

Article

Undergraduates' Conceptualization of Systems Thinking

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Abstract

This study investigated undergraduates' conceptualization of systems thinking (ST). An open-ended question was administered pre- and post-course. Pre-test findings revealed limited conceptualization, with most students unable to articulate core ST attributes. Post-course responses showed reasonable improvement, with seven key attributes—interconnectedness, feedback, causality, systems boundary, mapping, emergent behaviour, and synthesis—emerging to varying extents in their responses. While nearly all students indicated interconnectedness and mapping, fewer mentioned feedback and systems boundary, indicating these as higher-order cognitive skills. A continuum was also developed to categorize students' conceptualization from inadequate to canonical; this also indicated that only a few students demonstrated engagement with the key attributes of ST. Novel analytical approaches such as attributes prevalence tables, attributes continuum, and evolution of threshold concepts have contributed to different modes for exploring ST in the responses. Findings underscore the complexity of ST and the challenges in fostering holistic conceptualization. Overall, the study highlights a nuanced engagement with the attributes of ST from the intervention and suggests that further work is necessary to better foster these among the students.

Keywords: systems thinking continuum; systems thinking concepts; systems thinking education; systems thinking attributes; threshold concepts; undergraduates

1. Introduction and Literature Background

Various theories such as General Systems Theory, Chaos Theory, Complex-Adaptive Systems, and Integral Theory exemplify how systems work, and how a system organizes itself to adapt to change [1]. For example, General Systems Theory, developed by biologist Ludwig von Bertalanffy [2,3], emphasizes the importance of studying systems as whole entities rather than merely as the sum of their parts. Bertalanffy argues that traditional science often failed to explain phenomena by breaking them down into isolated units. Instead, this theory focuses on the concept of 'wholeness,' addressing issues of organization, interconnectedness, dynamic interactions, and behaviours that cannot be understood by examining parts in isolation. The systems thinking (ST) movement emerged as a way to address complex problems [4]. Gharajedaghi viewed ST as "the art of simplifying complexity. It is about seeing through chaos, managing interdependency, and understanding choice" [5] (p. 283). There are multiple valid frameworks for organizing the skills that support ST, each contributing to a deeper, more actionable understanding of complexity [6,7]. According to Sterman ST is "the ability to see the world as a complex system, in which we understand that 'you can't just do one thing,' and that 'everything is connected to everything else'" [8]



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(p. 4). Works of Sterman [9] and Meadows [10] in this area have also established that as everything is interconnected in the real-world, linear systems do not exist, and traditional thinking methods of solving complex problems by breaking them into smaller parts are no longer adequate. ST approaches are essential for solving complex problems.

ST is a higher-order skill and complex construct. It is also developmental in nature, meaning that it can be introduced, scaffolded, and progressively strengthened at either school or tertiary level rather than be expected to be mastered at once. The range of studies reported in the literature on ST at primary, secondary and tertiary levels attest to this [8,11–13]. Of course, a few limitations need to be kept in mind. Modelling complex scenarios using causal loop diagrams or stock-n-flow diagrams is unlikely to be within the ability of primary school students; and it may even pose challenges for lower secondary students. It is certainly suitable for assessment at the undergraduate level.

Recognizing its utility, the term has also entered into curricular documents of several countries. ST encourages a comprehensive view of problems and solutions, thus fostering a deeper understanding of the complexities and dynamics at play. It is both a mindset as well as a set of tools that can help students recognize and understand relationships and interconnectedness. Also, it can enable them to switch between examining parts and the whole of a system to see how interactions lead to positive or negative behaviours. The primary purpose of implementing ST and systems dynamics curricula is to help instructors and students recognize its inherent interdisciplinarity and its significant potential to equip students with the skills to address global challenges holistically [11,12].

To properly define ST, various studies have developed models that break down the skills into its fundamental components. The System Thinking Hierarchical (STH) model, for instance, presents an eight-level hierarchy specifically for Earth Systems [13]. Another model, the System Thinking Continuum (STC), suggests that ST skills lie on a continuum, ranging from the basic task of recognizing interconnections to the advanced skill of testing policies [14]. In contrast, Richmond proposes a non-hierarchical classification, arguing that effective ST involves operating on at least seven thinking tracks simultaneously [7] (Richmond, 1993). Richmond's updated set of skills includes Dynamic Thinking, System-as-Cause Thinking, Forest Thinking, Operational Thinking, Closed-Loop Thinking, Quantitative Thinking and Scientific Thinking. These seven skills complement each other, with each being utilized at different stages during the design of a ST intervention [15].

