The Future of Engineering Education
2024 Annual Conference & Exposition
Oregon Convention Center
Portland, OR . June 23 - 26, 2024
ASEE
Paper ID #41498

Advancing Engineering Education: Linking Systems Thinking Skills to the Tools through a Revised Framework

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Abstract:

Scholars have advanced the argument advocating for the integration of Systems Thinking (ST) into engineering education, positing its efficacy in equipping engineering students with the capacity to discern and comprehend intricate challenges and opportunities embedded within complex problem domains. This pedagogical approach fosters a holistic mindset that enables students to address multifaceted predicaments while remaining attuned to the dynamic shifts occurring in the market and the broader external landscape. Nevertheless, a noticeable research gap persists in the elucidation of the specific skillsets and cognitive paradigms that each ST tool augments. Within this paper, we embark upon a literature review encompassing an array of studies that have explored the prominent tools employed in instructing Systems Thinking. Our objectives are twofold: firstly, to delineate the diverse skill sets these tools serve to enhance; and secondly, to expound upon the distinct modes of cognition with which they are intricately associated. Finally, we propose a framework that connects the various ST tools to skills, based on the literature and work applied in the field.

Introduction:

Systems thinking (ST) is a very broad concept but is generally understood as the antithesis of linear thinking, instead focusing on understanding the whole of a system and everything that is affecting it on a deeper but also more holistic level. ST was created from General Systems Theory of Bertalanffy and is not limited to one field or discipline but is instead applicable to any problem or complex situation that may be difficult to understand or solve using traditional reductionist thinking [1]. It is this point that conveys the principle of excellently, instead of breaking complex situations into smaller pieces more comprehensible pieces with reductionist thinking, flips this narrative to focus on the larger systems and structures in place, which enables the user to understand complex relationships and behaviors that emerge not from each individual actor in a system, but from their complex and very nuanced reactions with other actors in the system [2]. ST is based on the basic principle that a system is more than a collection of its parts, and that ST can be viewed as a system of thinking about systems [3].

There is a very large body of literature on and its applications in different industries and contexts, but the core of this literature focuses on this holistic thinking which persists across all industries and contexts. One piece of literature by Monat and Gannon is a comprehensive literature review of some of the most popular and influential works in, which was curated and reviewed by many published experts in the field of ST [1]. Other literature has reviewed ST in a large body of literature and various the contexts such as education, management, engineering or healthcare.

Monat and Gannon attempt to coalesce the many different understandings of what is into a general definition that "is a perspective, a language, and a set of tools" [1]. Some key perspectives that they identify as core to is the holistic thinking as opposed to reductionist thinking as mentioned previously, the dynamic aspect of systems, the role of time, and focus on relationships. is a process that inherently recognizes that systems can change, both over time and space, and to understand a system one cannot understand it as a snapshot in time but must expand analysis to understand the change in a system which itself will reveal important aspects of the system that traditional thinking methods may not capture. Arnold and Wade define ST as "the application of systems thinking to itself" and elaborate on the challenging and adaptive definition of ST in large bodies of literature [4]. Furthermore, the focus on relationships and why actors behave in the way they do is core to this thought process, as no individual event is isolated and cannot be understood in isolation, it must be understood in the context of that actor's relationships and pressures at the time.

Scholars in this field have identified various terms prevalent in current literature on ST. These terms encompass a wide range of concepts, including events, patterns, systemic structures, mental models, accumulators, balancing loops and processes, complexity, emergence, feedback, flow, hierarchy, holism, leverage points, reinforcement, self-organization, structure, systems, and consequences [1, 3, 4]. The use of such language is ubiquitous in ST literature and plays a crucial role in conveying a comprehensive understanding of complex systems. Moreover, this language fosters a holistic perspective by emphasizing relationships and change, thus reinforcing the principles of ST.

In the following sections, we aim to bring together the findings from the literature and provide a deeper understanding on the skillsets and cognitive paradigms each ST tools augments by exploring studies which utilize these ST tools. The final goal of this paper is to add to the body of literature by proposing a framework that connects various ST tools to the skills, based on the snowball sampling of the literature and work applied in the field.

1.1 Systems Thinking Education

ST is becoming an increasingly popular framework for understanding the complex system that we face in our modern society and has shown to be of great importance for dealing with the complex issues we will face. For instance, in researchers' previous literature review of entrepreneurship and ST education in Canada, the increased emphasis for entrepreneurs to use ST to address complex challenges was highlighted [5]. The same review also noted that different disciplines utilize ST in various ways when discussing identical general principles, which aligns with findings from previous reviews [1]. Notably, this review found that ST education was mainly offered to disciplines including Business, Health Sciences, Sustainability, and to a lesser extent, Engineering, all mostly at the graduate level, therefore identifying that there may be a gap in ST education for undergraduate students, particularly in the engineering discipline where complex and multifaceted problems are common.

Additional research into the teaching ST to engineering students have led to a series of papers on researchers' observations on its effectiveness in the context of understanding complex problems [6, 7]. Some key findings in this research were that students saw marked improvement in their understanding and learning of ST processes and tools, a greater appreciation for engineering and the role they play in society, as well as improvements to their leadership skills, which ultimately resulted in the recommendation of extending this ST education in engineering and other fields. Furthermore, the researchers highlight the importance of the evaluation of the skills gained by the learners in a more detailed way such as through deeper assessment of the student's deliverables, to understand how the usage of these tools directly affect ST skill building.

1.2 System Mapping Course

The course titled "Systems Mapping of Complex Social and Environmental Problems," also known as TEP 448, was developed by the Troost Institute for Leadership Education in Engineering at the University of Toronto, drawing inspiration from the "Map the System" competition at the University of Oxford [8]. The course is primarily centered on comprehending societal and environmental challenges and aims to equip students with tools to visualize the overall scope of the problems they are addressing. Throughout a semester, learners delve into systems thinking and mapping techniques, engage with guest lecturers presenting diverse perspectives on real-world issues, and collaborate in teams to apply acquired knowledge to their selected wicked problems.

