledge by organizing facts, recognizing interconnections between parts, and describing concepts.

In SM instructional strategy, external visual representations can be used in education to present information, simulate scientific laws, and describe an engineering concept. For instance, the visual representation of ohm's law showing the relationship between voltage, current, and resistance – can be used to clarify the misconceptions on the relationships between the variables. When students interact with external visual representations, they are able to utilize clues to show the phenomenon; it can serve as a simulation to help them review their understanding and test their hypotheses (Rapp & Kurby, 2008).

SM and Enhancing Conceptual knowledge

SM instructional strategy could aid the construction of conceptual knowledge (Hung, 2008). This is because in the SM approach students are encouraged to examine the system's holistic behavior and the interactions between its parts and the whole (Sweeney & Sterman, 2000). This will enable students to see the entire system and understand the system's underlying structure, which is important in defining the problem domain. SM could also allow students to visualize abstract concepts and conceptualize the operations dynamic systems (Hung, 2009; Verhoeff et al., 2018), thereby promoting their conceptual knowledge.

Several studies have shown that SM instructional strategy can enhance students' conceptual understanding. For instance, Prince, Vigeant, and Nottis (2009) conducted a longitudinal study to determine whether inquiry-based models for conceptual change could be effective in mechanical engineering undergraduate students. Five activities were used to address the target concept's conceptual issue—three in heat transfer and two in thermodynamics—spanning from 2005 to 2008. In all, the study used two physical experiments and three computer simulations models. Data were collected from all five activities, including heat transfer in boiling liquid nitrogen, and heat transfer in chipped and block ice, both using physical inquiry-based activities, and heat transfer in hot blocks using simulation model inquiry-based activities. Students also learned the concept of thermodynamics in boiling liquid nitrogen and entropy of mixing using simulation models. The study was a pre- and post-test design in which students answered conceptual questions on target concepts and then a post long term test (assessing long term retention). Student learning outcomes were recorded using concept-inventories assessing conceptual change as well as open-ended questions. The researchers concluded that the inquiry activities simulation model significantly improved students' understanding of heat transfer and thermodynamics. The study also reported that students showed a long-term (after ten weeks) knowledge gain in both concepts when students used the model.

In another study, Grotzer and Basca (2003) investigated the impact of grasping the underlying causal structure (causal modeling) on students' understanding of ecosystems among elementary school students. The researcher implemented an intervention to address third graders' (N = 30) difficulty in learning ecosystem. The study involved three conditions: causal activities with discussion (CAD group), causal activities only (CAO group), and no causal activities (CON - control group). The causal structure activities involved helping students see the underlying cause and effect relation in the ecosystem. During the causal structure activities, the students modeled the food webs by illustrating how the sun's energy is cycled through the ecosystem. Students in the CAO group then discussed the connection asking questions like, "what would happen if all of the green plants were to disappear" (p. 20). The study data were collected using pre- and post-clinical interviews, which assessed students' understanding of links and the decomposition process within the ecosystem. A sample interview question was, "how do students initially describe the cause and effect relationships in a forest or pond food web?" (p. 19). The result suggested that the students in the CAD group significantly showed a better understanding of the relationships within an ecosystem than the CON group. The CAD group also showed a significantly higher understanding of the ecosystem's decomposition process than their counterparts.

In a more recent study, system modeling was used to promote conceptual understanding among high school science students (Rates, Mulvey, & Feldon, 2016). Rates and colleagues utilized an agent-based simulation model to improve students' understanding of complex systems. In their study, the students were required to detail their understanding of an ecosystem before and after the modeling activity. The students' models were then evaluated. The results suggested a significant difference in students' conceptual understanding.

SM and Facilitating Application Knowledge

SM instructional strategy presents students with an opportunity to facilitate their transfer of knowledge gained and apply in real-world problems. During the SM activities, students are encouraged to recall facts and concepts that relate to the problems under examination. This helps students link their prior knowledge to current instructional content. The students can then model the non-linear relationships between the concepts as it relates to the problem. In doing so, students organize their knowledge and contextualize instructional content to promote meaningful learning, thereby enhancing application knowledge. In SM, students identify and represent the inter-causal relationships within a system. As a result, students promote their understanding of the system and enhance their application knowledge. Hence, instructors seeking to improve their students' application knowledge may benefit from implementing a learner-centered instructional approach like SM.

A number of studies reported a positive effect of SM instructional strategy on students' application knowledge. For instance, Hubbs, Parent, and Stoltzfus (2017) examined the impact of modeling on undergraduate understanding and application of meiosis in biology. Participants (N=381) were undergraduate students in an introductory biology class. The students were asked to review a scientific blog on human gametogenesis and develop a model using their understanding to model the meiosis process. The students then applied their knowledge in predicting scientific outcomes and relate it to other biological phenomena like mitosis. The researchers reported that students effectively mastered the understanding and application of meiosis after the modeling activities.

In another study, Kamble and Tembe (2013) investigated the effect of concept maps, a type of external visual tool, on students' achievement in a thermodynamics class. Forty-seven engineering students participated in the study. At the beginning of the study, the students were trained on how to design a concept map. The students were then asked to design their own concept maps based on their understanding of thermodynamics. Data were collected using a concept map, achievement test, and students' perception survey. The concept maps assessed students' abilities to related concepts and were graded using a rubric, while the achievement test was used to assess students' application of thermodynamics. While the study did not report a significant effect of the concept map, the researchers claimed that the activity helped improve students' application knowledge based on the achievement scores. Also, the study findings indicated that students believed that the activities were helpful in understanding and applying thermodynamics concepts.

SM and Improving Problem Solving Skills

SM instructional strategy can help students develop problem-solving skills (Edson, 2008). The SM instructional strategy allows the students to first consider the whole system in which the problem exists. This holistic view helps identify the problem boundaries, clarify the current and goal state, and recognize the gap. This will aid the students' understanding of the problem, an important step in the problem-solving process. Indeed, system thinkers solve complex problems by examining the problem's underlying mechanism (Frank, 2002; Hung, 2009). Students can then define the problem and construct their problem space to solve the given problem with their understanding of the underlying mechanism. Hence, SM instructional strategies have the potential to help students develop their problem-solving skills in mechanical engineering education.

Previous studies have highlighted the benefits of SM instructional strategy in improving students' problem-solving skills. For instance, Mousoulides, Christou, and Sriraman (2008) examined the effect of modeling in problem-solving mathematical problems among high school students. The participants in the study (N=403) were divided into an experimental and control group. The experimental group participated in six modeling activities for three months. The activities included an introductory module on modeling and group tasks for students to create their model to solve mathematical problems. The control group, on the other hand, worked in the traditional mathematics instructions. A modeling ability test was administered three times to all participants in the study: at the beginning, during, and at the end. The test assessed participants' modeling and problem-solving abilities. The researchers reported a statistical difference between the two groups in relation to students modeling abilities over time. Thus, they claimed that students' modeling and problem-solving abilities improved in the modeling group.

In another study, DeFranco, Neill, and Clariana (2011) proposed a cognitive collaborative model (CCM) to enhance problem-solving in engineering teams and examined whether the model promoted a shared mental model among the team members. The CCM is an iterative model developed to facilitate problem-solving in a collaborative environment. It has six stages, including problem formulation, solution planning, solution design, solution translation, solution testing, and solution delivery. DeFranco et al.'s 2011 study only focused on the first two stages. The researchers reported three different experiments using the CCM. The first two experiments tested the hypothesis on whether CCM can improve the problem-solving process during a collaborative team task. In the first experiment, participants (computer science students) were randomly assigned into groups of three, and each team was randomly assigned into two groups – CCM group and no CCM group (control). Both groups were given the same problem task to design a supermarket simulation application. Data were collected using the Problem Formulation Document and the Solution Plan Document. Both documents were assessed to examine the problem-solving outcomes by expert judges. The second experiment was conducted among a different group of students (system design students). The experiment followed a similar procedure with the first except that the data, in this case, were collected using project completeness reflected in submitted design artifacts – use cases, sequence graphs, and system architecture documentation. The results from both experiments indicated that the CCM group significantly outperformed their counterpart. In the third experiment, the researchers examined whether CCM's effectiveness in the other experiments was because it promoted a shared mental model among team members. A different group of students (software and system engineering students) put in groups of three was randomly selected and placed into two groups – CCM group and no CCM group (control). All teams followed the same procedures described earlier in completing the problem-solving task. Members of each team were required to create individual concept maps that depict their mental model throughout the team activities. Students' concept maps were assessed for overlap, similarity, and commonality using Pathfinder analysis of concepts and their connections at the end of the task. The result indicated that the CCM group member has similar concept maps indicating that CCM helped students create a shared mental model.

The literature on system modeling instructional strategy has highlighted several benefits of its use in promoting students learning outcomes. While the literature on SM in mechanical engineering is scarce, empirical evidence of its effectiveness exists in other disciplines like management, business, mathematics, biology, and science.

Conceptual Framework

The current study explored the efficacy of system modeling (SM) instructional strategy in a mechanical engineering course. Specifically, the study sought to understand students' perceptions and experiences with the use of system modeling in enhancing their learning outcomes. The study focuses on learning outcomes such as factual, application, and conceptual knowledge, as well as students' self-perception of problem-solving and system thinking skills. Figure 6 displays the conceptual framework of the study.

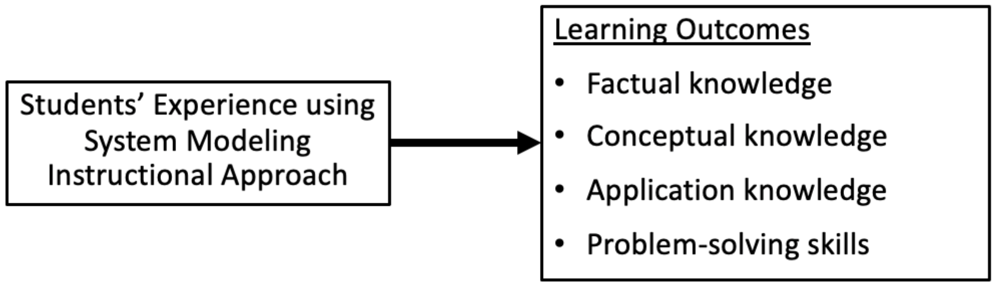


Figure 6. Conceptual Framework.

Summary

This literature review described the historical evolution of system modeling and system thinking, its definitions, and theoretical foundations. The chapter also discussed the characteristics of system modeling as a holistic instructional approach and the tools used in its implementations. An overview of the rationale and the effect of system modeling instructional strategy on student learning outcomes was also described. A discussion on the structure and challenges of mechanical engineering education and potential benefits of systems modeling instructional strategy in engineering. The final part of the literature review presented an overview of studies that implemented system modeling and thinking instructional strategy in education.

Evidence from the literature on the general characteristics and structure of SM suggests that there is a consensus among researchers that SM instructional strategy has the potential to provide an active and engaging learning experience, thereby promoting student learning outcomes (Davidz & Deborah, 2007; Hung 2008; Hmelo-Silver et al., 2017; Kordova & Frank, 2018; Plate, 2010; Tripto et al., 2017). The challenges confronting engineering education is how to present instructions such that students can systemically see the connections between engineering concepts learned in class and how these concepts interact in the real world (Felder, 2012). Previous literature on SM and ST has described some of SM's effects on student learning outcomes, especially in promoting system thinking and causal reasoning skills (Hung, 2008).

However, prior studies have not extensively explored the benefit of SM instructional strategy among mechanical engineering students considering learning outcomes such as application and conceptual knowledge and problem-solving skills. Moreover, while a few studies have examined the relationship between SM and problem-solving skills (e.g., Hung, 2009), empirical evidence of this relationship is limited in engineering education. Furthermore, this study is also unique because it uses a different methodology to assess students learning outcomes. For instance, problem-solving skills will be assessed in this study using the Problem-Solving Inventory (PSI).

The implementation of SM among mechanical engineering students will provide insight and understanding about the effects of SM on students learning outcomes. The current study will also allow instructors to compare the potential benefit of SM on engineering students' learning outcomes and determine whether it is a viable instructional approach in mechanical engineering. To summarize, the current study purpose, rationale, design, and operational definitions of variables were informed by the literature reviewed in this chapter. The next chapter, Chapter III, will describe the research methodology used in this study.

CHAPTER III

METHODOLOGY

The purpose of this study is to explore the efficacy of system modeling (SM) instructional strategy in a mechanical engineering course. Specifically, the study seeks to understand students' perceptions and experiences using system modeling to enhance their learning. The study focuses on learning outcomes such as factual, application, and conceptual knowledge, as well as students' self-perception of problem-solving and system thinking skills.

Research Questions

1. What are students' perceived efficacy of the use of SM instructional approach?
2. How do students describe their experience with SM instructional strategy in relation to their factual, conceptual, and application knowledge?
3. What perceptions do students have regarding the use of SM instructional approach in relation to problem-solving and system thinking skills?

Research Design

This study employs a qualitative approach to understand engineering students' perceptions and experiences using system modeling. The researcher adopted a qualitative approach because it is well suited to address the study's research questions. Moreover, Creswell and Creswell (2017) argue that qualitative research is an approach that explores the meaning of participants' experience as well as the understanding they attribute to a particular context or phenomenon. In addition, according to Merriam (1998), qualitative studies can explore participants' "meaning and understanding through their narratives, how they make sense of the world and their experiences" (p. 6). Ultimately, this approach enables the researcher to understand students' experiences and gain better insight into how students learn using the SM instructional strategy.

Study Setting and Participants

The study was conducted within the context of an undergraduate mechanical engineering course at a Midwestern university in the United States. The students were senior-level students enrolled in a Machine Component Design (ME 323) course during the Spring 2021 semester. The ME 323 course is advanced mechanical engineering course introduces the fundamentals of machine component design elements such as springs, bearings, gears, threaded components, and bonded joints. In this course, students learn the power screws and apply them to solve problems. The course is originally taught in the traditional instructor-led, lecture-type format with content delivered by the instructor and textbook references provided to students. Though the course was selected for this study partly because of the researcher's convenience and accessibility, it was also a course that requires students to demonstrate their factual, conceptual, and application knowledge competencies along with problem-solving and system thinking skills. The learning goals of the ME 323 course aligned with the purpose of this study. Hence, this setting offers an opportunity to implement the SM instructional approach and evaluate its impact on students' learning experience. The mechanical engineering topic that reviewed in this study was the power screw concept.

Topic: Power Screw

The power screw is an important machine component in mechanical engineering. Power screw converts rotational motion to linear motion and is applied in several mechanical systems used in lifting load, such as screw jacks, or to apply large force, such as in presses (Juvinail &

Marshek, 2012). The power screw concept focuses on the estimating the screw torque required to raise or lower the given load. This concept involves understanding the relationships between the friction coefficients, tangential forces (q), mean diameter of the thread contact (dm), and the specified load.

Participants

The participants in this study were enrolled in ME 323 during the 2021 Spring semester. The students were mostly seniors, completing undergraduate degrees in mechanical engineering at the university. The study was conducted at a Upper Midwest university where students were expected to have completed Mechanics of Materials (ENGR 203) prior to enrolling in ME 323.

The study invitation email was sent to the participants to explain the purpose of the study and invite them to participate (Appendix A). After the initial email, a follow-up reminder was sent to the students. The recruitment phase lasted for about 14 days. The goal was to recruit at least eight students.

Data Collection Methods

This exploratory study employs multiple data sources to ensure richness of data and data triangulation (see Figure 7). This allowed the researcher to gain a comprehensive understanding of students' perceptions of the SM instructional approach. The interview transcripts were the primary source of data collection and the students' artifacts, such as the perceived problem-solving skills survey and system thinking diagram, are the secondary sources.

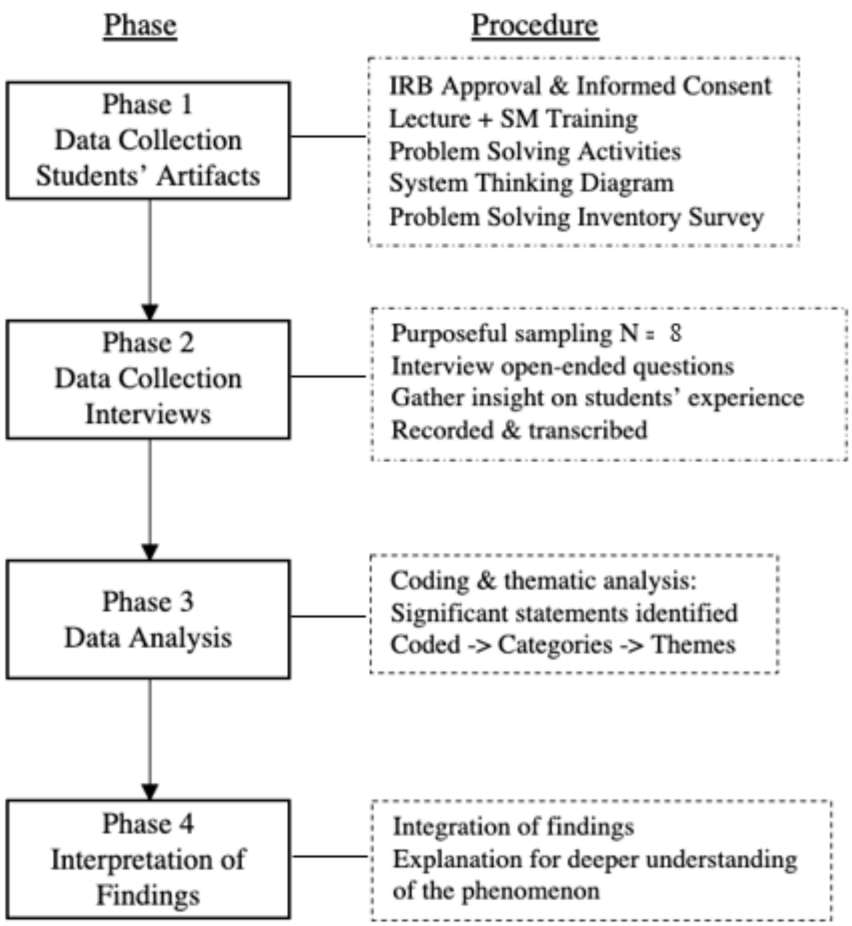


Figure 7. Qualitative Design. This figure illustrates the Study Research Design

Interview Transcripts

The interview transcripts were the primary data collection source. A purposeful sampling technique was employed to recruit mechanical engineering students to participate in the study. The sampling was homogeneous to ensure that all of the participants had similar experiences and backgrounds (Jacobsen, 2020). Textual data was collected via interviews using semi-structured questions and probing. The semi-structured questions were drafted to elicit the participants' perceptions and narratives of their experiences using the SM instructional approach and how it impacted their learning outcomes. The semi-structured interview questions include: the following:

• Explain how the system modeling instructional strategy influenced your learning experience (if at all)?