ST competencies extend beyond understanding systems—they encompass both gaining insight and using insight [16]. Gaining insight involves examining systems from multiple perspectives to understand their behaviour, even without complete information. Using insight entails manipulating system structures to influence outcomes, thus requiring understanding of system dynamics and feedback mechanisms [7,14]. These facets operate in parallel and in series, reinforcing each other. Arnold and Wade outline core ST skills: identifying, understanding, predicting system behaviour, and designing interventions for desired effects [17]. This process often involves moving from observing events or data, to recognizing behavioural patterns over time, and finally uncovering the underlying structures driving those patterns. Feedback loops—comprising stocks, flows, and variables—create dynamic behaviours that are often difficult to grasp without systems education [18,19].

A hallmark of ST, absent in reductionist approaches, is its embrace of complexity—non-linearity, circular causality, and interdependent interactions [2,3,20]. Assaraf and Orion proposed a hierarchical model of ST with four levels: identifying components and processes; recognizing relationships and dynamic interactions; understanding cyclic nature and generalizing; and predicting behaviour including hidden elements [13]. Similarly, ST can also be interpreted in terms of the ability to interpret complex systems emphasizing structure, behaviour, and function along with understanding other dimensions such as iden-

tity, emergence, and systemic effects [21–23]. Ultimately, ST requires seeing both the forest and the trees—understanding individual components and the system as a whole [7]. There are multiple valid frameworks for organizing the skills that support ST, each contributing to a deeper, more actionable understanding of complexity.

Richmond defines ST as “the art and science of making reliable inferences about behaviour by developing an increasingly deep understanding of underlying structure” [24] (p. 139). In addressing complex issues like climate change, ST guides decision-making and policy design [25]. Educationally, it involves modelling direct and indirect relationships among system elements to explain behaviour [26,27]. Key aspects include defining system boundaries, understanding cause-and-effect relationships, identifying interconnections and feedback loops, and predicting behaviour based on emerging patterns. These competencies foster deeper understanding of complex systems, enabling strategic problem-solving and effective interventions across learning contexts. Thus, key aspects of ST in educational contexts include defining system boundaries and structure, understanding cause-and-effect relationships, identifying interconnections and feedback loops, framing problems based on emerging behaviour over time, and predicting system behaviour. These elements collectively enhance the understanding of complex systems, aiding in effective problem-solving and strategic interventions across educational contexts.

Though the concept of ST has been the subject of numerous studies, there remains little consensus on its precise definition. Different scholars have conceptualized it in varied ways, though common threads can be identified. For instance, Senge describes ST as “a discipline for seeing wholes,” emphasizing the importance of viewing interrelationships and patterns of change rather than isolated elements [28] while other studies identify four foundational aspects of ST: identifying systems, understanding systems, predicting system behaviour, and devising modifications to achieve desired outcomes [17]. Some scholars have proposed broader interpretations that critical thinking is central to ST, though this is a generic skill applicable across many domains [29]. It is also suggested that ST involves solving complex problems holistically without delving into minute details—a valid but again general perspective [30].

ST interventions have targeted diverse populations. These include student teachers [31–33], middle school students [34], school teachers [35], undergraduates [36–38], and primary students [39]. Across these studies, ST skills are consistently found to be challenging to develop. Furthermore, ST enables learners to engage with multifaceted problems by recognizing interconnections, feedback loops, and emergent behaviours—skills foundational to creative reasoning and strategic problem-solving [7,10,40]. For example, several studies have examined ST within science education and assessment contexts, highlighting both its pedagogical value and the challenges in fostering it. Some explored how ST can be embedded in science curricula to enhance conceptual understanding [41–43], while others focused on assessing ST skills [44]. These studies consistently show that students often excel at identifying system components but struggle with higher-order skills such as recognizing interrelationships and dynamic interactions. For example, it is found that students had difficulty grasping the interconnected nature of earth and hydrological systems, despite being able to name their parts [13]. These findings underscore the need for more targeted ST instruction, especially in disciplines where understanding complexity is crucial.

A review of the journal literature indicates that hardly any studies have explored how students conceptualize ST. We were able to locate one study [45] but it examined ordinary people’s (the public) perceptions of ST. It was found that their understanding was limited or nil in relation to social systems and ST applications to aid the decision-making process.