Offered to engineering students across different disciplines and academic levels, the course has undergone three iterations since January 2022, attracting a diverse cohort of students from varied engineering backgrounds. Anticipated to become an annual elective offering for all University of Toronto engineering students, the course structure encompasses two hours of lectures and tutorials weekly. Lecture sessions are interactive, covering core concepts such as systems thinking, wicked problems, sustainable economics, energy, ecology, innovation, power structures, politics, and visualization tools, supplemented by guest lectures exploring practical challenges encountered in various sectors.

Guest speakers representing a spectrum of disciplines including policy, energy, urban planning, and community engagement share insights into their professional challenges and demonstrate how a ST approach aids in addressing complex issues. Tutorial sessions provide students with dedicated time to develop their system maps, receive feedback from instructors and teaching assistants, engage in collaborative brainstorming, and interact with campus and external experts for valuable insights and guidance. These sessions also serve as platforms for peer-to-peer knowledge exchange and constructive feedback on project proposals and system maps.

1.3 Systems Thinking Process as a Conceptual Framework:

A search for most fitting frameworks was conducted to best understand the connection between ST process steps and the various ST skills. The ST Process as a conceptual framework [9] was chosen to maintain consistent analysis across various research work previously conducted on the topic of ST skill building [6, 7]. This conceptual framework is also consistent with the literature review conducted by Monat and Gannon [1], using the perspective, language, and general processes of the tools, that Monat and Gannon put forward as a working definition of ST.

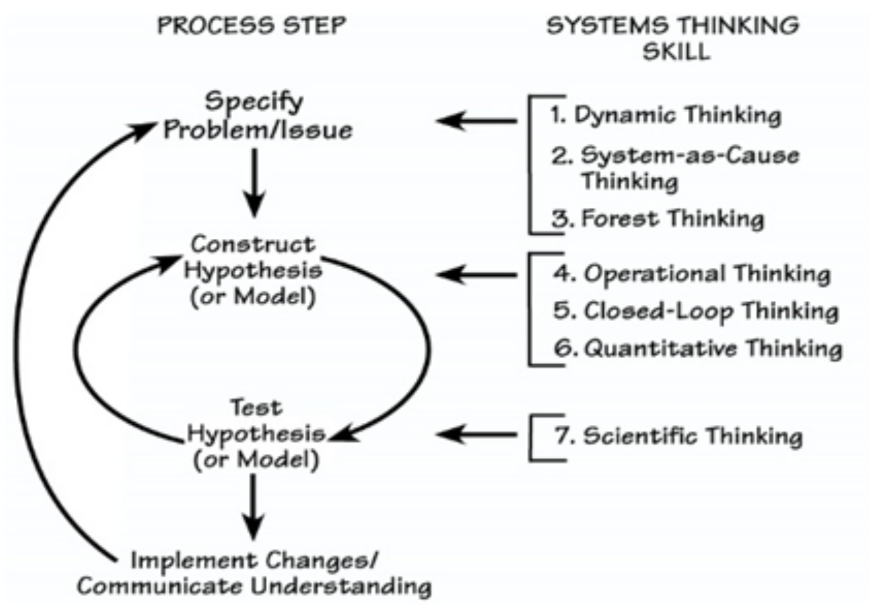

Figure 1. Systems Thinking as a conceptual framework [9]

The ST as a conceptual framework demonstrates the various ST skills utilized in different process steps of the ST process [Figure 1]. This specific research study focuses on the initial six ST skills as the aim is to understand and construct hypothesis around complex systems, and this body of research aims to ultimately support ST as a method to aid in engineering entrepreneurship outcomes specifically in the opportunity identification phase through better understanding of these complex problems and systems. These skills include Dynamic, System-as-Cause, Forest, Operational, Closed-Loop, and Quantitative Thinking, which all are shown to be key in the specification of problems/issues and constructing of hypotheses or models aspects of the ST process. It is important to note that there is overlap between these skills and they are interdependent [10], so future analysis should consider these skills in relation to one another rather than separate analysis of each tool and skill, to come to a more holistic understanding. These skills are explained in greater detail below, using definitions from [10, 11].

Dynamic Thinking

"Dynamic Thinking is essential for framing a problem or issue in terms of a pattern of behavior over time". Dynamic thinking incorporates the important aspect that an element its relationships with other elements in a system do not remain static over time, but are instead in constant change, and that change is a critical aspect of understanding the system, as any snapshot in time will miss the core aspect of change that may reveal key considerations about the system. Some keywords that are associated with this style of thinking include but are not limited to time, pattern, trends, change, behavior over time, temporal, sequence, duration, fluctuations, dynamics.

System-as-Cause Thinking

"Seeing internal actors who manage the policies and "plumbing" of the system as responsible for a behavior." System-as-Cause thinking is a critical skill to determine the boundaries of a system, by seeing which elements and relationships are in control of actors in the system, which can help reveal which relationships can be changed, allowing for critical understanding of which aspects of the system can be focused on while also revealing which aspects of the system may not be as a result of internal actors or subject to change by their behavior. Some keywords that are associated with this style of thinking include but are not limited to internal actors, policies, structure, responsibility, management, systemic, endogenous, infrastructure, governance, procedures.

Forest Thinking

"Seeing beyond the details to the context of relationships in which they're embedded." Forest thinking is critical to ensure the holistic thinking that is integral to the philosophy of ST, where though the details of each element of the system are important, it is equally as important to see the broader connections and relationships of the elements and how they interact, to see the system as a whole forest rather than a collection of individual trees. Some keywords that are associated with this style of thinking include but are not limited to big picture, context, relationships, holistic, systems view, interconnections, environment, overview, synthesis, integration.

Operational Thinking

"Understanding how a behavior is actually generated." Operational thinking is a key skill to determining true causality of a behavior, and Richmond describes how it is key to go beyond simply listing the factors that influence a behavior but ask the question of "What is the nature of the process at work?" of each influencer, to go beyond the simple influences, but why/how these influences do so and why they themselves exist. Some keywords that are associated with this style of thinking include but are not limited to true cause, underlying, mechanisms, processes, functioning, operations, implementation, procedures, execution, working.