• What aspects of your learning experience were influenced?

• Could you describe how the system modeling instructional strategy has affected your problem-solving skills?

• Can you describe how system modeling instructional strategy has affected your ability to apply knowledge to address real world problems?

• Do you think that the system modeling instructional strategy (SM) has impacted your conceptual knowledge of mechanical engineering?

• Could you describe how the system modeling instructional strategy (SM) has affected your factual knowledge?

Interview sessions were audio and video recorded to generate transcripts. All recordings were transcribed. The following precautions were taken during the qualitative analysis to improve the validity, credibility, transferability, and trustworthiness of the results (Creswell and Creswell 2017; Guba and Lincoln 1989). First, only direct verbal quotations from participants were used in the analysis. Also, data triangulation of sources by integrating multiple data sources, and the final transcript were verified and double-checked with the participants as well as integrating students' artifacts.

The participants' privacy and confidentiality was protected by using pseudo names, thus hiding the real names of the participants. All interpretations from this study were drawn from the data, and precautions were made to prevent personal assumptions or biases from greatly influencing the result. The study is intended to gain an in-depth understanding of the students' perspectives and thought processes about the use of system modeling in a mechanical engineering course.

Students' Artifacts

Yin (2017) recommended including artifacts in inquiry qualitative studies alongside other data evidence. Moreover, prior qualitative research that explored system thinking and modeling among students have employed artifacts to gain insights on participants' understanding of a phenomenon (Gillmeister, 2017). In the current study, students' artifacts that were collected include a system thinking diagram and the PSI survey. These artifacts provided additional data on the influence of the SM instructional strategy on students' perceived problem-solving skills and system thinking skills. By analyzing those data, more insight and understanding could be drawn on students' learning experience with the use of SM instructional strategy.

Students' Perceived Problem-Solving Skills Survey (PSI). The PSI scale was developed by Heppner and Petersen (1982) to assess students' self-perception of problem-solving skills, PSS. This study adapted the PSI scale with the permission of the survey creator. The PSI scale has three constructs containing 9 items. The constructs include: (1) problem-solving confidence (PSC), (2) approach-avoidance style (AAS), and (3) personal control (PC).

In this study, the PSI survey assesses the students' perception of problem-solving skills with reference to the completed activities. These included items such as 'the SM task helped me to thinking about the multiple ways of solving a problem' and 'the SM task enable me to make a problem-solving plan that will almost certainly work'. On the PSI scale, students indicated their perceptions of PSS on a 6-point Likert scale (1 = Strongly Agree to 6 = Strongly Disagree). Students' self-reported PSI scores was examined as part of the students' artifacts.

Students' System Thinking Diagrams. This study adopted a simple version of the Cognitive Mapping Assessment of System Thinking (CMAST) developed by Plate (2010). The CMAST is a cognitive tool used to examine students' causal structure (mental model) of complex systems. Students' abilities to develop an accurate causal structure of a system reflects their system thinking skills, which can be modeled/mapped using pencil and paper (Hopper & Stave, 2008). Students drew models on paper using causal loops, and stock and flow diagrams to model the system's causal structure based on their understanding. Students' models were then evaluated for quality and accuracy considering system thnking dimensions like identification of variables, linearity, interconnectivity, cause-effect relationship, and feedback loop processes.

Procedure

Prior to the commencement of the study, an approved Institutional Review Board IRB approval form was completed and submitted. The study began after the approval of the IRB. Participants were provided with a written informed consent form approved by the IRB via DocuSign at the beginning of the study (Appendix B). The consent form describes the aims of the study and what the participants did during the study.

This study employed a qualitative approach to understand engineering students' perceptions and experiences of using system modeling (see Figure 7). One week prior to the study, the study activities were explained to the students. The participants then received a 50-minute lecture from the class professor on the power screw topic.

After the lecture, the participants participated in problem-solving activities. They received a short system modeling training session and learned how to represent a system using causal loops diagrams. Participants then participated in a problem-solving activity (Appendix C) and modeled their understanding of the problem. The students drew causal loop diagrams using pencil and paper (see Appendix G for model diagram examples). They then completed the PSI survey (Appendix D). Participants PSI scores and the pencil and paper diagrams were collected and analyzed as students' artifacts.

The participants took part in interview sessions via Zoom (see interview protocol Appendix E). There was a brief demographic questionnaire and discussion questions presented in an informal, conversational format that explored students' learning experiences using the system modeling instructional approach (see interview questions Appendix F). The interview session was audiotaped and transcribed in order to analyze the data collected. The participants adopted pseudonym (fictional) names; their actual names were not audiotaped.

Data Analysis

The interview data was the primary data source in this study. The data was analyzed using a thematic approach. Creswell and Poth (2017) itemized a number of steps during the data analysis. First, the researcher developed bracketing, which involves setting aside personal perspective and biases about the phenomenon under investigation. Second, the data was collected from multiple individuals who had experienced the phenomenon or context–SM instructional strategy. Next, the researcher rigorously read the interview transcript to identify significant statements to be transformed into categories, which in turn was organized into textual and structural themes. This analysis approach allowed the researcher to deeply understand the common experience of the participants in regards to the phenomenon under study.

Students' artifacts were analyzed, i.e. students' model diagrams were assessed to determine their system thinking skills using the Cognitive Mapping Assessment of System Thinking (CMAST). Also, the students' perceived problem-solving skills were examined and included in the analysis of the data. The analyses provided more insight regarding the effect of

SM instructional strategy on students' learning.

Reliability and Validity

Unlike quantitative research, qualitative studies do not employ statistical tools to address the issue of reliability and validity. Instead, qualitative researchers are required to demonstrate measures that were utilized in the research to ensure the validity and reliability of the results. This study employed several procedures to validate and ensure reliable data collection.

Reliability

To ensure the reliability of the data collected, the researchers developed specific participation criteria. Participants in this study were then selected based on the identified criterion. These criteria included enrollment in ME 303 during Fall 2021, had completed a prerequisite course ENGR 203 (Mechanics of Materials), and were either a junior or senior at the designated university completing a mechanical engineering degree. This ensured that the interviewees were reliable sources of information related to the system modeling experience as the students were all current mechanical engineering students at the time of data collection.

Additionally, the interview sessions were audio-recorded and transcribed verbatim to minimize the threat to the reliability of data collected. This was to ensure that participants' perspectives were accurately represented, provide a reference for possible questions, and serve as evidence in the interpretation of the findings (Maxwell, 1992).

Validity

To promote the validity of the data collected, qualitative researchers suggested several measures, including data triangulation, peer review of interview questions, and member checking (Creswell, 2011; Roulston, 2010). Other measures included a sound process of thematic analysis (Braun & Clarke, 2006), a transparent audit trail, and the researcher's personal reflections of possible bias (Roulston, 2010).

Data triangulation involved gathering data from multiple sources about a particular phenomenon (Roulston, 2010). In this study, the researcher collected data from multiple sources, and supplemented interview data with students' artifacts (PSI survey & students' causal model diagram). This ensured that the researcher could generate rich data to deeply understand students' experiences about the phenomenon under study as well as evaluate students' claims.

Additionally, during the interview questions development, the researcher's potential bias was reduced by employing peer review of interview questions. The study interview questions were peer-reviewed by qualitative researchers, and feedback received was used to revise the questions. This was to guarantee the neutrality of the questions and ensure the validity of the data collected.

Also, the researcher utilized member checking to minimize the threat to the validity of the results (Creswell, 2011; Roulston, 2010). Upon completion of interview transcriptions, the interviewees were sent their respective transcripts for their feedback and confirmation of accurate representation. The full scripts were sent via email to the interviewees, and they were encouraged to edit them, add, or withdraw any incorrect representations. The email exchanges provided a means to further understand students' perspectives and validate the data collected.

Furthermore, data validity was promoted by employing a sound process of thematic analysis (Braun & Clarke, 2006). This process provided a clear, structured, and organized audit trail for the purpose of study result review. Moreover, an organized audit trail provides strong support for the identified themes in this study.

CHAPTER IV

FINDINGS

This qualitative study explores the efficacy of a system modeling (SM) instructional strategy in a mechanical engineering course. Specifically, the study seeks to understand students' perceptions and experiences using system modeling to enhance their learning outcomes.

The study focuses on learning outcomes such as factual, application, and conceptual knowledge, as well as students' self-perception of problem-solving and system thinking skills. The main research questions investigated includes:

1. *What are students' perceived efficacy of the use of SM instructional approach?*
2. *How do students describe their experiences with SM instructional approach in relation to their factual, conceptual, and application knowledge?*
3. *What perceptions do students have regarding the use of SM instructional approach in relation to problem-solving and system thinking skills?*

In this chapter, I provide summaries of participants' narratives from eight interview sessions. While only one interview was conducted with each participants, several measures were employed to ensure validity of results. For instance, the interview data was supplemented with both the students artifacts and email interview during the member checking process. These additional measures enable the researcher to generate rich indepth data about the phenomenon under investigation.

The participants' narratives offer insights and understanding about students' perceptions and experiences using the system modeling instructional strategies. This chapter also includes interview data analysis using a thematic approach that involves identifying codes transformed into categories, which in turn was organized into themes. The analysis approach allowed me to understand more in depth the experiences of the participants relative to the phenomenon studied. Direct quotations were used to underline participants' experiences in relation to the emerging themes. Additionally, I present findings from students' artifacts analysis–students' model diagrams and their perceived problem-solving skills PSI questionnaire. These analyses provide more insight about the effects of SM instructional strategy on students' learning.

Participants Demographic Information

This section includes demographic information about the study participants, including their educational and professional experiences. Eight students were interviewed and assigned pseudonyms to preserve anonymity; they are referred to as: Alex, Bob, Echo, Jack, Max, Sam, Sarah, and Tyler. The students have a variety of different backgrounds and work experiences with unique career motivations and varying perceptions. These distinctive, individual personalities contributed depth and complexity to the study narrative. Table 1 presents a summary of the participants' educational and professional experiences.

Table 1. Participants' Demography, Educational and Professional Experience

Participants	Age Range	Gender	Student Current Status	Years of Experience
1. Alex	31yrs. & above	Female	Senior	+15 years
2. Bob	20 – 25yrs.	Male	Junior	8 months
3. Echo	20 – 25yrs.	Female	Junior	8 months
4. Jack	31yrs. & above	Male	Senior	+20 years
5. Max	31yrs. & above	Male	Junior	20 years
6. Sam	20 – 25yrs.	Male	Junior	None
7. Sarah	31yrs. & above	Female	Junior	+7 years
8. Tyler	Below 20yrs.	Male	Junior	1 year

Alex has an undergraduate degree in Physics; she is currently a senior majoring in mechanical engineering. She has more than 15 years of experience working as an Ocean engineer, which is a mix of mechanical, electrical, and chemical engineering. Alex stated that her decision to pursue a mechanical engineering career was because she enjoyed designing, constructing, and building something that works. She highlighted perseverance, grit, attention to detail, ethics and honesty as some of the most important skillsets to become a successful mechanical engineer.

Bob is a junior in the mechanical engineering program. He has eight-months of engineering Co-op experience. Bob stated that his decision to pursue a mechanical engineering career was because of his interest in designing and building things that work. He recalled that prior to his Co-op experience, he believed that memorizing equations and formulas were the most important skills to be a successful engineer. However, after the Co-op his perspective changed and he now believes that it is one's ability to ask the right questions.

Echo is a junior in the mechanical engineering program. She does not have much professional experience, but she was a Teaching Assistant in one of the engineering courses. Echo likes to “tinker” with things and enjoys math. She believes that mechanical engineering is the broadest engineering field and is a good fit for her. Echo argued that a successful engineer must have problem-solving skills and a “try hard attitude”.

Jack is a senior pursuing his mechanical engineering undergraduate degree. Prior to enrollment in the engineering program, he obtained an associate degree from a junior college. He has more than twenty years of experience working in a local engine mechanic shop. He chose to pursue a degree in mechanical engineering because he likes to build and tinker with things. Jack believes that to be a successful engineer, one must know how things work and have a solid background in math.

Max has an associate’s degree in mechanical engineering from a two-year college. He is now a junior seeking a bachelor’s degree in mechanical engineering. He has twenty years of experience in engineering–the first ten years he worked as a drafter and the last ten years he worked as a design engineer. Max revealed that he decided to pursue mechanical engineering because he is good at math and loves to problem-solve. He considers being organized and having good communication skills and the ability to clearly state steps in problem-solving as the key skillsets required for successful engineers.

Sam is a junior completing his degree in mechanical engineering. He does not have a lot of professional experience but has completed multiple projects in several classes. Sam decided to pursue an engineering career because he enjoys learning how things work, why they work, how they can be improved, and problem-solving. He argues that successful engineers must be able to understand mathematical and engineering concepts.

Sarah has a bachelor's degree in Nuclear Engineering Technology. She is a junior working on completing her undergraduate degree in mechanical engineering. Sarah has seven years of professional experience working as a nuclear technician. Her interest to learn about the design process and make better quality products spurred her interest to pursue an engineering career. Sarah believes that being able to integrate all the knowledge is an essential skillset for successful engineers.

Tyler is a junior pursuing his bachelor's degree in mechanical engineering. He has about a year of internship experience at an engineering company. Tyler has always wanted to design and build things since he was in high school and believes the mechanical engineering degree is a great fit. Tyler believes that to become a successful engineer one must be strong in math, and possess spatial reasoning skills, as well as critical thinking and analytical skills.

Thematic Analysis of Interviews

A total of eight in-depth interviews was conducted to explore and understand students' perceptions and experiences using the system modeling instructional strategy. The transcripts generated from the interviews were analyzed using thematic content analysis, which is the process of developing descriptive themes that involve identifying significant statements and codes, and then generating them into meaningful categories (Moustakas, 1994; Vaismoradi, Turunen, & Bondas, 2013).

A thematic analysis was used to address research question one: *What are students' perceived efficacy of the use of SM instructional approach?* Using this analysis, I reviewed the transcripts and identified significant statements that were distilled into codes. The codes were grouped into meaningful categories and several themes emerged. A total of seven themes emerged from the thematic analysis in relation to how students described their experiences with the SM approach. Table 2 shows the themes, categories, and their respective codes.

Table 2. Thematic Analysis of Qualitative Data

Themes	Categories	Codes
Problem diagnosis	Problem analysis	• Visualize problem • Examine different parts of problem • Break down equation • Divide up problems into components
	Problem identification	• Identifying the problem • Gaining knowledge of problem • Brainstorm the problem • Identify what is needed
	Querying the problem	• Asking the right questions • Probing the problem
Interconnection & interdependency	Effect of variable change	• Visualizing real effects • Manipulating variables prior to calculations • Understanding the effect of change on other variables as well as the output • Changing variables to get desired outcomes
	Interconnection	• Identify interconnected parts • Intertwined (connected in multiple points) • Interrelated variables
	Concept's linkage	• Understand links between concepts • Linking equations • Connect different factual knowledge
Wholeness and decision making	Examining the wholeness	• Step back to see bigger picture • Think about the end product • Tying concepts to define application
	Decision making	• Identifying problem solutions

		• Helps in decision making
Linearity in Relationships	Linear relationships	• Visualizing relationships • Breakdown into relationship • Create relationships
	Non-linear relationships	• Multiple effects • Non-linear approach
Organized Problem-Solving Approach	Information organization	• Helps arrange information • Organized approach • Categorize things
	Logical steps	• Easy to follow • Logical flow • Step-by-step thinking process
	Good starting point for problem-solving	• Identify starting point • Identify important variables • Eliminate insignificant variables
External representation of causal relationship	Cause and effect visualization	• Seeing cause and effects • Identifying and thinking causal effect • Cause and effect charts
	System structure representation	• See underlying system structure • System visual representation • Laying down system components
Systematic and forward-thinking process	Pattern thinking	• See patterns • Patterning thinking • Planning problem-solving
	Forward-thinking	• Layout beforehand • Foresee and anticipate problems • Thinking ahead
	System thinking	• Think systematically

Theme 1: Problem Diagnosis

Problem diagnosis requires examining the nature of the problem and asking questions like "what is the problem?" Many of the participants believed the system modeling instructional strategy promoted their ability to diagnose engineering problems. Several categories supported the development of this theme including problem analysis, problem identification, and problem querying (see Table 2).