A few gaps in the literature are evident:

1. No study has explored students' understanding of ST from a general perspective though there are studies that have investigated students' understanding in specific contexts. The former type of studies is needed as it can provide a perspective not constrained by contexts.
2. There is underrepresentation of undergraduate samples in ST studies in general. While undergraduates may be argued to possess more developed ST skills due to their disciplinary exposure and maturity, this assumption remains largely untested and warrants investigation.

The research question for this study is as follows:

How do undergraduates conceptualize the term 'systems thinking' when they are requested to respond to an open-ended question that sought their general understanding of this term?

2. Theoretical Frameworks

This study is anchored in two key frameworks: constructivism and ST.

The constructivist tradition emphasizes that learners actively construct knowledge based on prior experiences [46]. Students' existing mental schemata play a crucial role in determining how receptive they are to new information. When learners can connect new concepts to their prior knowledge, they are more likely to internalize and integrate these ideas into their cognitive frameworks.

The second tradition is ST itself. While core systems theories encompass a range of frameworks such as General Systems Theory and Dynamic Systems Theory and Cybernetics [2,3], only the first is relevant for our study as it argues that developing a general science of "wholeness" requires a fundamental rejection of all forms of reductionism. In conceptualizing ST, Jackson positions it as an overarching tradition that integrates multiple strands of systems-oriented thought and practice [47]. Rather than a singular method, ST is framed as a diverse intellectual landscape that draws on systems philosophies, theories, methodologies, and models to make sense of complexity and guide purposeful intervention. Though ST is a multifaceted construct, certain core elements consistently emerge across the literature. Richmond defines ST as "the art and science of making reliable inferences about behaviour by developing an increasingly deep understanding of underlying structure" [25] (p. 139) while Forrester [40] and Meadows [10] describe it as a holistic thinking that involves understanding of a system through interconnectedness and interdependence, feedback loops, causality, system boundaries, mapping, emergent behaviour over time, and synthesis. The latter would be more useful for our study, including for categorizing post-test responses as well as generating the ST attributes continuum. A theoretical framing that aligns closely with the seven attributes identified in this study can be drawn from General Systems Theory (GST) [3], system dynamics and feedback-based ST [10,19,24,40], and hierarchical/continuum models of ST development [13,14,18]. Collectively, these traditions conceptualize ST as progression from recognizing components and relationships to understanding dynamic behaviour generated by feedback structures and synthesizing insights for purposeful action. Within this framework, interconnectedness and causality correspond to GST's foundational principle that systems must be understood as organized wholes rather than as isolated parts, while mapping operationalizes this understanding through representations such as causal loop diagrams and system models. Feedback and emergent behaviour are central to system dynamics theory, which emphasizes non-linearity, circular causation, and behaviour-over-time as defining characteristics of complex systems. The attribute of system boundary reflects longstanding discussions in systems science concerning boundary judgments and contextual framing, which determine what elements and interactions are considered relevant in a given analysis. Finally, synthesis aligns with

higher-order ST as articulated where multiple perspectives, structures, and dynamics are integrated to support inference, prediction, and intervention [10,15,16].

3. Methodology

3.1. Research Design and Ethics Approval

A qualitative approach using an open-ended question was used for data collection. This allows us to mine the students' written responses for useful insights. A pre-/post- test design was used, with inductive content analysis used for data treatment at pre-test while at post-test, it was deductive content analysis [48]. We chose to position our intervention as a pre-/post- design for ease of understanding the responses from the context of this study. Approval to conduct the study was obtained from the Institutional Review Board of the first author's university. Participating students provided informed consent to take part in this study. Students were informed that the study was purely for research purposes and that their involvement in this study would in no way affect their grades in the course.

3.2. Participants

The students came from a few disciplines: science, engineering, business, computing, arts and social sciences, medicine, design and environment, and law. They signed up on their own for this course following the course registration process. Ages were in the range from 19 to 22. All students came from the first author's university. At pre-test, there were 46 students; this is because not all of them completed the test. At post-test, there were 69 students.

3.3. Course

The first author taught the course on ST on energy systems. It comprised a series of lectures, tutorials and assessment.

One of the main learning outcomes was to enable students to apply ST to create qualitative models using causal loop diagrams (CLDs) that represent a system or problem under study. This involved recognizing system elements and their interdependent relationships, identifying feedback loops, understanding dynamic behavior (the emerging behavior of different variables or key elements) because of these feedback loops (internal structures and interrelationships), and synthesizing and applying feedback loops and causality to develop qualitative models.