Closed-Loop Thinking

"Viewing causality as an ongoing process, not a one-time event, with effects feeding back to influence causes, and causes affecting each other." Closed-Loop thinking is a critical aspect of the holistic and temporal aspects of ST, as it encourages the consideration of how causality of behavior is ongoing and the result of the behavior feeds back to what influences it, which will reveal "causality as an ongoing process, rather than a one-time event". Some keywords that are associated with this style of thinking include but are not limited to feedback, cycles, interdependency, loop, circularity, interaction, dynamics, reinforcing, balancing.

Quantitative Thinking

"Knowing how to quantify, though you can't always measure." Quantitative thinking focuses on considering which variables are left out of analyses because they are difficult to measure exactly, which when brought into analysis can help better explain the behaviors and actions in a system. Some keywords that are associated with this style of thinking include but are not limited to overlooked/hidden: metrics, data, variables, measurement, estimation, scale, quantification, numerical, analysis, statistics.

1.4 Systems Thinking Tools

ST can be greatly benefited using a tool to encourage this type of thinking, and across literature there are many ST tools that are used in different industries and contexts often with slight variations in their implementation and usage, though the core principles remain. Monat and Gannon qualified a number of such tools according to some criteria including that the tool is widely applicable, described in literature, easy to use, address ST language and concepts, focus on understanding systems not designing them, producing the following list of broad tool definitions: System Archetypes, Behavior over Time Graphs, Causal/Feedback Loop Diagrams, Systemigrams, Stock and Flow Diagrams, System Dynamics/Computer Modelling, Root Cause Analysis, and Interpretive Structural Modeling [1]. They also describe how these tools are often not sorted perfectly into a single category or only work in isolation, there is often much overlap between these categories and can be used in combination with one another to produce holistic understanding of the complex systems.

Later in this literature review, the Iceberg, Causal Loop Diagram, and 5 R's tools will be identified as popular tools that were used by other researchers and educators teaching ST concepts [5, 6]. In these definitions, the Causal Loop Diagram is represented by the Causal/Feedback Loop Diagrams, whereas the Iceberg and 5 R's models are more closely tied to the Systemigrams and Root Cause Analysis categories as described by Monat and Gannon.

Therefore, for the purposes of this research, though specific tool usage across literature and industries may vary in specific implementation, as long as the key principles and thought processes that the tool encourages remain the same especially in regard to the categories and principles highlighted by Monat and Gannon, it is valid to compare different implementations of a tool as one general process. This is a key generalization to allow, as in the following literature review regarding usage of these tools across industries and contexts, the tools do not use a single agreed upon implementation, but are similar in the principles and thought processes they enforce, so it is reasonable to coalesce slight variations of a tool into one general category in the interest of understanding this tool usage across a broader range of industries and contexts.

It is important to note that each of the tools mentioned in this following analysis are static, representations tools. In other words, Causal Loop Diagrams, Iceberg models, and 5R's are tools for representation of an instance state of a system and are different from simulation tools used in Systems Engineering which look at the behavior of the system over time. Dynamic models of a systems are required to analyze a complex system and utilize a series of tools which include STELLA, SysML+ Cameo, Simulink, etc. The reason for looking at these tools in this paper is to stay consistent with the tools used in the TEP448 course and the representation tools used in Map the Systems competition at Oxford.

1.4.1 Iceberg Model

The iceberg tool enables the user to go beyond the observable events that are happening, forcing them to dive into the underlying patterns, structures, and mental models that are creating the events in the larger system. Among the research it appears that slight variations of the iceberg model have been proposed and used, however they all follow a similar approach of understanding these underlying factors in a system and it remains appropriate for slightly different versions of these tools to be encompassed by this umbrella term of the iceberg tool. For some additional context, this research will use the tool as defined by Johnson et al. [8], allowing for more consistent comparisons. A visualization of this tool as defined by Johnson et al [8], can be seen in Figure 2.

This model uses the iceberg metaphor to highlight that the bulk of influencing factors in a problem or system lie below the surface of what can easily be observed. It specifically pushes users to understand patterns and trends that are first influencing the observed events, bringing in another dimension of time. Furthermore, it allows for an enhanced understanding of the system's structures, specifically what has influenced or formed these the various subcomponents or underlying factors of the system, as well as the interactions between these parts. Finally, the

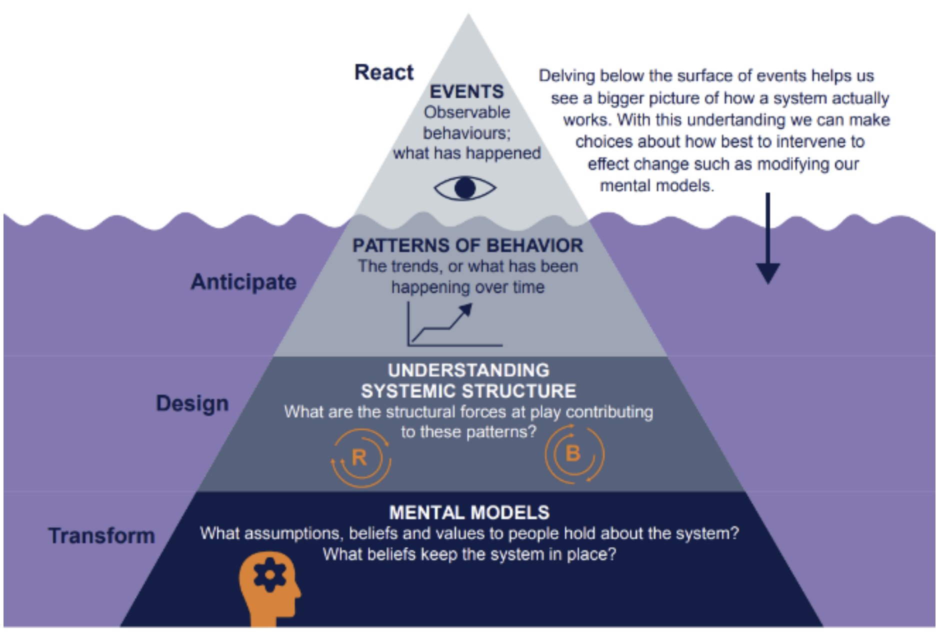

Figure 1: Iceberg Model [5]

model challenges users to dive into the deepest mental models that are influencing the structure of the system, as there are bound to be beliefs and values by actors or parts of the problem/system that are holding the structures and patterns in place. This tool thus provides the structure to glean a more nuanced understanding of the problem and system at hand.