The problem analysis codes include: visualize problem, examine different parts of problem, break down equation, and divide up problems into components. The code for problem identification includes identifying the problem, gaining knowledge of problem, brainstorming the problem, and identifying what is needed. Querying the problem codes includes asking the right questions and probing the problem and inquiring about the problem. Participants' narratives that exemplified these categories are discussed below.

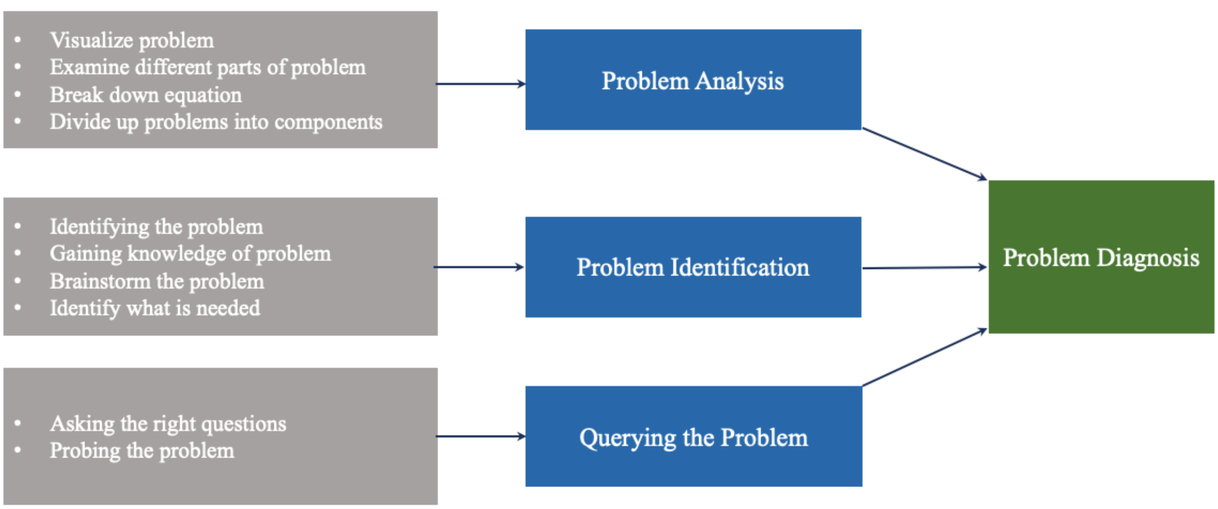


Figure 8. Theme 1, Problem Diagnosis Code Map

Problem analysis. The first category found for this theme was "analyzing the problem." Many of the participants described their experiences using the system modeling (SM) with phrases like it helps in looking at the problems and understanding them, as well as helps in breaking down problems, dividing problems into components, and picking problem apart. Participants indicated that the SM instructional strategy helped them break down the problems, thereby promoting problem understanding. For instance, Sam stated that when using the SM "… you're breaking down a problem… that can help you a lot, allowing you to further understand the breakdown of your problem." Like Sam, Sarah also expressed a positive reaction to the approach, maintaining that "the strategy helps you to divide up the problem into the different components… so you can fully understand the issue."

Other participants described their experiences expressing that the SM approach helped in breaking down the problem into common sense steps. For example, Max commented that, "I think the flow of it basically is a good experience and it breaks it down to, I would say common sense steps, but it also flows. It doesn't go out and tend to do something different. It flows, nice and easy, that's logical, and you can follow up pretty good."

Some of the participants believed that the SM approach assisted in breaking apart the problem not only to understand it, but also to help determine how to "attack it" or even delegate the problem among team members. Sarah stated that, "… if you kind of break it down into different areas and you can attack those different areas. And maybe divide up the different areas between … other people."

Participants interviewed also believed that the SM approach helped break down equations to promote understanding. Echo mentioned that "it kind of helped break down the equations we use in class to understand... doing so allowed me to kind of see formulas within the main equation." Similarly, Sam thought that it could help identify the right equation. He stated that "… see what equation I need to throw them into… to get what I want out of the problem."

Overall, the participants' descriptions highlighted above aligned with Ackoff's (2000) definition of the analysis approach of inquiry—the breaking down parts to examine them in isolation, focusing on revealing the problem structure, and helping to describe the problem. This problem-solving approach is considered fundamental in modern scientific methods.

Problem identification. The second category under the problem diagnosis theme was problem identification. Many of the interview participants acknowledged the importance of problem identification during the problem-solving process. For instance, Jack stated:

> … if you don't know what the problem is and be able to design or make a specific thing to solve that problem, you're not doing anybody any good… you got to be able to see what the problem is, and then figure out a way to solve that problem.

In describing their experiences with the SM approach, participants used phrases like seeing what the problem is, figuring out the problem, thinking and brainstorming the problem. Specifically, a number of participants highlighted how the approach promoted their knowledge of the problem. Sam said, "And it gives you a better idea of what exactly is going on here in this specific problem." Like Sam, Sarah also said, "So you can tell … what is really the problem?"

Interestingly, Sam also believed that the SM approach helped foster his thinking and brainstorming in a specific problem-solving situation. He stated:

> … allows you to further understand [what] you're given, and it lets you think more and brainstorm more about–well what conceptual knowledge do I know? What can I, what can be applied here in this specific instance?

Generally, the participants' descriptions supported the prior research on problem-solving. For instance, researchers Rittle- Johnson (2006) and Hung (2009) suggested that defining and identifying the problem is an important aspect of the problem-solving process and it promotes the construction of the problem space. Hence, identifying the problem is the first step in problem-solving (Jonassen, 2004; Newell & Simon, 1972; Reimann & Chi, 1989).

Querying the problem. The third category discussed by participants was querying the problem. Participants in this study highlighted several examples of "querying the problem" and asking the right questions, a process they said was assisted by the SM approach. For instance, Bob hinted that:

> Well, you have a problem, I would say this part is failing, but you need to ask the questions on why it's failing. Is it because of source A? Is it because of source B? or Is it because it just the bad part? … but it's asking the right questions.

Sam, like Bob, presented an example where he was probing the question. He commented that, "because often times you're, you're given a task… Say, improve this product, improve this bearing… So, you're given a problem. This bearing... fails easily. So, what can we do to improve that, to improve the longevity of this bearing?" For Jack, querying the problem involved asking "What's causing the problem?"

Some participants suggested that asking questions or probing during problem-solving might follow a specific pattern. Bob recalled common patterns in asking questions during the problem-solving process in his classes. He stated:

> Um, so, in my courses I've had so far, it always seems like there's some sort of pattern ... Let's say I have a beam, and I have a force on it. Okay, so the first question, what am I trying to find? Second question, what steps should I take to find it? Third question, can these steps be changed? Can they be simplified? Fourth question, how do I know my answer is correct? Fifth question, can I check this against someone else's work? Can I find the example, which would support my idea of…I think I did it correctly this way?

Theme 2: Interconnection and Interdependency

Interconnection and interdependency imply that all parts of the system or problem are connected and interrelated, thereby forming a network of things rather than isolated parts. Many of the participants believed the SM strategy promoted their ability to visualize interconnections and interdependencies within the given problem. Several categories supported the development of this theme including effect of variable change, interconnection, and concepts linkage (see Table 2).

The effect of variable change codes included promoting visualizing real effects, manipulating variables prior to calculations, understanding the effect of change on other variables as well as the output, and changing variables to get desired outcomes. The code for interconnection included identifying interconnected parts, intertwined (connected in multiple points), and interrelated variables.

Concept linkage was the final category and included codes like understanding links between concepts, tying concepts together, linking equations, and connecting different factual knowledge. Participants' accounts that illustrated these categories are discussed below.

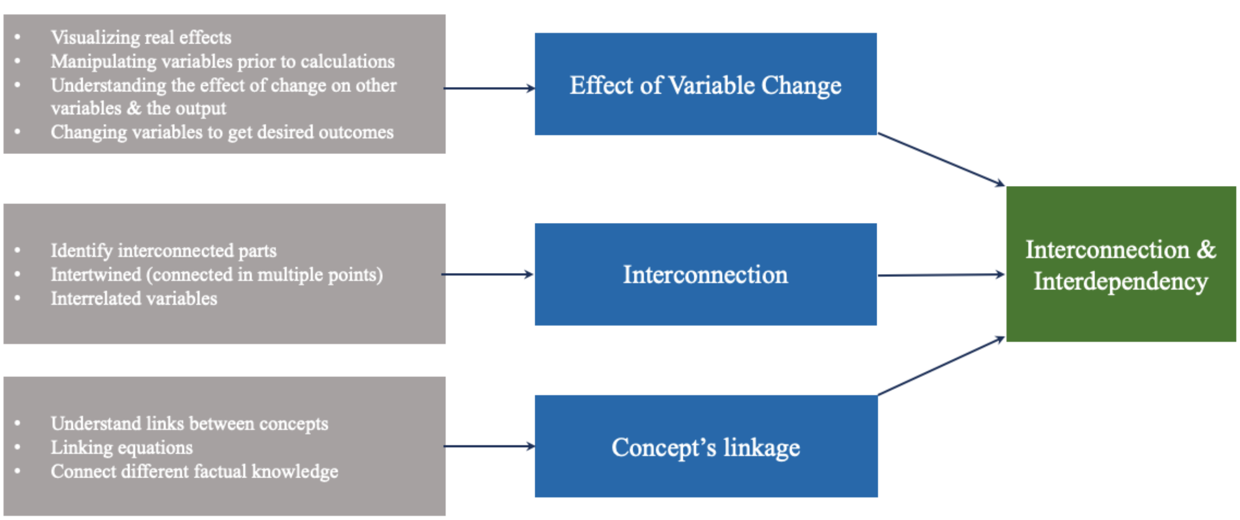


Figure 9. Theme 2, Interconnection and Interdependency Code Map

The effect of variable change. The effect of variable change is the first category that informed this theme. Many of the participants interviewed used phrases like change one…what happens, adjust beforehand, understand total change, and impact of change on the output to describe their experiences applying the SM strategy. Their descriptions indicated that SM helped them to: 1) visualize effects of variable changes on other variables and on the output, 2) understand the total and practical effects of change, and 3) visualize the effect of variable manipulation prior to calculation.

Participants gave specific examples of how the SM promoted their ability to visualize the effects of variable changes on other variables. Bob stated: "this single part could affect it that way... if this increases that must decrease, or if this increases this increase." The other participants asserted that the SM approach aided in examining the effect of variable changes on the output. Sarah commented; "It made me think more about how different variables affect the outcome." Like Sarah, Echo stated; "… if you were to change a certain part within that variable… how would that impact the output variable…."

Also, interviewees believed that the SM promoted understanding of the total and practical effects of changes. Tyler commented; "… it gives you a better opportunity to understand the total changes you might see." Alex highlighted that the approach provided a practical way of experiencing the effect of change. She stated: "having a sense for…, if I change just this one factor, what does that do to all the other components of the system… you can see what are the effects of this thing versus that thing in a very realistic way…."

Interestingly, some of the participants contended that the SM approach helped in visualizing effect of variable manipulation prior to calculation of a given problem. Tyler commented: "…then I'd say okay, this is kind of the problem I would run into if I had messed with say the chord length, or this is the problem I would run into if I mess with the height or the thickness. So, I would adjust it beforehand. Instead of after running the calculations."

Interconnection. Participants described their experiences using the system modeling (SM) approach as promoting their ability to picture interconnections within the problem or system. For instance, Jack commented: "It got me thinking, first part, third part, how do they intertwine…." Also, Alex provided a comprehensive example of interconnections related to the problem-solving activity in this study. She stated:

> But yeah, so if you look at… changing the helix angle means that you can generate more torque as long as you have enough force to push it, but you can quickly get beyond the ability of a person to move that lever right. But it would change the amount of torque applied or a smaller range of motion, which could help if you're in a confined space, but then if friction is a factor, well, greater diameter to generate torque, then you're gonna have more friction, which then decreases your amount… So, everything's kind of interconnected…

Concept linkage. Some of the interviewees provided discussion about how the SM approach helped them to understand the links between concepts and formulas. Sarah mentioned that it "…helps to better understand how different concepts are linked." Tyler also stated: "... it helps you understand better and then how to tie them in together… this concept can be tied together with this concept to define this application."

On the other hand, Echo had a different perspective. She believed that the approach was particularly helpful in identifying and linking formulas. Echo stated: "it allowed me to kind of see formulas within the main equation. And doing so allowed me to kind of link it back to, like, even like calculus."

Theme 3: Wholeness and Decision Making

Participants believed the SM strategy helped in viewing the bigger picture and promoted better decision-making during problem-solving. Several categories supported the development of this theme including examining the whole problem and decisions during problem-solving (see Table 2). The examining the whole codes includes stepping back to see the bigger picture, thinking about the end product, and tying concepts to define application. The decision-making category includes codes like identifying problem solutions and helps in decision making. Participants' descriptions that exemplified these categories are discussed below.

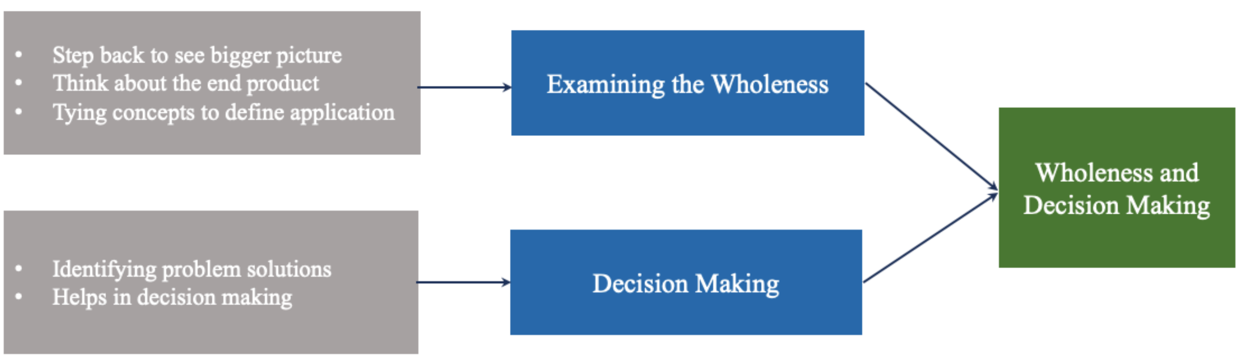


Figure 10. Theme 3, Wholeness and Decision-Making Code Map

Examining the whole. Participants described how the SM approach assisted in examining the entire problem rather than an isolated linear process. Alex stated: "So rather than a really linear march through equations with numbers, it actually was step back, see the whole picture." She emphasized the importance of seeing the bigger picture during problem-solving. Alex stressed: "Because if you're going to actually build something that works, you really have to see the whole picture because you could build something that works on a lab bench but could never have any practical application or use." For Jack, it was important to think about the final end product (bigger picture). He commented: "It got me to look at, like my homework problems in a bigger view. Okay, this is what I'm looking for, as an end product what will cause me to achieve this end product."

Decision-making. Many participants narrated the positive effect of the SM approach on their ability to make decisions during problem-solving. Sarah maintained that the approach helped in solving problems that involved manipulating variables to get desired outputs. She stated: "I guess it just helps to make decisions. You can… more easily see which are the variables that are easiest to control or to change, to get the desired outcome." Sam contended that the SM strategy could aid decision making during problem-solving in the workplace. He suggested: "… it can create, you know those ideas, … it can create your ideas for finding your best solution to any given issue that you're given in the workplace."

Theme 4: Linearity in Relationships

Participants described how the system modeling (SM) instructional strategy helped them visualize both linear and nonlinear relationships within the problem. Two main categories supported the development of this theme including linear relationships and non-linear relationships (see Table 2). Linear relationships codes include: visualize relationships, breakdown and create relationships. The codes for non-linear relationships include: multiple effects, and non-linear approach.

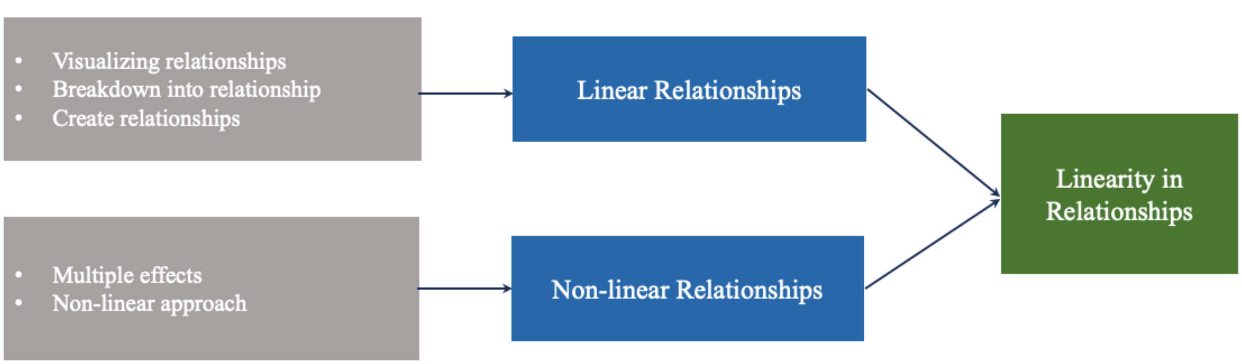


Figure 11. Theme 4, Linearity in Relationships Code Map

Linear relationships. The first category within this theme found in the study was linear relationships. Participants described their experiences using the system modeling (SM) approach with phrases like, help find linear relationships, visualize a linear approach, breakdown into relationships, create and tie relationships. For instance, in referring to the SM approach, Sam said: "It's basically asking you to find relationships between different variables… finding relationships that will let you further understand your material and make everything easier, which is always good." For Alex, the approach was "… a very linear way of problem solving." Similar to Alex's description, Tyler stated that, "I mean because it's basically a more comprehensive linear cause and effect chart".