During the initial two weeks of instruction, the focus was on introducing the concepts and tools of ST. Students were taught that ST involves asking a few key questions when applying it to studying and modelling a system:

- Is a system identified with its elements or components?
- Do these elements or components represent the system adequately?
- Are these elements or parts interdependent and affect each other?
- Are these interdependent and circular cause and effect relationships mapped out correctly to identify and develop feedback loops?
- Do all the elements or parts together through the feedback loops produce an effect as a dynamic behaviour that is different from the effect of each individual part?
- Does this dynamic behaviour or effect over time persist under different circumstances?
- Through the above, can a system be modelled and represented as comprising feedback loops?

Thus, essentially, these questions align with the tasks and one of the key learning outcomes intended to enable students to map interdependencies among different parts of a systems to identify feedback loops and to develop causal loop diagrams as models.

Methodologically, ST and modelling offer a suite of tools for understanding complexity, including behaviour-over-time graphs (BOTGs), CLDs, stock and flow diagrams (SFDs) and system archetypes, and systemic root cause analysis [10,19,24,40]. Among these, CLDs are particularly effective for qualitative ST and modelling, enabling students to map interconnectedness and interdependencies among system components to understand causality, and it generates emergent behaviour of key system components over time. Thus, ST involves modelling the complex interactions among components within dynamic systems through a structured, qualitative methodology. This includes problem identification, proposing dynamic hypothesis (emergent behaviours), model development, simulations and policy analysis—tools that help students understand and manage complexity [40]. The development of CLDs follows a cyclic and iterative process, emphasizing continuous refinement and learning. This approach is defined by two key aspects: it progresses from problem definition to the design of learning strategies or interventions, and it generates intermediate outputs that deepen understanding of the system under study. In general, the methodology begins with problem identification, where a complex issue, system, or topic is clearly defined for exploration through a systems approach. It then moves to system conceptualization, which involves examining the problem from multiple disciplinary perspectives, mapping subsystems, and identifying non-linear, interdependent relationships among variables. Finally, the process advances to qualitative modelling, where key variables are selected to establish system boundaries, assumptions are proposed, and causal loop diagrams (CLDs) are constructed to represent the feedback structures that drive system behaviour [40].

3.4. Instrument

A simple survey on ST was developed by one of the authors. It read as follows:

What is your understanding of the term ‘systems thinking’? Elaborate as much as possible.

The other author felt that the question was adequate for the purpose of this study and that no changes are needed. That is, face validity and content validity constituted the validation process. External validity was not sought for three reasons: (a) the question was rather simple and just a line in length; (b) it would have mattered if the instrument was longer in length or complex in scope; and (c) the Flesch–Kincaid readability index was 7.2, meaning it was within the reading level of even 7th grade students.

The use of a single open-ended question is not unprecedented. Studies in science education [49–51] and mathematics education [52] have successfully employed single-question formats. Advantages include eliciting rich, free-form responses, minimizing time demands, and enabling qualitative analysis.

3.5. Procedure

In the first week of instruction, the pre-test was administered using a classroom response system called *Poll Everywhere*. Not all students completed the pre-test—some came late, others registered for the course later and a few did not respond. Students logged in and answered the question using their mobile devices. Anonymous mode was used for the polling so as to encourage as many students as possible to respond. Students were given about 15 min to complete this open-ended question. While their responses were shown on screen, their names were not displayed. The students’ responses afforded some scope for the instructor to engage with them about ST prior to the course proper.

The pre-test also afforded an opportunity to pilot-test the instrument. The first author ascertained verbally from the students whether they were clear about the phrasing of the question and whether any clarifications were needed. None of the students asked for clarifications while writing their responses. So, no change was made to the instrument for

use in the post-test. However, it was noted that most of the pre-test responses were rather brief and lacked articulation—not surprising as students were new to ST. This gave a few pointers to keep in mind when administering the post-test later.

After the completion of the course on ST on energy systems, the students were administered the post-test in hard copy. About 15 min was again given for the students to document their understanding. (Taking into account the experience with the pre-test, the first author reiterated verbally to the students during post-test administration that they needed to write in as much detail as possible). The hard copies were then collected.