Moreover, the iceberg tool enables users to think in ways consistent with ST principles and language as defined by Monat and Gannon [1], and as such, should enable users to build critical ST skills. It follows logically from its definition that this tool would help with dynamic thinking by framing a problem in terms of behavior of type, as that is the second step in forming an iceberg model. Furthermore, this tool also very much aligns with the forest thinking of seeing beyond the details to the context in which they are embedded and operational thinking to understand how a behavior is actually generated because the model forces users to dive into the deeper roots that result in that overall behavior with the system structure and mental model steps.

The current literature for use of the iceberg tool encompasses many different industries and applications, which is useful to provide context to how this tool can be used in a broader context. Much of this literature proposes the iceberg model as a useful tool to better understand complex problems and systems than current methods and shows the use of the tool across these industries. This tool has specifically been investigated in applications such as business supply chain management, global pandemics, healthcare systems, disaster management, farming disease prevention, and large-scale problem solving.

The use of the Iceberg model has been suggested in the context of Business Supply Chain Management [12], proposing the tool as a method for understanding the repetitive events of the supply chain, helping to identify leverage points in the system. The focus in this industry use case was on understanding how small changes in the supply chain can lead to significant impacts over time, which is at the heart of dynamic thinking. Furthermore, there was an emphasis on seeing the entire effects of emerging events within the firm's supply chain, which relates to seeing the larger context, to not make a decision for a small win today that might not be optimal longer term.

Medical use cases such as tackling the unexpected stressors on the healthcare system like COVID have suggested use of the iceberg model to reinforce the idea for individuals and organizations to see their effect on the whole system and address the underlying cause, over simply addressing the noticeable events. With this model, they were able to stress the importance of policymakers building programs that can handle unintended consequences, focusing on internal actors and their decisions. Furthermore, this tool urges users to look at their impact to the system overall, not simply making changes that limit themselves to looking at noticeable impact, and missing something more valuable that cannot be seen immediately.

This Iceberg model has also been used other healthcare applications such as to characterize problems at the intersection of chronic conditions and reproductive health [13], which used this tool among others to stimulate broader thinking about actions within these complex systems. In using this tool to stimulate broader thinking, the tool was used to encourage looking beyond the details of single actors to the broader scope and relationships that govern the whole system, consistent with ST processes and skills such as forest thinking. Furthermore, this tool helped identify that by changing problematic beliefs and mental models revealed by the iceberg tool, the goals, structures, and outcomes, of the healthcare system could be altered, indicating a focus on deeper system behaviors change.

The Iceberg tool has also been used to better understand the very complex nature of disaster management on a large scale [14]. The tool was used to identify the mental models and systemic barriers that cause the structures and patterns that can be observed in these crises. Interestingly, the paper suggests that though the Iceberg tool can help identify root causes, it reminds individual stakeholders that though they may find root causes of their individual issues, fixing that root cause alone may not achieve the desired behavior, but they should instead work as part of a bigger system. This may suggest that the Iceberg tool is very good to dive deeply into the root causes of issues but may need to be combined with other ST tools to consider the broader context of where these root causes are in a system, in order to gain and appropriate understanding of the complex system.

The iceberg tool has also been used in farming disease prevention to better understand the root causes of the bovine respiratory disease outbreaks that affect the cattle industry [15]. This usage focuses on understanding the structure that drives the behavior of the system in stocker cattle operations and requires recognition of the interconnected behaviors and the broader context of this complex issue with many stakeholders.

Overall, the utility of the iceberg tool spans various sectors, enhancing problem-solving and root cause analysis capabilities. For instance, in business supply chain management, it aids in identifying impactful leverage points, whereas in healthcare and pandemic response, it helps in anticipating unintended consequences and reinforcing systemic health. Similarly, in disaster management, the model assists in discerning systemic barriers and mental models that influence crisis dynamics. It also offers a foundational framework for policymakers tackling complex problems, promoting a multifaceted perspective that encompasses both immediate and root causes of systemic issues, such as in farming disease prevention where it highlights the structural drivers behind cattle health crises. The current literature appears to suggest that the iceberg tool supports the learning of several ST skills, particularly dynamic, forest and operational thinking, to see the underlying causes of the system, and analysis of these connections will be covered in the future discussion of the aforementioned research questions, detailed in the future work section of this report. However, it should be noted that there is a lack of concrete research on the iceberg tool specifically building these ST skills and its success being evaluated, as much of the current research simply proposes its use and the potential utility of it, without evaluating its success of skill building particularly. This provides even more reason to investigate how this tool promotes ST skill growth in practice.

1.4.2 Causal Loop Diagram

Causal Loop diagrams are a widely used tools for understanding complex relationships between many actors within systems and have been used across all industries and literature due to their simple but very powerful nature. There are many definitions and distinctions on how this tool is used, that vary between industry and use cases. However, they all focus on visualizing the various subsystems, their interconnectedness, and the causality. For the purposes of this research, the definition as used by Johnson et al. will be used, where actors or elements in the system are linked visually by arrows which can be positive or negative in nature, either reinforcing a pattern or force in the system or reducing its affect over time [8]. In Figure 4, Sterman outlines a causal loop diagram that is consistent with the definition provided by Johnson et al. [16, 8].

Due to the nature of this tool, it is clear that this tool would be particularly apt at developing the ST skills of dynamic and closed-loop thinking, as it by definition encourages users to understand the cyclic nature of the system over time and how causality is ongoing and has continued influence over time. Furthermore, in seeing these relationships over time, one can build their operational and forest thinking skills by seeing beyond the individual actors and details of the system to the overall context of the system and how the behaviors seen are truly generated. The current literature is extremely vast with an incredible amount of this tool being used across all industries and backgrounds, which speaks to its utility in understanding complex problems.