Non-linear relationships. Non-linear relationship is the other category found within this theme. Non-linear relationship implies that changing one variable can have multiple non-linear effects on the other parts of the system. Participants interviewed in this study mentioned that the SM approach helped them to see and think about non-linear relationships within the problem. Alex gave an example to support how the approach helped in her thinking about non-linear relationships and multiple effects. She stated: "… you have to think way beyond the effect of just changing one thing." Like Alex, Tyler also believed that the SM approach is a non-linear problem-solving approach. He said: "And it lets you, I guess, spiderweb your way … to figure out what has changed and why, or what should change and why."

Theme 5: Organize Problem-Solving Approach

Many of the participants described the use of SM strategy as an organized problem-solving approach. A number of categories exemplified the development of this theme including information organization, logical steps, and good starting point for problem-solving (see Table

2). Information organization codes include: helps arrange information, has an organized approach, and categorizes things. Logical steps codes include: easy to follow, logical flow, and step-by-step thinking process. Good starting point for problem-solving codes includes: identify starting point, identify important variables, and eliminate insignificant variables. Participants' narratives that illustrated these categories are discussed below.

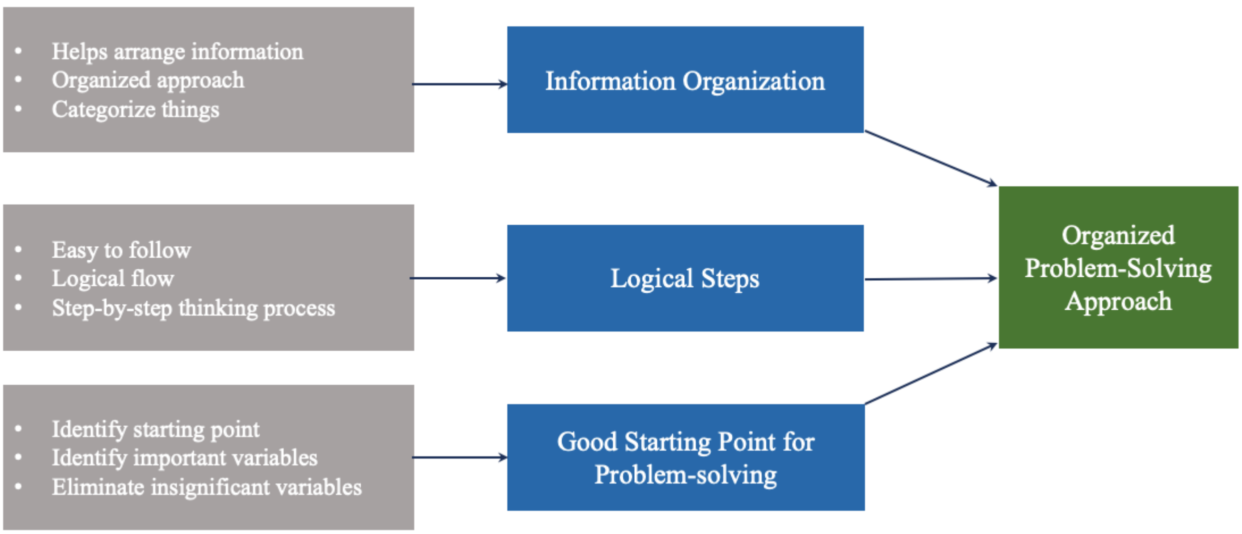


Figure 12. Theme 5, Organize Problem-Solving Approach Code Map

Information organization. Participants in this study indicated the SM approach helped in the organization of information during problem-solving. Sarah stated: "Yeah, I think it provides you kind of an organized way to approach to approach a problem." Bob echoed Sarah's perception when he confirmed: "It has influenced me to try a new approach, and how I categorize, different things I learned." Bob explained the organization helps during problem-solving. He stated that the SM approach "… organizes it [the problem] in a way… you can look and you can see what parts of this information you need to find."

Logical steps. Interviewees in this study also believed that the SM approach was a logical step-by-step problem-solving process. Max explained: "I think the flow of it basically is a good experience… It doesn't go out and tend to do something different. It flows, nice and easy, that's logical, and you can follow up pretty good." He also highlighted the SM approach prevented the problem solver from skipping steps and jumping to the solution. Max emphasized: "You can't just go one step to get the answer, you got to think about it, organize your thought process and go through step by step, solving whatever the problem is asking you to solve."

Good starting point for problem-solving. Participants interviewed held that the SM approach provided a good starting point for problem-solving. Knowing where to start solving a problem may be challenging for some students. This is supported by Echo's statement: "… they don't know how to start a problem." Sam contended that the SM approach could present a good start in problem-solving. He stated: "Even though you might have to come back to the other ones, but this can give you a good, a good basis on what to start off, and it gives you a better, big picture."

Participants also believed the SM strategy helped identify important variables during problem-solving activities. Sarah mentioned: "It helps me be more aware of which variables are the ones that I need to pay attention to." Alex presented a practical example to illustrate how the SM could help identify significant variables in problems. She stated:

> … I guess theoretically, the smallest little things, like, oh, what's the temperature in the room that could cause a different thermal coefficient of expansion for different parts of that screw? But that's going to be… a minor degree compared to what's the helix angle that you're using? Then you know you can say, big picture–I can just ignore the temperature effects right now, and just look at what that helix angle is going to do… You can evaluate realistically what is important than what's not."

Sam hinted that the SM approach helped to eliminate insignificant variables.

Sam said: "And you can say, well, increasing a force on something will increase the overall torque, and I want a better torque, so now I have to look at force. So, by doing that, you can now kind of eliminate some variables, and consider other ones more."

Theme 6: External Representation of Causal Relationship

External representation of causal relationship implies depicting and describing the operations, structure, and underlying causal relationships that exist within a system. Participants interviewed believed the system modeling (SM) instructional strategy promoted their ability to externally represent their understanding of causal relationships in the problem. Several categories supported the development of this theme including cause and effect visualization as well as system structure representation (see Table 2). Cause and effect visualization codes include: seeing cause and effects, identifying and thinking about causal effect, and cause and effect charts. System structure representation codes include: see underlying system structure, system visual representation and laying down system components. Participants' descriptions that exemplified these categories are discussed below.

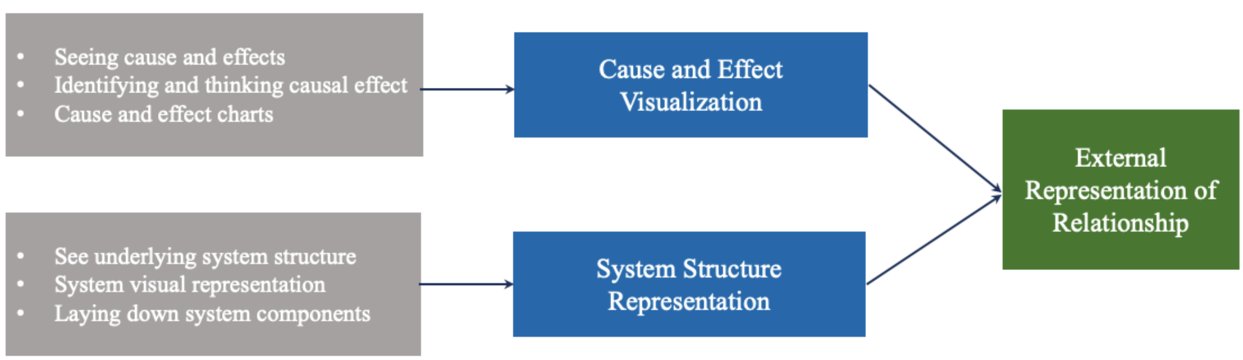


Figure 13. Theme 6, External Representation of Causal Relationship Code Map

Cause and effect visualization. Cause and effect visualization is the first category within this theme. Interviewees in this study narrated how the SM approach influenced their cause-and-effect visualization during problem-solving. Bob stated: "…this is the cause of this, if I decrease this then my force over here must increase, that was very helpful and nice to have." Similarly, Sam described specifically how the SM approach promoted the picturing of cause-effect relationships which helped during problem-solving. He said:

> So, by using this specific approach ... it forces you to kind of break things down into relationships, cause and effect–for the cause-and-effect diagram. And it gives you a better idea of what exactly is going on here in this specific problem. Once you know what's going on, that's what helps you to know, okay, so, if, if I have this cause and effect, I'm looking to get a certain effect, so which causes am I looking for? And you can say, well, increasing a force on something will increase the overall torque, and I want a better torque so now I have to look at force. So, by doing that, you can now kind of eliminate some variables, and consider other ones more.

Representation of the system structure. This is the other category within the external representation of causal relationship theme. Participants indicated the SM approach aided their representation of the problem or system. Bob stated that the SM helped "… solve the problem by laying down what you know." He explained further that it "... would give us a nice visual representation of what is happening... I'm a very visual hands-on learner." Also, Sarah mentioned that SM could help "…you see what the different components are… [in the problem]."

Theme 7: Systematic and Forward-Thinking Process

Participants revealed how the SM approach provided a systematic and forward-thinking approach to problem-solving. Three main categories informed the development of this theme including: pattern thinking, forward-thinking, and system thinking (see Table 2). Pattern thinking codes include: help to see patterns, patterning your thinking, and planning problem-solving.

Forward-thinking codes include: layout beforehand, foresee and anticipate problems, and thinking ahead. Participants' descriptions that exemplified these categories are discussed below.

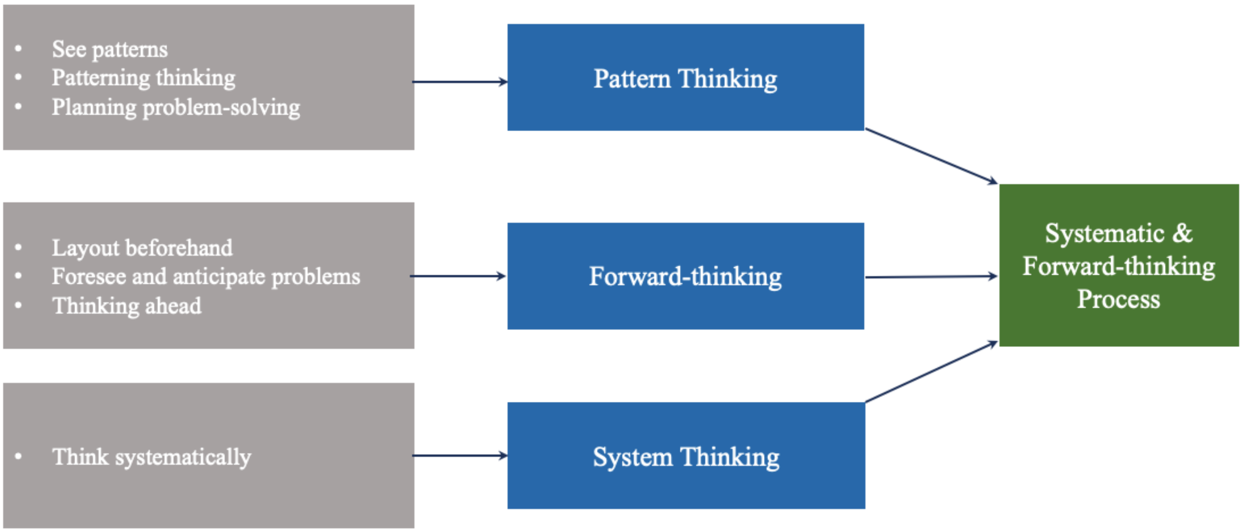


Figure 14. Theme 7, Systematic and Forward-Thinking Process Code Map

Pattern thinking. Interviewees in this study described how the SM approach aided them during the problem-solving activity by patterning their thinking. Alex hinted: "I guess it's, um, like patterning your thinking. It's teaching you to look at things in a certain way...." She explained: "...everything involved in category, without even realizing it, in categorizing what to tackle first, what's the biggest, most important part to tackle." Bob echoed Alex's perspective and added: "… if I would have had some sort of flow chart or a sheet like this when I'm trying to learn or understand the equations, I feel like being able to see the pattern on why something works, this particular way, would have been a lot easier."

System thinking. Interviewees also believed that the SM approach encouraged them to think systematically. Max mentioned: "Hmmm, I guess, it is forced you to think step by step and not go right away into conclusions ...." Tyler reiterated: "If you have a more complex system with different parts, if you can't tie them together, … there's no guarantee your systems gonna work out."

Forward-thinking. Participants described their experiences using the SM approach as promoting their forward-thinking. Tyler stated: "…I'd say okay, this is kind of the problem I would run into if I had messed with say the chord length, or this is the problem I would run into if I mess with the height or the thickness. So, I would adjust it beforehand. Instead of after running the calculations." He further explained: "Yeah, it just forced me to think about the beforehand, rather than considering possible after effects."

Students' Learning Outcomes

The second research question addressed was: *How do students describe their experience with SM instructional approach in relation to their factual, conceptual, and application knowledge?* Participants interviewed in this study described varying experiences using the SM approach in regards to their learning outcomes such as factual, conceptual, and application knowledge.

Factual Knowledge

When the participants in this study were asked about the importance of factual knowledge for mechanical engineers, most believed that it was important. Echo described the importance of factual knowledge as: "Super-duper important … factual knowledge is extremely important because you need to understand your basics… Is basically the ground that you're standing on." Max reiterated Echo's perspective stating: "That's key, you need to understand the basics before you can actually solve the problem." Alex also confirmed: "I don't think you can build concepts without knowing the facts first." However, interestingly, Alex believed that engineers may not need to memorize factual knowledge as long as they know where to find it. She said: "I think … maybe that mechanical engineers, knowing that there is a fact, out there is almost good enough because you can go look it up. So, you don't have to have it memorized."

Participants were then asked to describe their experiences using the SM instructional approach in relation to their factual knowledge. They expressed varying perspectives on the effect of SM approach relative to their factual knowledge. Some participants believed that the SM approach affected their factual knowledge. For instance, Echo revealed that understanding the facts about units can greatly influenced the understanding of equations. She stated:

> The system modeling definitely helps kind of solidify the ground that you're standing on … understanding how each variable comes across, or even each unit comes across was super helpful … Especially thermodynamics, we used it all the time, because you had to come out to a certain unit, and understanding the relationships between certain units based on their variables … and just really helps you understand what you're learning.

However, the other participants did not believe the SM approach affected their factual knowledge. Sarah commented: "I don't really think it affects the factual knowledge as much as…." Similarly, Alex explained: "Not really. That strategy doesn't seem like it's focused on increasing factual knowledge but more on the way you use factual knowledge in problem-solving."

Conceptual Knowledge

All participants believed that conceptual knowledge was important for mechanical engineers. John described the importance of conceptual knowledge as: "…you gotta have the basic knowledge of everything you're working with, be it electrical, be it structural and statics and dynamics … So, the actual conceptual knowledge is very important." Like John, Echo stated: "… conceptual knowledge really is important, because you're going to be using it for everything, everything is connected and you definitely see that as you go into all your courses." For Sam, conceptual knowledge is important to be able to apply knowledge. He stated: "… you need to have a good base education on conceptual knowledge of all these different concepts so that you can apply them and use them in your career and be able to solve problems easier… have good problem-solving strategy."

When the participants were asked about the effect of the SM approach on their conceptual knowledge, most described a positive experience. For instance, Sam narrated how the SM approach helped him solve problems. He explained:

> "…because it allows you… to break down a problem, and pretty much look at different parts… Finding those different parts can allow you to tap into your conceptual knowledge, and then apply your conceptual knowledge and find out, okay, so I'm given all of these variables. Let's see what equation I need to throw them into to get what I want out of this problem."

Likewise, Sarah also recounted the positive effect of the SM strategy stating: "Yeah, I think it provides you kind of an organized way to approach a problem." Tyler supported Sam's and Sarah's perspectives. He stressed: "So, it allows me to, or it would allow me to, I guess, a little better express the concepts and how they relate to one another."

However, some of the participants did not believe that the SM approach affected their conceptual knowledge. Max stated: "I think that's what's missing here… They don't seem like they give you a starting point to go by and you can feed off that." John also echoed Max's concern. He stated: "I don't think it helped or impacted, helped or hindered in any way..."

Application Knowledge

All participants interviewed believed that application knowledge was important for mechanical engineers. They all agreed that the ability to apply knowledge is essential to become a successful engineer. John emphasized: "Application knowledge is very important for any engineer… to be able to apply that knowledge to what you're doing is just so important." Like John, Echo also believed application knowledge is central to solving problems. She said: "… if you come across a problem… application knowledge is basically how you're going to apply everything that you learned to solve this problem… And so, knowing how to apply all these equations that we learned is very important."

When the interviewees were asked about the effect of the SM approach on their application knowledge, all gave positive responses. They narrated the different ways that the approach helped them to apply their knowledge. For instance, Sam stated:

> "So, like all applications in engineering, the ability to break down problems to better understand them, is a skill of every good engineer. So, using … the system modeling approach can help you break down your problems to make them easier to understand."

Alex went further to argue that the SM strategy helps students think like engineers. She stated: "So this instructional strategy and the loop… feedback loop was really helpful for people to think like an engineer… Where you can see what the effects of this thing are versus that thing in a very realistic way."

Problem-Solving and System Thinking Skills

Research question three was: *What perceptions do students have regarding the use of SM instructional approach in relation to problem-solving and system thinking skills?* To address this question both interview data and students' artifacts were collected and analyzed.

Problem-Solving Skills

Interview data. When the participants in this study were asked about the importance of problem-solving skills (PSS), they all agreed that it was important. Participants affirmed that all engineering is solving problems and as such problem-solving skills are paramount. Alex stated:

"… all of engineering is trying to tackle problems… so you definitely need good problem-solving skills and strategies to come out with anything helpful." Mike also agreed with the importance of PSS. He mentioned: "Well, to start, we are always solving problems. So, you need to have some kind of skill set to solve the problems."

When the interviewees were asked if they could describe how the system modeling instructional strategy had affected their problem-solving skills, all participants responded that the SM approach influenced their problem-solving skills. Reflecting on their experiences, participants used phrases like good intuitive feeling, visualizing bigger picture, seeing variable effects on output, eliminating variables, showing variables to pay attention to, and identifying solutions. For instance, Alex commented:

> Um, yeah it was a good exercise in… looking at the bigger picture and having a sense for… if I change just this one factor, what does that do to all the other components of the system … and to have a good intuitive feel for if this goes up that goes down, rather than looking at a complex equation that has everything wrapped together into one thing with lots of coefficients and variables and signs….

Also, Echo said: "I guess it could affect, it affected my problem-solving skills by understanding how the variables affect the output…." Mike, who had more than 20 years of experience working as a field engineer, believed the approach mirrored what he has been doing in his work by helping "organize the thinking process."

Students' Perceived Problem-Solving Skills. Data from the Problem-Solving Inventory Survey scale, which assessed students' self-perception of problem-solving skills, was analyzed as part of the students' artifacts. The PSI scale has three constructs containing 9 items (see Appendix D). The constructs include: (1) problem-solving confidence (PSC), (2) approach-avoidance style (AAS), and (3) personal control (PC). The survey assessed students' perceptions of problem-solving skills with reference to the completed SM activities. Participants were asked to select their response using a Likert scale (1 = Strongly Agree to 6 = Strongly Disagree). Table 3 reveals participants' responses on the problem-solving survey.

Overall, participants' responses suggested that they believed the SM instructional approach affected their perceived problem-solving skills, especially their approach avoidance style (see Table 2). For instance, all participants reported that using the SM approach enabled them to think systematically during the problem-solving process. In addition, most of the participants indicated that the SM approach helped in promoting their problem-solving confidence. For example, most respondents reported that the SM task made them feel confident that they could solve new problems using the same method. Additionally, the survey showed that most of the participants believed the SM approach helped in making problem-solving plans, in solving new problems, and in thinking about multiple problem-solving approach. These were also common themes described during the interview.

Table 3. Participants' Responses to the Problem-Solving Survey

Constructs	Questions (All items assessed problem-solving skills with reference to the SM activities)	Some form of agreement	Mean
Problem-Solving Confidence	The SM task helped me to make a problem-solving plan that will almost certainly work.	87.50%	3.88
	The SM task makes me feel confident that I can solve new problems using the same method.	87.50%	4.13
	The SM task helped me to think firstly about what exactly the problem is.	75.00%	4.50
Approach-Avoidance style	The SM task helped me to first evaluate the problem to identify important information about it.	75.00%	4.50
	Using the SM approach enabled me to think systematically during the problem-solving process.	100.00%	4.88

	The SM task helped me to thinking about the multiple ways of solving a problem.	87.50%	4.63
Personal Control	When presented with a problem, I avoid jumping directly into the solution.	50.00%	3.75
	When my first efforts to solve a problem fail, I become uneasy about my ability to solve the problem (R).	25.00%	2.75
	When I work on a problem, I feel that I am not getting to the real solution (R).	25.00%	2.75

System Thinking Skills—Students' Artifacts

This study adopted a simple version of the Cognitive Mapping Assessment of System Thinking (CMAST) developed by Plate (2010). The tool was used to assess students' causal structure. The participants' causal structure reflected their system thinking skills, which was modeled/mapped using pencil and paper (Hopper & Stave, 2008). Hung (2008) used a similar technique to assess system thinking skills considering dimensions like identification of variables, linearity, interconnectivity, cause-effect relationship, and feedback loop processes. These system thinking dimensions were used in the current study.

As described in the method session, participants completed system modeling training and were given problems solving activities related to the power screw topic (see Appendix C). On completion of the problem-solving task, students were asked to draw/model their understanding of the power screw system when raising a given load. Participants used a causal loop diagram to depict their understanding of the behavior of the power screw system including all relevant relationships. Students' models were evaluated for quality and accuracy (i.e., examining the number of identified variables, linearity, interconnectivity, cause-effect relationship, and feedback loop processes). Table 4 below shows the result of participants' casual loop diagram analyses including the five dimensions of system thinking evaluated.

The tallies in the table indicate the number of correctly identified dimensions in participants' causal loop diagrams (see sample model diagrams in Appendix G). Overall, the casual diagram analyses suggested that all participants showed system thinking skills. Most participants were able to identify important variables within the power screw problem including screw pitch, lead angle, thread depth, mean pitch diameter, helix angle, and acme screw diameter. Interconnected parts within the problem were also accurately identified including the connection between the load and the required torque as well as the relationships between screw diameter and torque. Additionally, participants in this study correctly recognized cause-effect relationships in the problem such as the effect of increasing helix angle and coefficient of friction on torque in the system. However, some of the students were unable to identify the feedback processes within the system, and others recognized only linear relationship in places where multiple directional relationships existed.

Table 4. Participants' Casual Loop Diagram Analyses with the Number of Identified ST Dimensions

Participants	Important Variables Identified (ID) *Total = 7*	Interconnect (IC) *Total = 7*	Cause-Effect Relationship (CE) *Total = 7*	Linearity (L) *Total = 5*	Feedback Processes (FP) *Total = 5*
1. Alex	100%	57%	57%	100%	100%
2. Bob	100%	14%	14%	80%	80%
3. Echo	86%	57%	43%	80%	80%
4. Jack	43%	43%	43%	40%	40%
5. Max	86%	43%	57%	40%	0%
6. Sam	100%	29%	29%	80%	80%
7. Sarah	100%	57%	57%	80%	80%
8. Tyler	86%	100%	100%	20%	20%

Additional Findings

Mental Models

Participants in this study used phrases that can be interpreted as mental models during the interview. These phrases included thought processes, visual representation of what is happening, and how things are working. For instance, in describing how the SM approach influenced his mental model, Sam stipulated: "…it gives you that base knowledge of what is going on in your problem and how things are working with each other." He explained further: "... it makes it so much easier to look at something and just understand what's going on there." Bob also mentioned that the SM approach "… gives us a nice visual representation of what is happening." Like Bob, Max also believed that SM influenced his mental model. He stated it: "…organize[s] your thought process…"

SM Approach Implementation and Challenges

Some participants interviewed identified initial difficulty with the SM approach. They admitted being confused and expressed difficulty during the SM activity. For instance, Sam indicated that he found the approach initially confusing. He stated: "I found it at first…a little confused of what exactly to look for, but once I looked at the problem…it's very easy...."

Other participants expressed concern with the difficulty of changing or deconstructing their established mental structure of problem-solving (analytic approach). For example, Alex stated: "it was almost more work to figure out how to do it this way than just to solve it the way I already knew, right." Echo provided a more detailed explanation, stating:

> … Um, so basically, if I am taught a method of solving a problem, say I am solving beam deflection. Once I learned how… to do it, but if I'm taught another way to do it within a few days after initially learning that method, then I get more confused because there's

more than one way to solve it. Which is fine … you got to kind of rearrange how to solve a problem rather than understanding a simple method. So, I tend to like block off that second method of solving it because it gets you the same ideas. And it's just more confusing…."

Participants interviewed did offer some recommendations to improve the SM approach implementation. Some suggested that the SM approach may be better introduced at a lower-level engineering course. For instance, Alex said: "I think if I had that way of problem-solving introduced to me early on, then it would become a really useful tool for me to use that would be much more instinctual...." In support of Alex's perspective, Echo stated: "I guess it would be more efficient for those lower-level classes to understand how the variables affect each output and then as you develop, you grow into those upper-level classes...."

However, not all participants agreed that SM was better implemented in lower-level engineering classes. For example, Tyler stated: "I think it's definitely more applicable in higher-level classes." He justified his opinion by saying: "…lower-level classes… [are] pretty linear in terms of the problem to solution …." So, Tyler believed that the SM approach was more applicable for more complex engineering phenomenon.

Summary

In this chapter, the qualitative data from participants' interviews about their experiences using the system modeling instructional approach was presented. The analysis of interview data generated multiple significant statements that were transformed into codes and categories, which in turn were organized into themes. It also revealed findings from students' artifacts analyses–students' model diagrams and their perceived problem-solving skills PSI survey. These analyses provided more insight about the effect of SM instructional strategy on students' learning. The final Chapter V presents additional interpretations, discussions, and implications, as well as the study limitations.

CHAPTER V

DISCUSSION

This qualitative study explores the efficacy of a system modeling (SM) instructional strategy in a mechanical engineering course. The main research questions investigated include:

1. *What are students' perceived efficacy of the use of SM instructional approach?*

2. How do students describe their experience with SM instructional approach in relation to their factual, conceptual, and application knowledge?

3. What perceptions do students have regarding the use of SM instructional approach in relation to problem-solving and system thinking skills?

In this chapter, I discuss the findings from Chapter IV, including the seven themes that emerged from the interview data and students' artifacts, which includes a model diagrams analysis and a perceived problem-solving skills survey. The discussions relate the findings to the literature review and deliberate its interpretations, implications, and limitations, as well as conclusions.

Discussion and Implications of Study Findings

Research Question One: *What are students' perceived efficacy of the use of the SM instructional approach?*

Qualitative themes that emerged from the thematic analysis indicated students' perceived usefulness of the system modeling (SM) instructional strategy. Specifically, students' descriptions of their experiences using the SM approach during interviews fit into seven major themes, including: problem diagnosis, interconnection and interdependency, linearity, external representation of causal relationship, wholeness and decision making, organize problem-solving approach, and systematic and forward-thinking process.

Theme 1: Problem Diagnosis. Many of the participants believed the SM approach promoted their ability to diagnose the engineering problem including identify, analyze, and query problems. Specifically, most of the students acknowledged that the SM approach helped in problem identification, an important step in problem-solving. For instance, Sam stated that, "And it gives you a better idea of what exactly is going on here in this specific problem."

Prior studies have suggested that system modeling instructional strategies could help in the problem-solving process by promoting problem identification (Hung, 2008; 2009). Indeed, identifying and defining the problem is the first step in solving any problem (Jonassen, 2004; Newell & Simon, 1972; Reimann & Chi, 1989). Researchers like Rittle- Johnson (2006) and Hung (2009) suggested that the problem-solving process requires identifying and defining the problem in order to construct the problem space, which is the gap that exists between the given and the goal state of the problem (Newell & Simon, 1972).

From an instructional point of view, SM could help foster problem identification and definition during problem-solving. For instance, the issues with students' inability to diagnose engineering problems (Flemming & Johnston, 2020) might be alleviated by implementing the SM approach. This can be explained in part because the SM approach provides scaffolding that facilitates students' cognitive process during problem-solving activities and reduces students' cognitive load, which in turn promotes their problem-solving process.

Theme 2: Interconnection and Interdependency. Many study participants believed that the SM strategy promoted their ability to visualize interconnections and interdependencies within the given problem, using phrases like observe effects of change, see intertwined variables, and linking concepts. For instance, Echo stated, "… if you were to change a certain part within that variable… how would that impact the output variable…"

Previous studies have indicated the effect of system modeling on students' abilities to visualize interconnections and interdependencies within a problem. For instance, Hmelo-Silver et al. (2017) reported that conceptual representation intervention (an example of a modeling tool) helped students to examine the different elements of the system and how the individual parts are interconnected. Similarly, Hung (2008) indicated that the system modeling instructional strategy does allow students to visualize interconnections and interdependencies.

This reported effect could be because the SM approach enabled the visualization and representation of abstract concepts and their interrelationships (Hmelo-Silver et al., 2017). Indeed, visualizing interconnections and interrelationship is essential in understanding a given problem. In other words, it is critical to first understand the network of interrelationships within a system in order to comprehend the emergent properties of that system (Hung, 2009).

Although the interviewees identified interconnections in the given problem, they could not recognize the SM approach's emergent properties. The emergent property is the product of the interacting parts within a system (Ackoff, 2004) and an integral characteristic of the SM approach. The lack of this realization might be because participants do not have sufficient cognitive and system thinking abilities to visualize the resulting effects of the interactions within the problem.

Theme 3: Wholeness and Decision Making. Participants in this study held that the SM instructional approach helped in seeing the bigger picture and enhanced their decision-making abilities. According to the participants, examining "the wholeness of the problem" fostered their decision-making processes. For instance, Sarah mentioned that, “I guess it just helps to make decisions. You can… more easily see which are the variables that are easiest to control or to change, to get the desired outcome.”

This theme was supported by Sedlacko et al. (2014), which revealed that system thinking could help system thinkers make inferences on the possible consequences during problem-solving. Furthermore, Hmelo□Silver et al. (2015) suggested that representational tools (like system modeling) could help students in the understanding of a system/problem by enabling them to observe the whole system instead of isolated parts. Observing the whole instead of individual parts is crucial because “the whole is more than the sum of its parts” (von Bertalanffy, 1950, p.142). In other words, once a system is broken down into its parts, the fundamental properties of the whole will no longer exist (Capra, 1996). Hence, understanding a problem requires considering the whole system in which the problem exists. Evidently, a better understanding of a problem will foster the problem-solving decisions making process.

Instructions that intend to guide students to see a problem as a whole and promote the decision-making process might benefit from adopting the SM approach. This is because, unlike traditional instructions, the SM approach guides problem solvers to not only visualize the isolated parts of the problem, but also to consider the problem as a whole. Indeed, when problem solvers are able to see the whole problem, they are able to focus on understanding the underlying causal structure of the problem rather than only its individual parts.

Theme 4: Linearity in Relationships. Participants interviewed described how the system modeling (SM) instructional strategy helped in visualizing linear and non-linear relationships, therefore promoting their understanding of the problem. For example, Alex believed that the approach was “… a very linear way of problem solving…” On the contrary, Tyler argued that the SM approach is a non-linear problem-solving approach and stated that, “And it lets you, I guess, spiderweb [non-linear] your way … to figure out what has changed and why, or what should change and why.”

A plausible explanation could be that the SM approach focused students’ attention on recognizing the relationships that exist within the problem. This could be because the approach guides students to see and understand that one variable has multiple non-linear effects on other variables since all the parts of the problem are interconnected.

Previous research has established that system-oriented instructions could foster students’ ability to identify non-linear relationships (Hung, 2009). In support, system thinking researchers have associated the ability to identify multiple dimensional relationships with the understanding of the system. For instance, Plate (2010) claimed that system-based instructions (like system modeling approach) could help students better identify non-linear relationships in a system, thereby demonstrating a deeper understanding of the causal relationships. Causal relationships within a system depict the underlying relationship pattern in a system (Capra, 1996).

While participants identified simple linear relationships, they failed to recognize the looping effect of the SM approach. This was evident in interviewees’ narrations as well as their causal model diagram. The looping relationship is an integral characteristic of the SM approach and includes both the reinforcing and balancing loop. The students’ inability to recognize the looping effect could be related to their limited mental framework. Unlike novices, expert system thinkers have developed a complex mental framework that supports their ability to identify feedback loops that exist within a problem. Expert system thinkers recognize feedback loops that reflect sequences of action and information flow that exist within a problem.

Theme 5: Organize Problem-Solving Approach. Participants portrayed the use of the SM strategy as an organized problem-solving approach. In their descriptions, they used phrases such as organizes information, categorizes things, logical steps, and identify the starting point and important variables. Interestingly, participants also believed that the systemic nature of the SM approach prevented them from jumping to the answer, that is skipping steps and rushing to the solution. For instance, Max mentioned, "You can't just go one step to get the answer, you got to think about it, organize your thought process and go through step by step, solving whatever the problem is asking you to solve."

Prior research has established that students sometimes skip steps during the problem-solving process (Czabanowska et al., 2012; Moust et al., 2005), thereby missing important details and jumping to the solution. SM approach may offer an instructional scaffold to support students' problem thinking process in order to minimize the skipping of steps. This is because the system thinking process (SM approach) is a systematic step-by-step process (Goodman & Karash, 1995).

Perhaps one of the most striking findings was that participants described the SM approach as "giving them a starting point for problems." Students revealed that knowing where to start solving a problem could be challenging; therefore, having a strategy such as the SM approach may provide a good starting point during problem-solving. This provision could be because the SM approach allows students to focus on only the important variables in the problem. This was evident in Sarah's narration when she said: "It helps me be more aware of which variables are the ones that I need to pay attention to."