One source is a literature review of many papers relating to the pandemic which included use of causal loop diagrams to understand these complex issues [17]. This paper shows how the causal loop diagrams help reveal how health policies, the economy, and social behavior change over time, focusing on the dynamic and time-based nature of many of these issues. Furthermore,

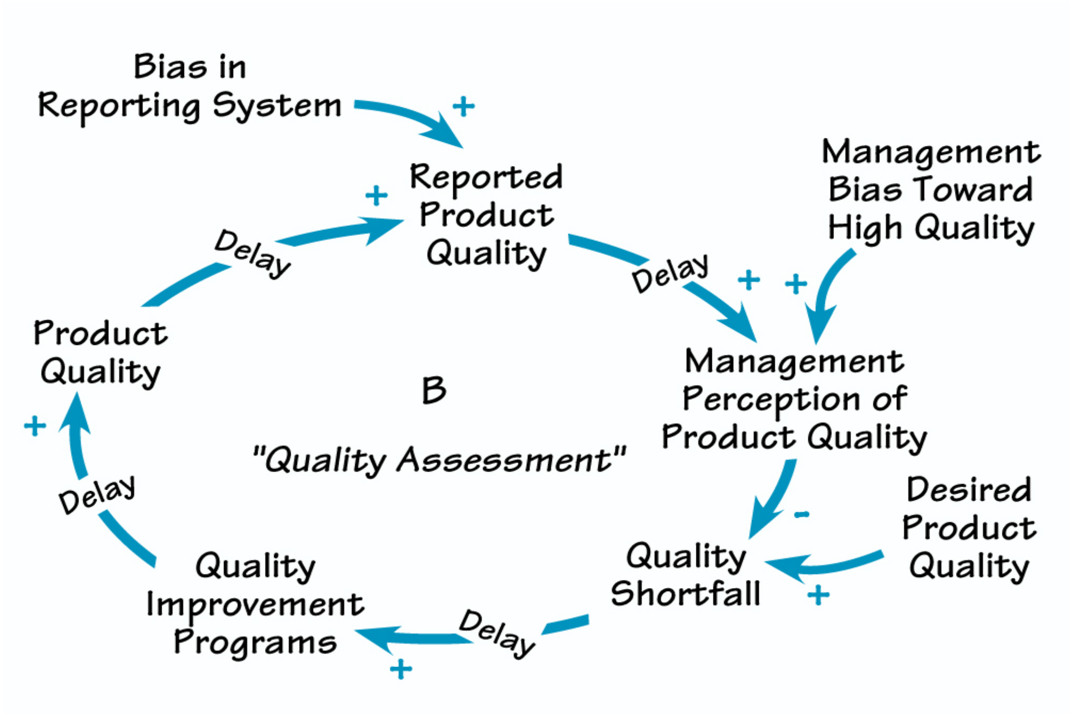

Figure 2: Causal Loop Diagram [16]

identifying the interconnectedness of such a large issue was aided through use of this tool by highlighting how decisions and actions in the pandemic cause effects that loop back and influence future decisions, such as how a lockdown decision may affect the economy which can influence public health policies and social behavior in reaction to these changes, which can then loop back to influence future lockdown decisions. In understanding these details and the connectedness of influential factors, the causal loop diagrams help to also see beyond the details of individual actors to the broader system at large [18].

Another source investigates the use of causal loop diagrams to help understand the complex issue of HIV transmission from mother to child, specifically to understand how poverty, gender, and health system factors influence women's participation in services to prevent these outcomes [22]. With the use of this tool and identifying a significant number of feedback loops that influence this process, they were able to clearly identify how influential time is in this issue in how poverty and health systems change over time, and enabled them to think about the system in fluctuation as patterns and trends over time, rather than a snapshot in time which is easy to do with traditional analysis methods for simplification. Furthermore, in seeing the system as interconnected loops, they were able to see the broader system as a complex relationship as completely connected rather than separate issues.

Causal loop diagrams were also used as a tool to develop an analytical framework to address the gap in traditional climate change assessments of bioenergy supply chains that didn’t account for broader systems including the global nature of this market, or the dynamic and interconnected nature of different sub-systems that this supply chain embeds itself in Groundstroem and Juhola's work [19]. The causal loop diagrams facilitated the understanding of how this issue is much more nuanced than originally thought, and helped bring in many complex factors into analysis, such as the feedback nature of the problem in how climate change affects the supply chain, the supply chain affects markets, markets affect supply and demand, and supply and demand affect climate change. These causal loop diagrams therefore enabled a greater understanding into the looping and interconnected nature of the problem, allowing the users to better see the entire picture, as well as help identify leverage points in the system that did not seem initially obvious or connected.

The causal loop diagrams encourage analysis of the interconnectedness and feedback nature of a system, incorporating critical factors such as time and broad relationships into analysis, which can enable a greater understanding of how the system truly works, and why behaviors are occurring. This focus on patterns, trends, and relationships is at the core of ST and connects to many ST skills. Furthermore, it is important to note that this review is not a comprehensive literature search as there is an incredible amount of literature on the topic of or using causal/feedback loop diagrams, however, much of this literature is consistent with these examples.

1.4.3 5 R’s Framework

The 5 Rs model is a ST tool used for mapping complex systems by breaking it down into five key components, Resources, Rules, Roles, Relationships, and Results. This research paper will use the tool as defined by Johnson et al. [8] and adapted from USAID [20] and pictured below [Figure 4]:

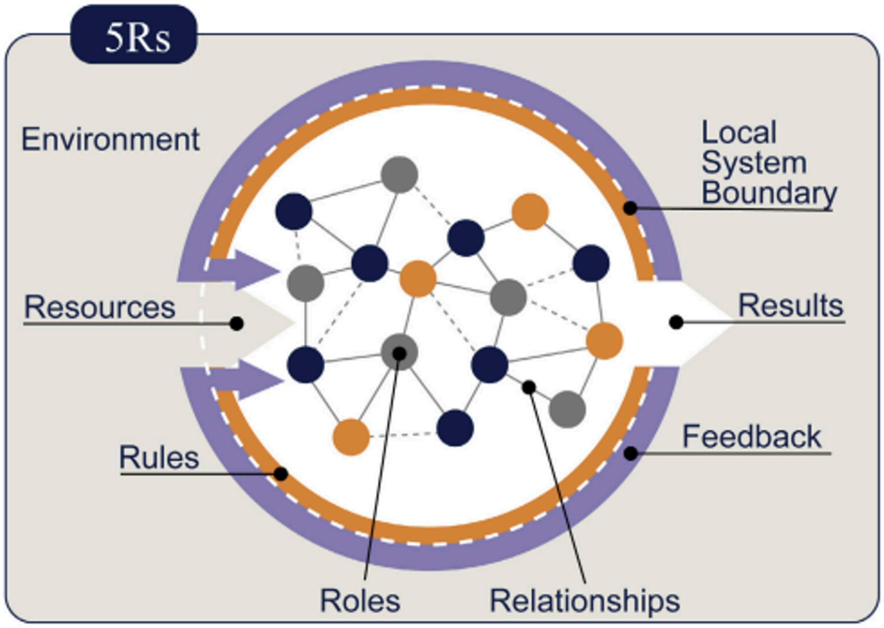

Figure 3. 5R's Framework [8]

To use this tool, it is suggested that users first start with the Results, which is what is currently happening in a system, and work back from the output of the system to determine how it is produced. This Results can include both quantitative and qualitative data to help inform the other components. Then the user proceeds to understand the resources that supply the system, as well as the roles and relationships between different actors within the system, and finally the rules that govern the system, either through legislature, societal norms, or expectations that drive these decisions.

From the definitions alone, one can see the similarities this tool has to both the causal loop and iceberg model. First, this tool starts with the clearly visible results of the system like the iceberg tool, and then aims to dig deeper into the system to determine the underlying structures that cause the system to be the way it is, particularly in the rules section. Furthermore, like the causal loop diagram, there is a large focus on determining the relationships between actors and the roles they play in the system with the resources and rules that govern them. For these reasons the 5Rs model seems to be represented within the Iceberg and Causal Loop tools, in the ways the tool encourages users to think about the system, and the components and relationships between components that it highlights.

From this definition it is clear that the 5 Rs aligns with the ST thought processes of understanding wicked problems, and it logically follows that this tool would indeed help build ST skills. It is hypothesized that this tool would specifically aid in the building of system-as-cause thinking through the analysis of the roles and their relationships within the system, and operational thinking via the process of understanding how the results came to be.

There is a notable lack of current literature on this tool, both in the quantity and quality of research found. In the few mentions of this 5 Rs tool in the literature, they all used this tool as defined by USAID [20], further cementing this as an appropriate definition for the tool. However, between the University of Toronto Library and Google Scholar, there were only a few quality sources on the use of the 5 Rs tool found, when using many combinations of search terms including, 5 Rs, five Rs, Results, Roles, Rules, Relationships, Resources, ST, mental models, frameworks, tool. Furthermore, it is worth noting that a 5 Rs tool was mentioned in literature often, but upon further inspection in most cases the tool mentioned was often a different 5 Rs tool used in different specific industry/discipline contexts and would not apply to this definition of the 5 Rs model.

The one source that was identified that did use this 5 Rs tool [21], applied the 5 Rs model in the context of road safety by applying different ST tools to understand this large and complex issue more effectively. In this research, the 5 Rs tool is used effectively as a starting point to understand the broader system and suggest that this tool allows the user to better understand how the system can generate problematic outputs by better understanding the roles and relationships within the system and identifying the gaps in these systems, allowing them to better "pinpoint potential opportunities for change or system strengthening". In this tool one can see many ST skills at play, specifically the system-as-cause thinking by better understanding the individual actors and rules that manage the system, and operational thinking to see the true reasons of why these behaviors and results are generated, as suggested in how it allows them to better pinpoint the opportunities for change in the system. Furthermore, this source then goes on to use causal loop diagrams to further understand this system, more so using the 5 Rs model as a starting point to generate higher level understanding before diving deeper into the system.

Aside from this source however, there was very limited quantity and quality of literature on the 5 Rs tool. As a result of this lack of literature, the 5 Rs tool will likely not be used as a major tool to analyze to identify which ST skills are being developed when analyzing the learning within the TEP448 course. However, as previously mentioned, since this tool has similarities in the other tools such as the Iceberg model and causal loop diagrams, the spirit of the tool and the ST processes this tool encourages will still be applicable. Furthermore, as suggested by Naumann et al. [21] , it would be interesting to see whether this 5 Rs tool is also used a preliminary starting point to understand the larger system before diving deeper into the other tools to generate deeper understanding of the wicked problems, so there is certainly some use in keeping this research in mind, while not using it as a major pillar of understanding the students' learning of these ST skills.

The lack of literature on this 5 Rs tool suggests an area of potential research to better understand the utility of the tool itself, especially in the context of how it relates to ST skill building. Furthermore, more corroborating research into where this tool is most useful, such as a preliminary understanding method before using other tools to dive deeper into the system may be valuable research and could suggest new ways to use these tools in combination with one another to develop a better method of understanding systems. For example, a broader framework of many tools combined, each of which helps understand these wicked problems and systems better, may comprehensively enable effective ST skill building beyond the capabilities of these tools individually.

2. Discussion:

Based on the analysis of the current literature and the high-level goals of this paper, an update is proposed to the ST Process as a Conceptual Framework, so that it includes the ST tools of the Iceberg model and the Causal Loop Diagram, and how these tools support the ST skill building process. Figure 5, is a modification proposed to the original ST framework, such that the solid arrows represent where the literature suggests a link between the tool and skill building, whereas the dotted lines are connections that are not explicitly revealed in the literature in a concrete way, but have logical connections that do suggest a link, even though it might not be as strong as the full solid line connections.