Instructors who intend to help students understand how to initiate the problem-solving process may consider implementing the SM approach. This approach guides students into developing a logical mental map that can enable them to envision and pinpoint solution paths within the problem. In this way, students can effectively identify the starting point, solution paths, and the end result of a given problem. This strategy may be particularly helpful with complex engineering problems in which students have difficulty identifying a starting point. In support of this, Echo stated during the interview:

> And so, just having the system modeling in those lower-level classes might limit the use of chegging [an online homework resource discouraged by professor] because they don't know how to start a problem… system modeling will definitely help you understand … how to start a problem….

Theme 6: External Representation of Causal Relationships. Participants believed the system modeling (SM) instructional strategy promoted their ability to represent their understanding of causal relationships externally. For example, Bob stated that the approach help you see, "…this is the cause of this, if I decrease this then my force over here must increase, that was very helpful and nice to have."

A plausible explanation for this result could be that the visual representative nature of the SM approach, as discussed in Chapter II. The SM approach is a representation tool that depicts the variables in the problem, the underlying mechanisms, the relationships, and their interactions. This external representation helps in visualizing abstract or non-perceivable variables and their causal relationship, thereby promoting the development of an effective mental model of the problem.

From an instructional perspective, the SM approach could help scaffold students' problem-solving process. For instance, novice problem solvers tend to overlook important variables and lack understanding of the causal relationship in the problem, thereby having difficulty in solving the given problem. Scaffolding students to construct comprehensive and effective mental models of the problem using the SM strategy could minimize the tendency of students missing important problem variables, thereby promoting their construction of the problem space. Moreover, the representation of the causal relationship of a system enables students better grasp the underlying system structure, thereby promoting understanding of the problem (Hmelo-Silver et al., 2017).

Theme 7: Systematic and Forward-Thinking Process. Participants recalled that the SM approach provided a systematic and forward-thinking approach to problem-solving. They detailed how the approach helped in patterning their thinking, seeing patterns, forward-thinking, thinking systematically, and planning problem-solving. For instance, Alex stated, “I guess it's, um, like patterning your thinking. It's teaching you to look at things in a certain way...”

One possible explanation could be that the SM approach guides students to see and think systematically. The method scaffolds the thinking process during problem-solving by providing a step-by-step guide. This step-by-step technique helps in laying out the important variables and relationships, thereby promoting the understanding of the underlying causal structure of the problem.

Studies have found that system-oriented instructions like system modeling can promote students’ system thinking (Hopper & Stave, 2008; Plate, 2010). For instance, Sedlacko et al. (2014) reported that the SM approach provided a means for guiding complex systems thinking as well as facilitating the systematic understanding of the problem. This could be particularly helpful in understanding the underlying structure of the problem during the problem-solving process.

From an instructional point of view, the SM approach could be implemented to foster the development of system thinking skills among engineering students. This might be explained in part because the SM approach could provide visual clues to lead students into identifying system boundaries, its different levels of organization, its feedback process, and emergence properties within the system. In this way, students can develop higher-order cognitive skills that will support the complex mental structure they require to tackle real-world and ill-structured engineering problems effectively.

Research Question 2: *How do students describe their experiences with the SM instructional approach in relation to their factual, conceptual, and application knowledge?*

Factual Knowledge. This is the basic knowledge of content elements in the discipline, including facts, definitions, and terminologies (Anderson & Bloom, 2001; Krathwohl, 2002). Participants in this study concurred that factual knowledge was important for mechanical engineers. Surprisingly, they gave varying descriptions of the influence of the SM approach on their factual knowledge. While some acknowledged the effect of SM, others did not. For instance, Echo stated, “The system modeling, definitely helps kind of solidify the ground that you're standing on … [helps] understanding how each variable comes across, or even each unit comes across was super helpful …” Contrary to Echo’s believe, Alex claimed that, “Not really. That strategy doesn't seem like it's focused on increasing factual knowledge but more on the way you use factual knowledge in problem solving.”

These differences might be explained in part by the fact that participants in the study may have understood the definition of factual knowledge differently. While the researcher provided the definition of terminologies used in this study during the interview, participants may not have been able to relate it to their experience during the problem activities.

Some of the participants believed that the SM approach influences their factual knowledge. One plausible explanation may be that the SM approach could have helped students to meaningfully connect new abstract information (on the topic) with their prior knowledge. Prior research suggested that making meaningful connections between new information and prior knowledge can promote factual knowledge and its application (Anderson & Schönborn, 2008; Buch & Bucciarelli, 2015).

Another possible explanation could be because of the external visual representation property of the SM approach. This may have helped reduce the level of abstraction of the problem, thereby allowing the students to visualize the abstract facts and concepts. By so doing, students can meaningfully organize their mental models such that they are easy for them to relate to and make necessary connections and establish the relevance of the content.

One implication for this finding is that engineering instructors seeking to introduce new concepts or phenomena might consider adopting the SM approach. The SM approach is a cognitive activity that involves identifying abstract facts and recognizing non-perceivable variables within a given system. This cognitive activity enables students to see abstract variables, which can help in triggering their prior knowledge, thereby promoting their understanding of the engineering facts and phenomena.

Conceptual Knowledge. This is the "knowledge of concepts" (Siegler, & Alibali, 2001), as well as the "understanding of the essential parts and cause-effect relationships that exist within a system" (Guenther, 1998, p. 289). All participants believed that conceptual knowledge was important for mechanical engineers. Most participants interviewed described the positive influence of the SM approach on their conceptual knowledge. For example, Sam stated that it allow you, "…to break down a problem, and pretty much look at different parts… Finding those different parts can allow you to tap into your conceptual knowledge, and then apply your conceptual knowledge" This result was consistent with prior studies that examined similar system-based instructions (Grotzer & Basca, 2003; Hung, 2008; Prince, Vigeant, & Nottis, 2009).

This result may be explained by the fact that students were able to identify and connect multiple concepts during the SM activities. Making these connections may have enabled them to understand the concepts associated with the problem and their underlying relationships, thereby promoting problem space construction (Rittle- Johnson, 2006). Moreover, the ability to connect multiple concepts is crucial in solving complex engineering problems. This is because students mostly encounter difficulty when using the functional-reduction reasoning approach (i.e., linear approach) in solving complex engineering problems (Rozier & Viennot 1991; Wattanakasiwich et al., 2013).

Surprisingly, not all the participants believed that the SM approach influenced their conceptual knowledge. This might be explained in part by the participants prior knowledge and experience. Interestingly, most of the participants who believed that the SM method did not contribute to their conceptual knowledge had several years of experience working as engineers. Therefore, they may already have had some background knowledge and developed complex engineering thinking patterns. In fact, unlike novices, experienced engineers use a non-linear multifaceted approach, such as SM thinking techniques, since they have been tackling real-world engineering problems. As a result, they may not have gained additional conceptual knowledge during the problem-solving activity.

Overall, the result of this research finding has instructional implications. The SM approach could be adopted to foster the development of conceptual knowledge. The approach could not only bolster the understanding of concepts but also the relationships between them. Moreover, SM approach could be a viable cognitive tool in addressing the issue of misconceptions in engineering. Misconceptions are learning issues, concept misunderstandings, or non-scientific beliefs that may interfere with the learning process (Sinatra, Brem, & Evans, 2008). The SM approach might facilitate conceptual change and remedy misconceptions by guiding students to visualize the phenomenon, thereby observing its property, interpreting and generalizing its conclusions, and retaining accurate conceptions.

Application Knowledge. This is the knowledge required to apply or use a procedure or content knowledge in a specific context (Krathwohl, 2002). All participants believed that application knowledge was important for mechanical engineers. Expectedly, they all indicated that the SM approach influenced their application knowledge. For instance, Sam stated that, "… the ability to break down problems to better understand them, is a skill of every good engineer… the system modeling approach can help you break down your problems to make them easier to understand." This result was in line with previous studies that found that modeling instructional strategies have a positive influence on students' application knowledge (Hubbs, Parent, & Stoltzfus, 2017; Kamble & Tembe, 2013).

A possible explanation for this might be that the SM approach forced students to identify, gather, and organize important variables as well as all possible interactions within the problem. In this way, students may have developed complete and effective mental structures that enabled them to contextualize their understanding of the problem, thereby promoting meaningful learning. In fact, Jonassen (1999) argued that instructions guide students to meaningfully connect abstract content knowledge with situations (where) and how the knowledge can be applied in real life promoted application knowledge. In other words, meaningful, logical, and contextualized instructions help trigger students' prior knowledge, thereby activating their pre-existing schema to help them interpret the content (Schunk, 2012) and foster its application.

Moreover, application knowledge requires a highly complex cognitive process that involves making connections between concepts and real practical applications. This is an important step in knowledge integration and application. Application knowledge could be facilitated by developing a multifaceted conceptual understanding of the content domain and constructing a mental model of the problem-solving process. Hence, active learning instructions like SM could foster active engagement with the content (Hung, 2009) and facilitate the construction of a complete mental model of the problem, thereby promoting students' application knowledge.

Research Question Three: *What perceptions do students have regarding the use of the SM instructional approach in relation to problem-solving and system thinking skills?*

Problem-Solving Skills. This is the ability to define the problem by identifying the unknowns and the gaps between the present and the desired state of the problem (Hung et al., 2008). All participants in this study acknowledged the importance of problem-solving skills in engineering. Both the interview data and the perceived problem-solving survey indicated that the SM approach influenced participants' problem-solving skills. For instance, Echo stated that, "I guess it could affect it [affected] my problem-solving skills by understanding how the variables affect the output…" These findings supported the work of other studies linking system-based instructional strategies with enhancing problem-solving skills (DeFranco, Neill, & Clariana, 2011; Mousoulides, Christou, & Sriraman, 2008).

Several factors could explain this finding. Firstly, SM might have assisted the participants to identify the knowns and unknowns as well as the gaps in the problem. This is a vital first step in the problem-solving process (Jonassen, 2004; Newell & Simon, 1972; Reimann & Chi, 1989). Indeed, the problem identification and definition promote understanding of the underlying mechanism, which in turn foster the accurate construction of the problem space (Hung, 2009).

Another factor could be that the SM strategy aided students' thinking processes, thereby allowing them to think through the problem-solving process and consider multiple solutions. This fact was evident in the students perceived problem-solving survey—specifically the approach-avoidance style. On the approach-avoidance style construct, all the participants indicated that the SM approach allowed them to think systematically, while 87.5% agreed that the approach helped them think of multiple ways to solving problems. Hence, SM instructional strategies may have the potential to help students promote problem-solving skills, especially the step of defining the problem and problem space.

From an instructional perspective, SM could promote problem-solving skills among students, thereby offering engineering instructors an alternative to traditional instructions. The SM approach tends to guide problem solvers to effectively identify the problem, the current and desired state of the problem, as well as the gaps within a given problem. The focus on identifying the important elements in the problem and understanding the missing elements of the problem is an integral characteristic of the SM approach.

System Thinking Skills. System thinking can be characterized into several dimensions, including identifying important variables, linearity, interconnectivity, cause-effect relationship, and feedback loop processes (Hung, 2008). Participants' causal loop models were evaluated, and results suggested moderate system thinking skills. While most were able to identify critical variables and interconnections, and correctly recognized cause-effect relationships, others were unable to identify the feedback loops and non-linear relationships within the system.

A possible explanation for these results may be the lack of adequate system modeling training. The short length of instructions on the SM training may have contributed to students not fully grasping the SM concept. The issues with the SM instructions came up during the interview. John suggested that the SM training "… would have been better with more than just the one video… maybe stretch this out over like a month...." Similarly, Echo also stated: "And not only like one way of how to approach the system modeling strategy but like, providing a multitude of ways on how to approach the system modeling…."

The students had a limited amount of experience with the SM, and as a result, the learning curve could have a major influence on their understanding of the approach. This appeared to be evident in the lower "Personal control" percentage reported in the PSI survey. The lack of adequate practice with the SM approach could have affected the participants' ability to identify the feedback loops and non-linear relationships within the system, which require a higher cognitive understanding of the SM approach. Also, the short instructional time could have affected some students' perception of the SM's effectiveness in promoting their factual and conceptual understanding. The traditional instructions that the students are familiar with could also have affected their understanding of the SM approach.

Another plausible reason why participants could not identify feedback loops and multiple dimensional relationships could be their analytic learning style (mechanistic). Hung (2003) found that the mechanistic reasoning process might hinder students' ability to see multiple dimensional relationships. Moreover, system thinkers explained that mechanists believe that the world works like a clock (that is orderly, hierarchical, & linear), and as a result, they can only understand how things works by studying each individual part (Ackoff, 2000). Hence, this perspective of reality does not highlight the relationship between the whole and parts, and causal relationship.

These results have implications for engineering education. The SM approach has the potential to facilitate the development of system thinking skills among students. This is because the approach allows students to identify several dimensions of system thinking, including essential variables, linearity, interconnectivity, and cause-effect relationship. Unlike the traditional teaching method that emphasizes understanding individual parts of a problem in isolation, the SM approach fosters a systemic approach and knowledge integration rather than isolation.

Additional Discussion and Implications

Mental Models and Learning Outcomes

Mental models represent an individual's understanding of how things work (Monat & Gannon, 2015; Senger, 2006). Participants in this study indicated that the SM approach influenced their mental models. There are several plausible explanations for this result. The external representation property of the SM approach may have afforded students the opportunity to internally and externally validate their mental representations, thereby consolidating their mental model of the problem. This mental validation process can promote the construction of an accurate and complete mental model of the phenomenon under study (Hung, 2009).

This result could also be partly explained by the fact that the SM approach is a cognitive activity in which students are engaged in identifying key variables and their causal relationship within a given problem. As a result of this activity, students become aware of non-perceivable variables in the problem, which in turn foster the development of their mental model. Moreover, the fact that the SM approach has the potential to guide and direct students into reorganizing their mental structure could also explain this result.

This study shows promising results in teaching and learning complex engineering problems. System-oriented instructions, like SM instructional approach, could offer a viable alternative to the traditional instructor-led instructions in promoting the construction of students' mental models. The SM approach could provide an appropriate scaffold for identifying the unknowns and the gaps that exist between the current and desired state of a given problem, and as a result, help students in the construction of their mental model. By engaging in SM cognitive activities, students construct visual representations of problems, helping them alleviate the difficulties attributed to the abstract nature of engineering phenomena.

SM Approach Implementation and Challenges

Some participants reported being initially confused about the SM instructional strategy. This initial confusion may be related to the traditional analytic instructions that the students were accustomed to, and as such, they could not grasp the SM approach. Another interviewee stressed that it was difficult to change or deconstruct her established mental structure of problem-solving (analytic approach) in order to complete the SM activities. This resistance to unfamiliar instructional strategies (SM approach) has been widely reported in the literature. Prior studies have reported that traditional instructions which emphasize simple and linear causal structures impeded students' learning about system thinking and understanding complex systems (Plate, 2009; Perkins & Grotzer, 2005). Thus, students' prior instructional preferences might explain their initial confusion and difficulty experienced during the SM activities.

Participants interviewed did offer varying recommendations to improve the SM approach implementation. While some suggested that the SM approach might be better introduced at a lower-level engineering course, others believe that it is suited for higher-level classes. Participants who advocated that the SM approach be implemented at the lower-level classes argued that introducing the approach early on in the engineering program will help students become more acquainted with the approach. On the other hand, proponents of implementing the SM approach in higher-level classes claimed that the SM approach is more suited of addressing complex problems which are not available in lower-level classes.

Both arguments appear to be reasonable. The findings from this study suggest that the SM approach might be suited for both lower and higher-level engineering classes. Generally, the concepts taught in lower-level classes are mostly basic factual knowledge (lower-level skills) which might be supported by SM approach as indicated by the findings of this study. Similarly, higher-level classes that deal with more complex engineering problems requiring higher-order skills like problem-solving and system thinking skills can also be supported by the SM approach. Therefore, system-based instructions could be adopted at lower-level all the way to higher-level classes to facilitate the development of students' systemic mental models required to deal with real-world engineering problems.

Limitations

Duration of Instructions

One limitation of this study was the duration of the SM instructional strategy training. During the interview, some participants recalled having difficulties understanding the SM approach. Participants might not have been familiar with the SM approach. Therefore, extending the duration of the SM approach for an entire semester and including several examples for students to experience might have helped them better understand the approach. This could have reduced the initial learning difficulty experienced by the participants.

Interview Sessions

Another limitation of this study was the number of interviews conducted. While, this study utilized a single interview session per participants, follow up email interviews were conducted during the member checking sessions. Also, to ensure richness and accuracy of data collected, data triangulation was employed as described in chapter 3. The researcher collected data from multiple sources, and supplemented interview data with students' artifacts (PSI survey & students' causal model diagram). This multiple data sources enabled the researcher could generate rich data to deeply understand students' experiences about the phenomenon under study as well as evaluate students' claims.

No Control and Experimental Group

The current study does not have a control and an experimental group for using the SM instructional strategy. Instead, the study explored in-depth student perceptions and experiences using SM and its influence on their learning outcomes. Thus, the results from the PSI survey should be interpreted with caution as they only reflected the perceptions of students who used the SM instructional strategy and was not compared with a control group.

Interview Medium

In this study, interviews were conducted via Zoom because of the global Covid-19 pandemic restrictions, that is the researcher and students were not able to meet in a face-to-face environment. However, several precautions were implemented to ensure the validity and reliability of the data collected. For instance, interview manuscripts were sent to the interviewees to verify that the script reflected their perceptions and experiences. Also, triangulation of data sources was conducted to ensure the validity of the results. Data triangulation of sources by integrating multiple data sources including interview data, member checking as well as integrating students' artifacts. This was discussed more extensively in chapter 3.