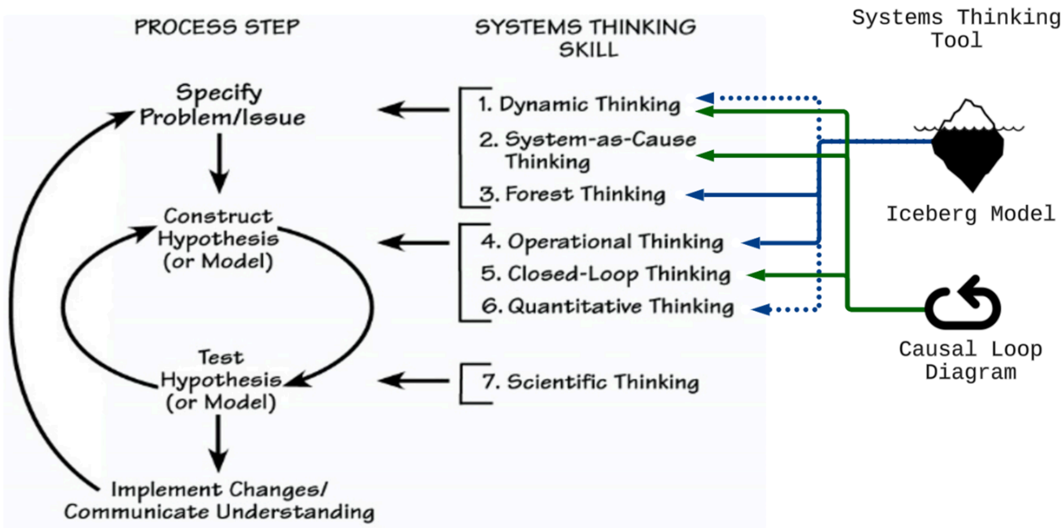

Figure 4. Proposed Update to Systems Thinking Process as a Conceptual Framework

The Iceberg Model, renowned for its utility in revealing underlying patterns and structures, is hypothesized to directly support Forest and Operational Thinking. This suggests a literature-backed connection whereby the model aids in recognizing the broad context and operational mechanics within systems, that reveal the true underlying causes of behaviours in systems that emerge when seeing elements as part of the systems as a whole, these strong connections will be discussed in greater detail later in this section. The model also potentially fosters Dynamic and Quantitative Thinking; however, this connection is less established in the literature, suggesting a logical but not empirically verified relationship. The connection to dynamic thinking is inherent to the Iceberg model in the second step of the model that focuses the user on analyzing patterns of behaviour over time, which is in direct support of the dynamic thinking skill.

This is only one early step of the Iceberg model however, used as an informing step to enable the future analysis to discover the true causes for behaviour in a system, that is more supportive of forest and operational thinking, so though we believe the connection to dynamic thinking is logically present, it does not appear to be as strong of a focus of the iceberg tool, which may encourage other skill building to a greater degree.

Furthermore, though there is not much literature supporting the connection to quantitative thinking, this research proposes the logical connection between mental processes the iceberg model suggests that are consistent with utilizing the quantitative ST skill. Recall the definition of quantitative thinking which focuses on considering which variables are left out of analyses because they are difficult to measure exactly, which when brought into analysis can help better explain the behaviors and actions in a system. The iceberg model encourages delving into the hidden factors that cause behaviors that are not necessarily obvious from surface level observations, diving into the assumptions, beliefs, and mental models that are held within the system, and much of these variables are difficult to quantify, and so by encouraging factoring in difficult to quantify variables into analyses, the iceberg tool appears to potentially support the development of this quantitative thinking skill, though this connection would need to be empirically validated in future research, both in the TEP448 course and beyond.

The Causal Loop Diagram is proposed to reinforce System-as-Cause, Dynamic, and Closed-Loop Thinking. This tool, with its focus on feedback loops and causality, is instrumental in understanding the relationships between system elements and how they evolve over time, which is consistent of the principles of each of these skills. By visually mapping the cause-and-effect relationships within systems, the Causal Loop Diagram encourages a deeper comprehension of system dynamics and the iterative nature of cause and effect, and the strong connection that appears to these three ST skills will be outlined in detail below. This is based on the much-needed gap in the literature on the connection between ST skills and the tools [6, 7].

To further understand the connections within the updated framework, this next section will delve into each ST skill to understand how this skill is supported by the applicable tools from the perspective of the skill.

2.1 The connection between the skills and the tools

Dynamic Thinking, which is potentially influenced by both the Iceberg Model and the Causal Loop Diagram, involves recognizing and understanding the change within systems over time. This skill is crucial for anticipating future states of a system and preparing for potential scenarios. The Causal Loop Diagram, by highlighting feedback loops, enables thinkers to appreciate the non-linear and ever-changing aspects of system dynamics, which provides a mental model for thinking about systems that encourages thinking about patterns of behavior over time which is consistent with the principles of dynamic thinking and would support building of this skill. The iceberg model also has been suggested to potentially support this ST skill, though not as a major focus, as outlined in detail previously.

System-as-Cause thinking involves seeing the relationships between actors in a systems and which actors are responsible for the policies and rules of the system, which has the benefit of seeing which relationships can be changed and how that will affect the broader system. The causal loop diagram is shown to help identify relationships between actors in the literature, understanding how situations where many elements come together and the rules that govern the overall behaviour of the system by making visual connections between these actors. This is consistent with the principles of the system-as-cause skill, where use of this tool teaches the value of understanding the relationships between different elements of the system and how this system operates through these relationships, building mental models consistent with this skill.

Forest Thinking is critical for the holistic thinking aspect of ST, which requires seeing beyond the details of elements in a system to the broader relationships that produce overall system behavior, producing that holistic understanding from not just the details, but the interaction of the details. The iceberg model takes the user through a series of steps where the user dives into deeper and deeper details of the system before drawing the holistic understanding of the system that emerges from these elucidated details. As described in the literature review, there was consistent evidence of this tool helping users to see broader aspects of the system that emerge when seeing the details as part of a holistic system, which logically follows from use of a tool that encourages identifying the details and bringing these details together to see the bigger picture of how these details produce the observed behaviour of the system. Therefore, though the iceberg model involves diving into deeper and less obvious details from the observed behaviour, it is in identifying these details and how they contribute to the overall behaviour (moving up the iceberg) that produced the mental model skill of seeing how details relate to form larger system behaviors, that is so consistent with the forest thinking skill.

Operational Thinking emphasizes understanding the true causality of how a behavior is generated, and this research proposes that this is the skill most strongly supported by use of the Iceberg model. This is because the Iceberg tool has been widely described in literature as aiding in the process to find the true cause of behaviours in the system, as each step in the Iceberg process involves diving into a deeper underlying cause of the behaviour in question, which appears to encourage the development of mental models that involve trying to determine underlying causes of behaviour through strategies such as looking at trends, structural forces, or assumptions and belief. This literature process of looking at underlying causes that is integral to the Iceberg model is core to the mental models of operational thinking for understanding true causality for behaviour, and so the connection between this Iceberg tool and the operational tool appears to be very strong, and so will be a major focus of future analysis such as in analysis of Iceberg tool usage in the TEP448 course.

In the context of Closed-Loop Thinking, the Causal Loop Diagram provides a concrete tool for visualizing and understanding the feedback mechanisms that govern system behavior. The connection between this skill and the tool is very clear within the literature, which is very unsurprising given the definitions of this skill and tool, as they are very similar, by viewing systems as an ongoing process that interact with itself over time. This connection is very clear, because the causal loop diagram enables users to see the connections between elements within a system to see causality over time, and one aspect of this is how these causal loops are loops in nature where they link back to themselves. By forcing this element of self-connection, this tool teaches how system causality is not a one-time event, but more accurately viewed as an ongoing process where effects feedback to influence causes and these causes then produce these future effects and so on. Therefore, this tool clearly appears to help assist with learning the mental models and ways of thinking that are consistent with those required with the Closed-Loop thinking skill.

This updated framework, therefore, presents a multidimensional approach to developing ST skills through the application of specific tools. It is proposed that the solid arrows in the diagram are presenting a better support of these connections while the dotted arrows invite further empirical study to verify the proposed logical connections. However, one thing that should be very clearly noted is that though the literature appears to suggest these connections, there is no research specifically identifying these tools building these systems skills as part of this framework or evaluating their skill building effectiveness outside of the tool. Therefore, there are many areas of future research that can be done to provide empirical support to these connections. One such example is of this future work will be conducted by analyzing the skill building effectiveness of use of these tools in the TEP448 course at the University of Toronto to see if there is evidence of the skill building effectiveness of each tool. However, this will be limited to the existing material that was produced by students, where this course was not designed to specifically investigate this connection but teach ST principles more broadly. Therefore, this may have the gap of not being able to see if use of these tools results in these ST skills being built, where these skills are seen to be used outside of use of these tools, which would require time and resources that are not in scope of this research but will be outlined in the future work section of this paper.

In conclusion, while the updated framework offers a potential comprehensive guide for integrating ST tools into cognitive skill development, it also presents several research opportunities. These include verifying the tentative links suggested by the framework, assessing the generalizability of the framework across various domains, and understanding the practical implications of the framework in real-world applications. As ST continues to gain prominence in addressing complex problems, frameworks such as the one presented will become increasingly valuable for both theoretical exploration and practical application.

3. Conclusion

In conclusion, our analysis of the current literature prompts a proposed update to the ST Process as a Conceptual Framework. This update incorporates the Iceberg model and the Causal Loop Diagram to enhance ST skill development. Our framework, illustrated in Figure 5, delineates connections between these tools and skill building, with solid arrows representing robustly supported links and dotted lines suggesting logical yet less validated connections.

The Iceberg model is hypothesized to bolster Forest and Operational Thinking by unveiling underlying patterns and structures within systems. While its connection to Dynamic and Quantitative Thinking lacks empirical support, it encourages exploration of hidden factors and consideration of hard-to-quantify variables, potentially facilitating skill growth.

Similarly, the Causal Loop Diagram is proposed to fortify System-as-Cause, Dynamic, and Closed-Loop Thinking by visually elucidating feedback loops and causality within systems.

Further analysis delves into how each tool supports specific ST skills: Dynamic Thinking involves discerning change over time, System-as-Cause revolves around understanding relationships between system elements, Forest Thinking stresses holistic comprehension beyond particulars, and Operational Thinking seeks to grasp true causality. The connections between these skills and the tools are examined in detail.

While our framework offers a comprehensive guide for integrating two ST tools into skill development, it suggests numerous research opportunities to verify connections, assess generalizability, and understand practical implications. As ST garners prominence, frameworks like ours hold significant value for both theoretical exploration and practical application in addressing complex problems.

4. Future Work

This research highlighted the connection between ST tools and how they link to various ST skills in the context of problem identification and hypothesis creation gathered from the ST Process as a conceptual framework [8]. The next step for this research is to produce a rubric or framework for how to evaluate the use of a tool in showing ST skill building. The purpose of creating this rubric or framework is to provide a structured procedure for understanding the use of these ST tools in the teaching of ST concepts evaluating the effectiveness of the material for the learners.

This evaluation aims to substantiate some of the current literature's claims of how these tools can be used to aid ST outcomes by showing the direct building of critical ST skills. This also aims to address a gap in the analysis of the TEP448 course, where general ST outcomes have been analyzed, but not the methods of this skill building and evaluation of these tools' teaching effectiveness. This rubric will thus be used to evaluate the skill building effectiveness of these tools in a ST education context, by analysis of research done by Azad and Moore, as well as primary research into deliverables produced by the students using these tools to understand wicked problems in addition to interviews with students about the course conducted by Azad [3. 4].

This analysis aims to provide better context to compare with the current literature's understanding of these ST tools' skill building capabilities, which may result in modifications to the proposed conceptual framework and skill-tool rubric created based on the current literature. Ultimately, this research aims to synthesize the current literature and extend the ST conceptual framework to include relevant tools, and better understand how these tools result in skill building both in the current literature and in an engineering education context, to both provide reference for and inform future research on ST tool usage, as well as improvements and potential avenues for improving the ST education offered in the TEP448 course at the University of Toronto.

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