Researcher's Bias

This study is a qualitative inquiry that employed individual interviews to collect data about students' perceptions and experiences using SM instructional model. The researcher implemented a rigorous protocol to minimize the effect of bias in the results. These rigorous measures included developing a robust research protocol that ensured that interview questions were the same and neutral throughout the interview process. Also, the researcher supported findings with direct quotations from the interviewees to minimize bias.

Future Research

This qualitative study provided insights into students' perceptions and experiences using the SM instructional strategy in a mechanical engineering course. There is a need for mechanical engineering educators to adopt more active learning approaches in order to address the problems with traditional instructions identified in Chapter II. Thus, further studies (with larger sample sizes) that capture the perceptions and experiences of engineering students using system-oriented instructions would be immensely valuable to this area of research. Findings from such research could inform pedagogy in engineering education.

This study identified seven major themes that described students' perceptions and experiences with the use of the system modeling instructional approach. Future research could further explore the possibility of developing these themes and other similar qualitative studies into quantitative survey instruments that could be used to gather data regarding students' learning outcomes in mechanical engineering. Limited research exists in academic literature about creating effective assessment tools specifically for mechanical engineering students.

Additionally, future research could contribute to the development of a generalizable system model tool that would build on the findings of this study and other similar work. For instance, this study reported findings from simple problem-solving activities. However, Jonassen and Hung (2008) described problems as varying in complexities and structure, and as such real-world problems require a different breadth of knowledge and difficulty. Therefore, further research could examine the effect of SM instructional strategy on more complex and diverse problems.

Conclusion

This qualitative study aimed to understand students' perceptions and experiences using the system modeling instructional strategy in a mechanical engineering course. The findings indicated promising effects of the SM approach on students' learning outcomes. Seven major themes emerged from the in-depth interviews conducted to gain insights into students' experiences using the SM approach. These themes included: problem diagnosis, interconnection and interdependency, linearity, external representation of causal relationship, wholeness and decision making, organize problem-solving approach, and systematic and forward-thinking process.

Student artifacts and data presented in this study supported their positive experiences using the SM approach. The PSI survey responses indicated that most of the participants believed the SM approach affected their perceived problem-solving skills, especially their approach-avoidance style. Furthermore, the causal diagram analysis suggested that all participants showed moderate system thinking skills after the SM instructional strategy.

Overall, the study findings provide potential evidence for SM instructional strategy as an alternative instruction to the traditional methods as well as to inform instructors of the potential benefit of undergraduate educational instructions. Furthermore, this research serves as an example for instructors on how to implement the SM instructional strategy in a mechanical engineering course. The study partly demonstrates the efficacy of system-based instructions in supporting engineering students' learning processes, thereby preparing them for their future workplace challenges. Hence, engineering education could benefit from implementing a constructivist, learner-centered approach like the SM approach to help foster students' learning outcomes such as conceptual and application knowledge and problem-solving and system thinking skills.

APPENDICES

APPENDIX A

Invitation Email

Dear Students.

We would like to invite you to participate in a study on exploring engineering students' perception of the effect of system modeling (SM) instructional strategy on their conceptual knowledge and problem-solving skills. If you agree to participate, you will complete a consent form. We will ask you to complete a problem-solving task and take a PSI survey. You will be invited to participate in an individual interview about your perception of the SM instructional strategy. Your participation is voluntary and will not affect your grade in this class.

The results of this study will help us gain an in-depth understanding about how to improve the teaching of mechanical engineering concepts and promote problem-solving among college students using the SM instructional strategy.

If you have further questions about this study, you can contact the researcher, Ademola Amida at ademola.amida@und.edu.

Thank you.
Ademola Amida (Principal Investigator)
Doctoral Student

APPENDIX B

INFORMED CONSENT STATEMENT

THE UNIVERSITY OF NORTH DAKOTA
CONSENT TO PARTICIPATE IN RESEARCH

Project Title: SYSTEM MODELING: AN EXPLORATORY STUDY OF ENGINEERING STUDENTS' CONCEPTUAL KNOWLEDGE AND PROBLEM-SOLVING SKILLS

Principal Investigator:	Ademola Amida
Phone/Email Address:	*ademola.amida@UND.edu*
Department:	Teaching, Leadership & Professional Practice
Research Advisor:	Dr. Woei Hung
Research Advisor Phone/Email Address:	woei.hung@UND.edu 701.777.3486

What should I know about this research?
- Someone will explain this research to you.
- Taking part in this research is voluntary. Whether you take part is up to you.
- If you don't take part, it won't be held against you.
- You can take part now and later drop out, and it won't be held against you
- If you don't understand, ask questions.
- Ask all the questions you want before you decide.

How long will I be in this research?
We expect that your taking part in this research will last a week.

Why is this research being done?
THE PURPOSE OF THIS STUDY IS TO GAIN AN INDEPTH UNDERSTANDING OF STUDENTS' PERCEPTIONS OF THE EFFECT OF SYSTEM MODELING INSTRUCTIONAL STRATEGY ON THEIR CONCEPTUAL UNDERSTANDING AND PROBLEM-SOLVING SKILLS.

What happens to me if I agree to take part in this research?
If you decide to take part in this research study, you will:
- Sign a digital consent form via DocuSign before day of experiment
- Be provided a link to complete the pre-PSI survey (problem-solving inventory), filled before day of experiment. This will take about 10 mins and you are free to skip any questions that you would prefer not to answer.
- YOU will receive lecture ON A MECHANICAL ENGINEERING CONCEPT.
- YOU will use the system modeling strategies to solve the problem activities. The system modeling strategy will be explained by the PI to the participants. The system modeling

Approved: 4/12/2021
Expires: 8/9/2021
University of North Dakota IRB

Date: __________
Subject Initials:

APPENDIX C

System Modeling Activity

Student Name: ___________________

Instructions:
Before you begin this activity, please review the System Modeling (SM) Training Module video attached to this activity. In this exercise, you will use the techniques you have learned from the SM training to represent and solve the Power Screw problem. This activity has two parts. Read the instructions carefully and provide your response.

Part 1: Power Screw Problem Scenario
The power screws concept is applied in systems such as the screw-type jacks, which are designed to generate a huge mechanical advantage in raising a given load (W). Imagine yourself as an engineer, and you need to design a screw jack system that will lift a nonrotating load (W). The screw jack system uses a double-thread Acme screw with a thrust collar.

Applying your knowledge of the power screw concept, determine:

a. What assumptions do you need to consider?
b. What do you need to know to estimate the torque required to lift the given load?
c. What relationships exist between the screw torque and the different variables required to raise the given load?
d. How does an increase in torque affect the other variables and in what direction (increasing or decreasing)?

Part 2: Draw a Causal Loop Diagram
From the scenario above:

1. Identify the different variables/elements of the problem (e.g., identified variables)
2. Identify the interconnections between the variables and how one affects the other (what is changing and in what direction?)
3. Identify the feedback process/paths in the scenario problem (if at all)
4. Using circles and arrows (causal loop diagram), sketch the relationship between the different elements of the problem scenario on paper (include the torque and other variables you identified). Indicate whether your diagram is a reinforcing or balancing loop or both. Specify the direction of change using "+" for increasing and "-" for decreasing relationships. You will submit your diagram as part of the activity.

Note: Please draw your causal loop diagrams on paper and take a picture or scan your diagram. Please submit only a clear diagram and show your thinking process. Please feel free to contact me if you have questions about this activity ademola.amida@und.edu.

APPENDIX D

Problem-Solving Inventory Survey scale

Please complete this post-Problem Solving Inventory (PSI) Survey ONLY after completing the problem solving activity.

For your participation in this study, your will receive $50 your participation in all the activities in this study. Please enter your email at the end of this survey.

Please enter your name below (Name will ONLY be used to link study data). Your participation will be anonymous and confidential. Names will be delete from analysis.

What is your gender?

- ◯ Male
- ◯ Female
- ◯ Others (please specify)
- ◯ Choose not to specify

Indicate your current status as a student:

- ◯ Freshman year
- ◯ Sophomore
- ◯ Junior
- ◯ Senior

What is your ethnicity?

- ◯ Hispanic or Latino or Spanish Origin
- ◯ Not Hispanic or Latino or Spanish Origin

What is your age?

- ◯ Below 20 years
- ◯ Between 20 - 25 years
- ◯ Between 26 -30 years
- ◯ 31 years and above

Are you a mechanical engineering major?

- ◯ No
- ◯ Yes

Directions: Please read the items below and select the option that best describes how you conduct problem-solving tasks. Your response should reflect your thinking **during the problem-solving task relating to Power Screw Concept**.

Read each statement and indicate the extent to which you agree or disagree with that statement based on **the System Modeling (SM) activity**, using the scale provided.

	Strongly disagree	Disagree	Somewhat disagree	Somewhat agree	Agree	Strongly agree
The SM task helped me to make a problem-solving plan that will almost certainly work.	○	○	○	○	○	○
The SM task makes me feel confident that I can solve new problems using the same method.	○	○	○	○	○	○
The SM task helped me to think firstly about what exactly the problem is.	○	○	○	○	○	○
Using the SM approach enabled me to think systematically during the problem-solving process.	○	○	○	○	○	○
The SM task helped me to thinking about the multiple ways of solving a problem.	○	○	○	○	○	○

Read each statement and indicate the extent to which you agree or disagree with that statement based on **the System Modeling (SM) activity**, using the scale provided.

	Strongly disagree	Disagree	Somewhat disagree	Somewhat agree	Agree	Strongly agree
When presented with a problem, I avoid jumping directly into the solution.	○	○	○	○	○	○
When my first efforts to solve a problem fail, I become uneasy about my ability to solve the problem.	○	○	○	○	○	○
When I work on a problem, I feel that I am not getting to the real solution.	○	○	○	○	○	○
The SM task helped me to first evaluate the problem to identify important information about the it.	○	○	○	○	○	○

APPENDIX E

Interview Protocol

Introduction Script
Thank you for talking to me today. My name is Amida and I am conducting a research on the effect of system modeling on mechanical engineering students.

Specifically, the study will seek to understand students' perceptions and experiences with the use of system modeling in enhancing their learning outcomes–such as factual, application, and conceptual knowledge, as well as their perceptions of problem-solving and system thinking skills. Your participation is very important for our understanding of this topic.

During this interview, I will ask you questions about your experience with the use of system modeling instructional strategy. Please note that there are no right or wrong answer. Instead, I only intend to understand your perceptions about the SM instructional strategy. You do not have to answer any questions that you are not comfortable with. You can ask me to skip questions or clarify or repeat any question you do not understand.

We do encourage that you select a pseudonym for this session. For this interview, I will refer to you with your selected pseudo names (fake name).

As indicated in the consent form you signed via UND DocUsign, all your comments will be confidential, so please answer openly and honestly. With your permission, I will audio record this session so that I do not miss any of your comments and I elaborate on my notes. It is my responsibility to ensure that your name does not appear in my dissertation. I will share with you a copy of the transcript to look at.

This interview will last about 60 minutes or if no new information is emerging, the session will be concluded.

Some of the questions may appear repetitive. Please answer as best as you can.

APPENDIX F

Interview Questions

Background Questions

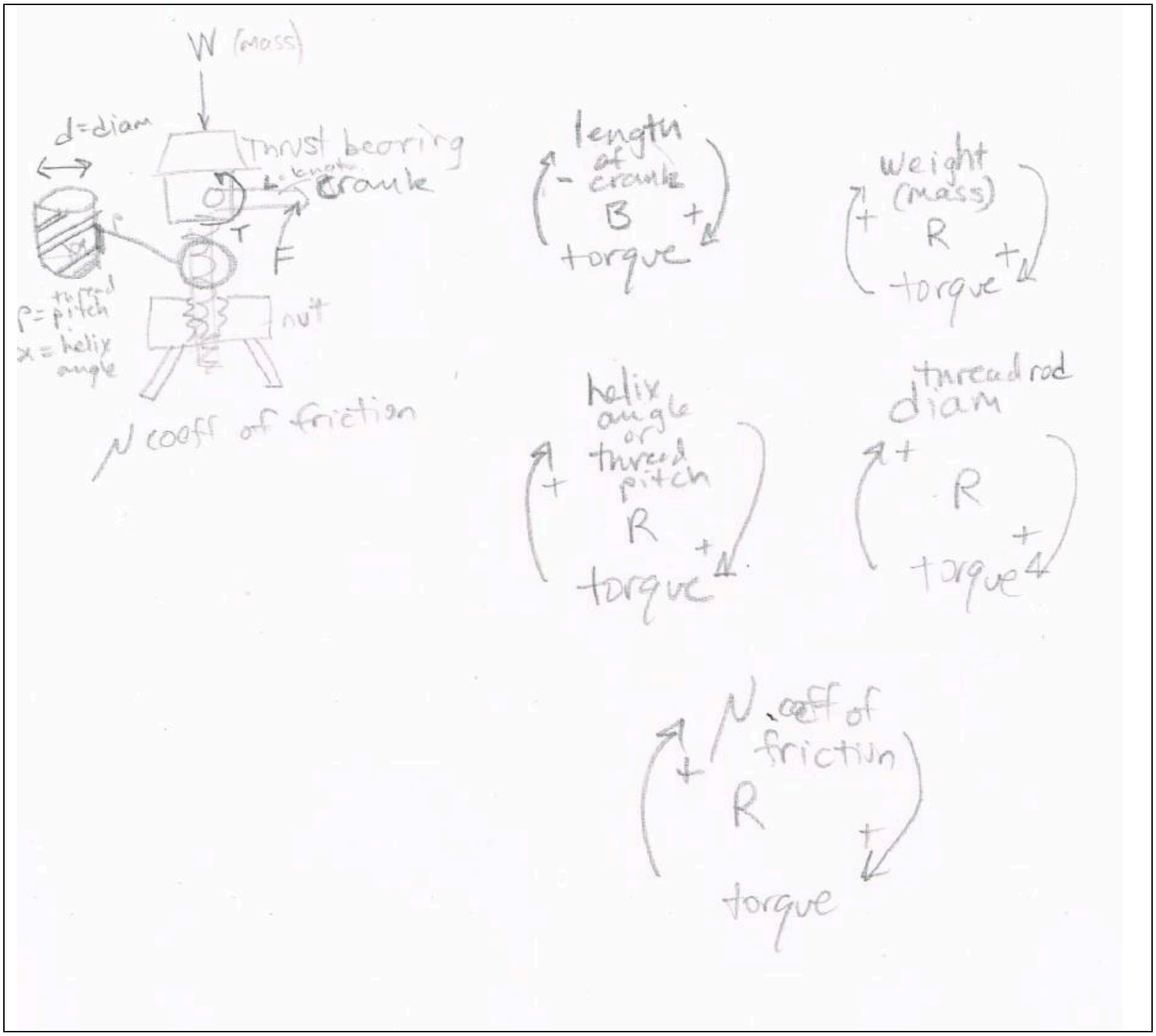
1. Could you please provide a background of your education and professional experience?
2. Could you describe why you chose to pursue a career in mechanical engineer?
3. What do you believe to be the essential skill sets and knowledge required to become a successful mechanical engineer?

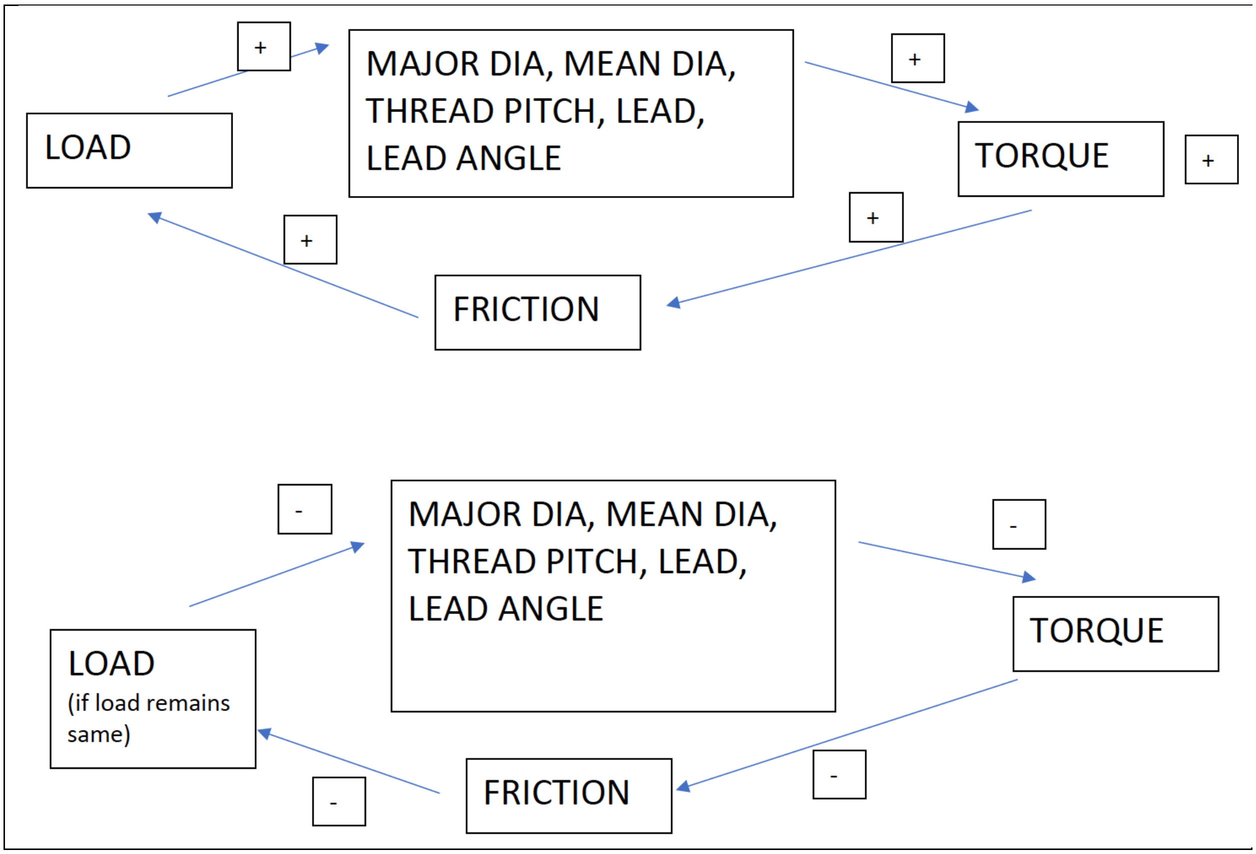
SM Questions

4. Explain how the system modeling instructional strategy influenced your learning experience (if at all)? What aspects of your learning experience were influenced?
5. Could you explain why problem-solving skills are important for mechanical engineers?
6. Could you describe how the system modeling instructional strategy has affected your problem-solving skills?
7. Could you describe how application knowledge is important for mechanical engineers?
8. Can you describe how system modeling instructional strategy has affected your ability to apply knowledge to address real world problems? Why?
9. Why is it important for mechanical engineers to gain conceptual knowledge of mechanical engineering? Do you think that the system modeling instructional strategy (SM) has impacted your conceptual knowledge of mechanical engineering? Why?
10. How important do you think factual knowledge is for mechanical engineers? Why?
11. Could you describe how the system modeling instructional strategy (SM) has affected your factual knowledge? Why?

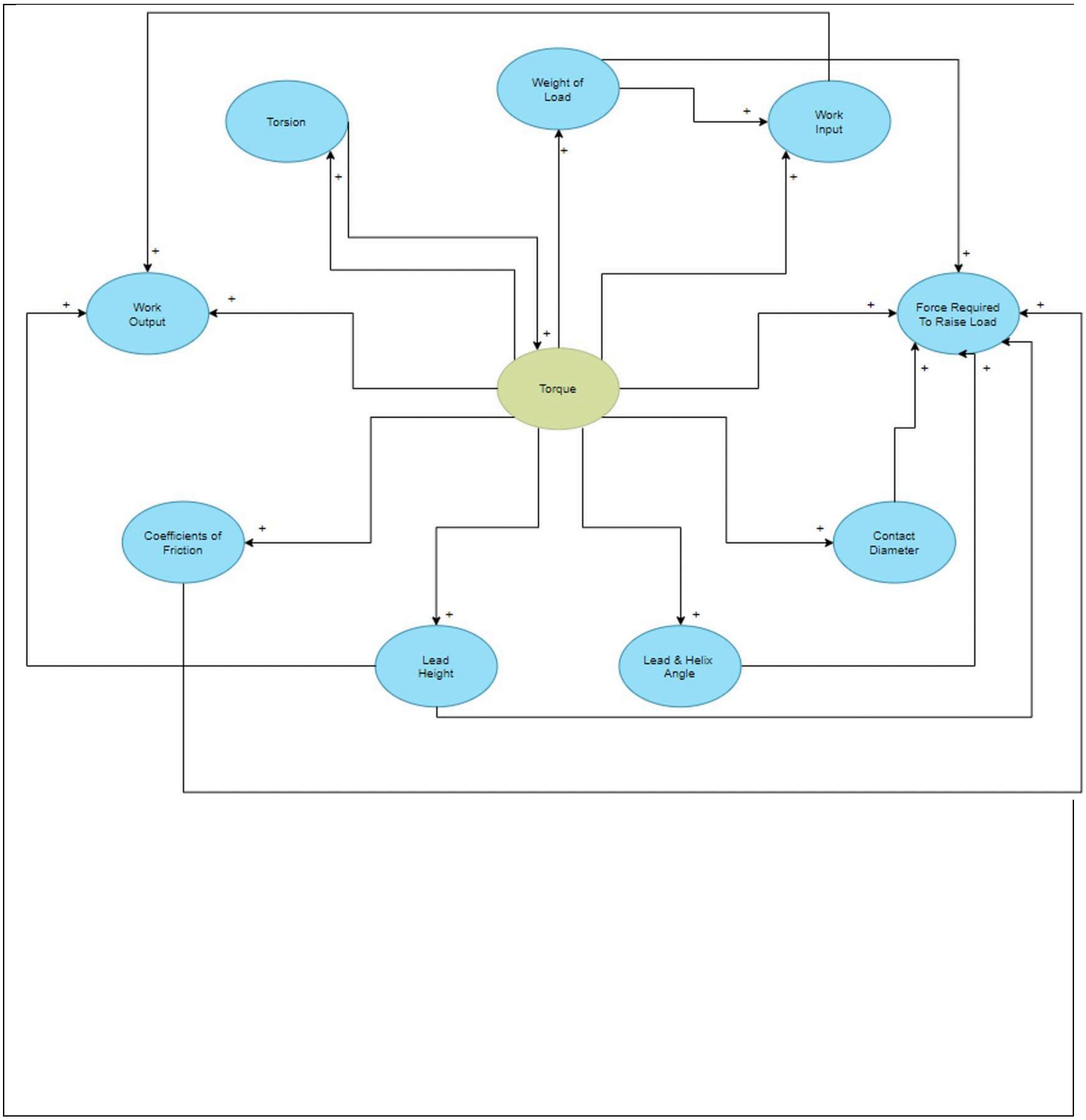
APPENDIX G

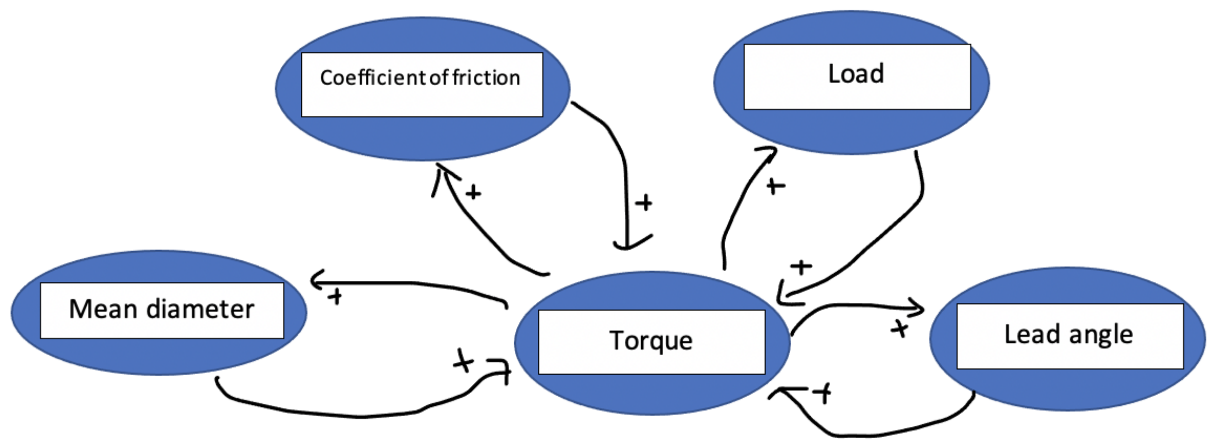
STUDENTS' MODEL DIAGRAMS



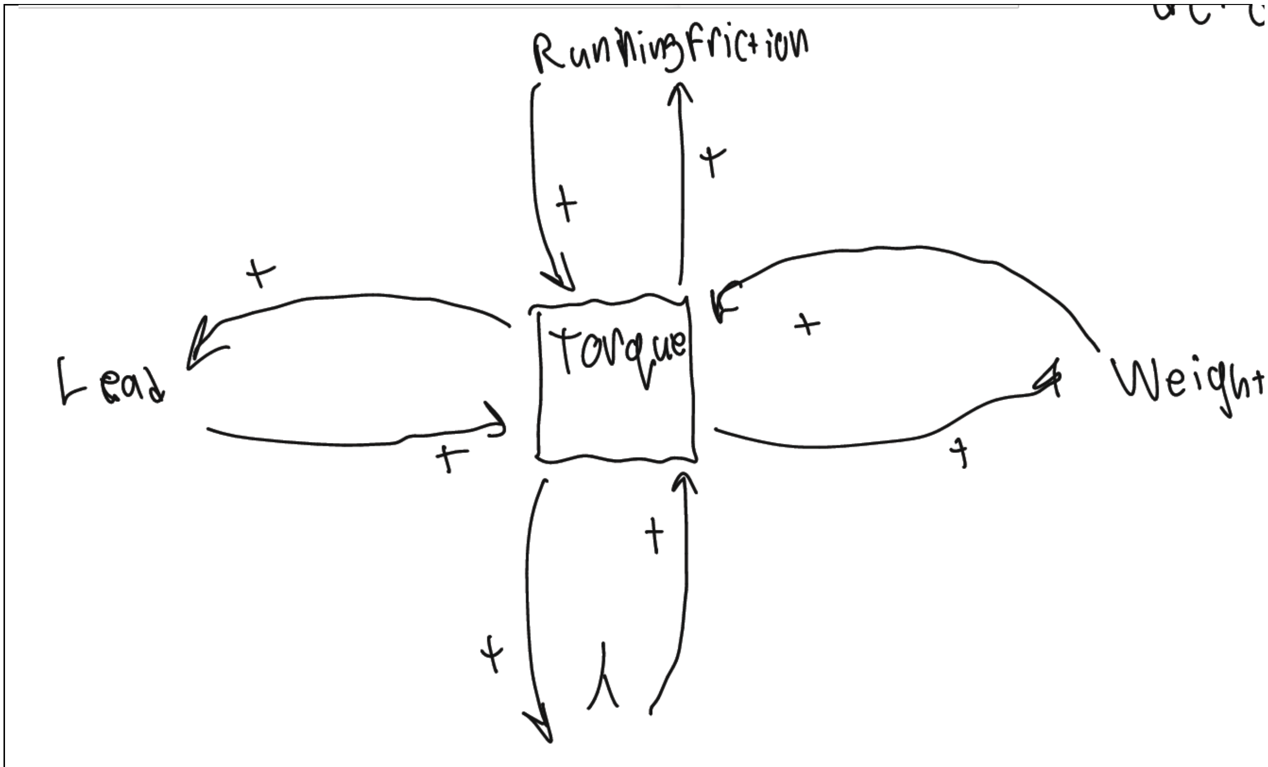


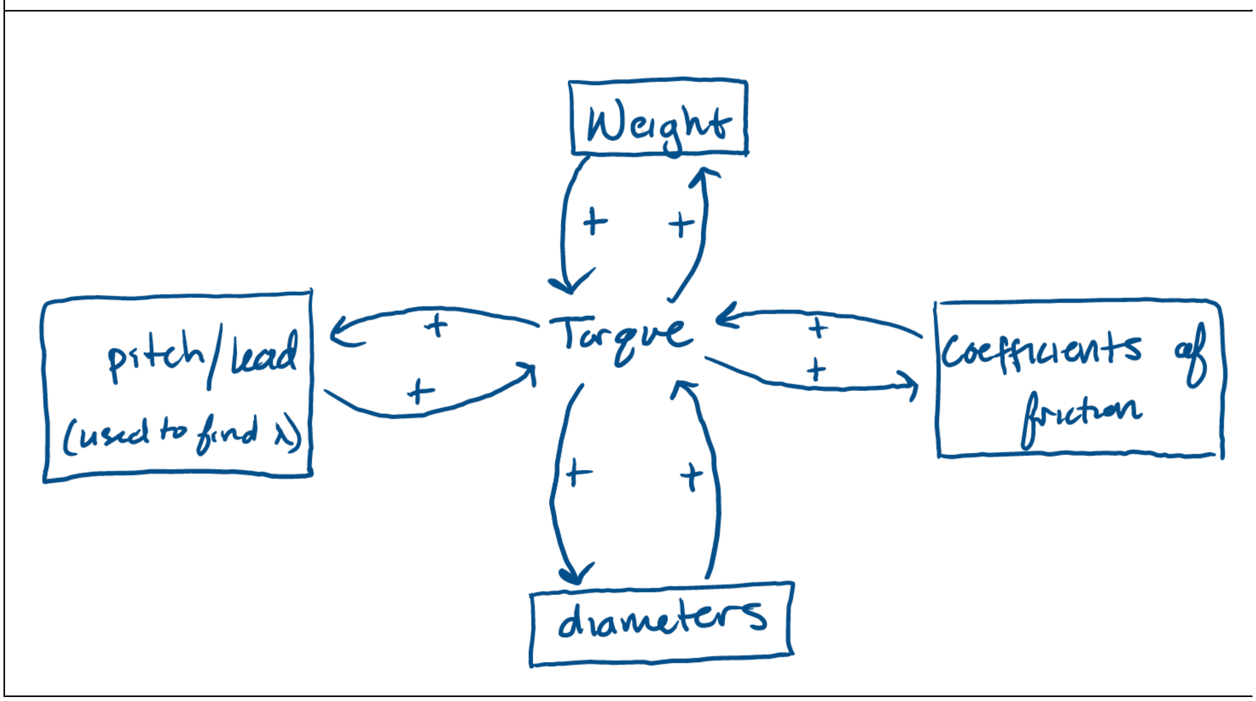
LOAD
+
MAJOR DIA, MEAN DIA, THREAD PITCH, LEAD, LEAD ANGLE
+
TORQUE
+
+
FRICTION
+
-
MAJOR DIA, MEAN DIA, THREAD PITCH, LEAD, LEAD ANGLE
-
TORQUE
LOAD (if load remains same)
FRICTION
-
-

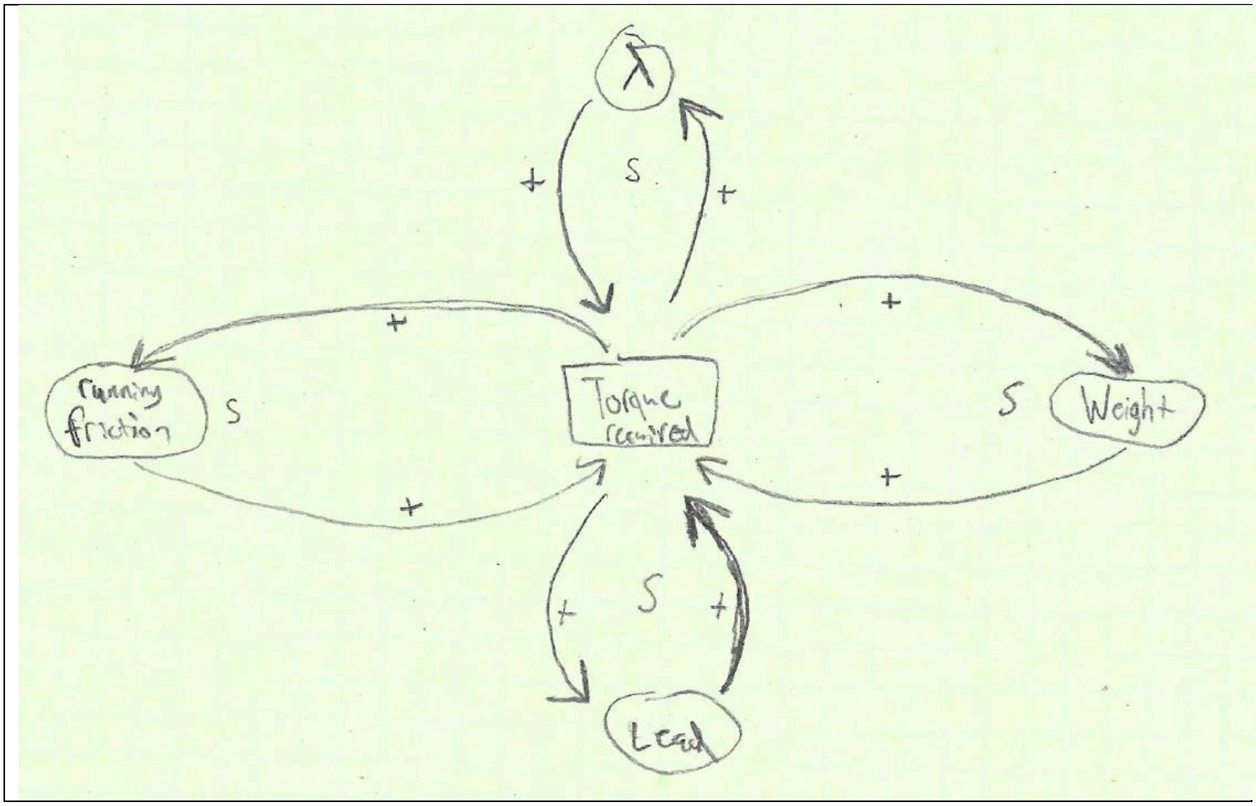

Weight of Load
Torsion
Work Input
Work Output
Force Required To Raise Load
Torque
Coefficients of Friction
Contact Diameter
Lead Height
Lead & Helix Angle


Coefficient of friction
Load
Mean diameter
Torque
Lead angle
+
+
+
+
+
+
+
+


W
F
+
+
-
-


Running friction
Torque
Lead
Weight
λ


Weight
pitch/lead
(used to find λ)
Torque
Coefficients of friction
diameters


λ
S
+
+
Torque required
+
+
running friction
S
+
Weight
S
+
S
+
+
Lead

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