3.6. Data Analysis

The pre-test and post-test responses of the students were entered into separate Excel files. The authors briefed a research assistant to classify these responses.

It is not possible for pre-and-post responses to be matched for participants. The numbers at pre-test ($N = 46$) and post-test ($N = 69$) were different for the following reasons:

1. The pre-test was conducted via electronic polling at the start of the course. It was configured in anonymous mode so as to get as many of the students to share in writing their conceptualization of what is ST.
2. Not all students took the pre-test at the start of the course. Some came late for the lesson while others registered for the course only later. As a result, the number of pre-test responses are lower than the post test.
3. Since the pre-test was done via anonymous mode while the post-test was done using students' names, it is not possible to match their responses.

We wished to preserve the uniqueness of the data for the pre-test and post-test, and that is why we used the entire data sets for this study.

It is not the intent of the study to grade the responses of the students according to assessment rubrics. While this would provide a numerical score, it lacks depth in terms of the range of conceptualizations inherent in the responses. Likewise, it is not our intent to explore how students responded according to their disciplinary specializations; this is because within each specialization, there were inadequate numbers to do a proper comparative analysis. Thus, analysis was done on the entire sample.

At pre-test, the students expressed their understanding of ST rather briefly and somewhat generally. As a result, inductive qualitative content analysis was used to examine the data [53]. This entailed going through the students' responses to get a feel for the distribution of the data. Another read-through was done slowly to see what strands of commonalities emerged from the responses. Next, each student's response was examined carefully. It was found that detailed coding to unpack nuances in students' responses was not productive as the responses were rather brief. Instead, we found that the coding led to three strands of thought in the students' responses, and these were operationalised as follows:

- Naïve: Rather simplistic mention of conceptualization of ST.
- Acceptable to limited extent: Responses are not wrong when viewed through a broad lens but not expressed in the lingo of the discipline.
- Informed to some extent: Responses demonstrate elements of some conceptualisation of what ST is but lacks depth.

The inspiration for the coding came from the Nature of Science literature, where it is common to code students' responses to questions as uninformed, naïve or informed [54]. However, taking into account the nature of the responses for this study, we found that the above bulleted categorizations would be more appropriate to represent the three levels of conceptualisations inherent across the responses. These were tabulated, and their overall prevalences documented.

Examination of the responses elicited at post-test showed students were using the vocabulary of ST in their responses to varying extents. These responses were explored using deductive qualitative content analysis [55] and this was found to be adequate rather than exploring emergent themes at the nuanced level. We used common categories from ST to code the responses in a deductive manner, and this was found to be adequate for all the responses. The categories are as shown in Table 1.

Table 1. Nature of attributes used in coding post-test responses.

Attribute Number	Attribute	Definition [6,10,13,15,17,40]
1	Interconnectedness/Interdependence	ST involves understanding interconnections and interconnectedness among system components.
2	Feedback	ST is a closed-loop thinking to understand feedback loops operating in system.
3	Causality	ST is to understand cause and effect relationships in a system.
4	Systems boundary	ST is to understand the system boundary by identifying its components and what is considered relevant within a system.
5	Mapping	ST involves mapping interdependent interactions among system components.
6	Emergent behaviour or behaviour of a system over time	ST is to understand the emerging behaviour patterns of a system over time.
7	Synthesis	ST involves the segmentation of complex problem into parts/components and then integrating them into new models containing feedback loops to derive and interpret emerging dynamic behaviours.

Each response was examined carefully and coded appropriately. Where the relevant attribute manifests in the responses, it was assigned this label. It has to be noted that there could be more than one attribute manifesting in the response, so this was also coded as such. Similarly, the remaining responses were coded and the attributes emerging were labelled against the respective response. In this way, all the responses were coded and the prevalence of the relevant attributes documented.

The classifications arrived at by the research assistant for pre-test and post-test was independently checked by both authors. An inter-rater agreement of 0.85 was obtained for the classification of responses for pre-test while that for post-test was 0.90. These were considered good indicators of the efficacy of the coding process [56]. A reason why the inter-rater agreement did not attain unity for the pre-test responses was that a few responses could be classified into more than one category—for example, the response on ‘It is about thinking as a whole’ could be parked into either of the two latter categories. As the agreement exceeded the recommended norm, the authors did not aim for consensus in categorizing such responses. That for post-test was found to be adequate, and again the authors did not aim to achieve unity for the rating.

We also sought to see to what extent the students’ responses can be classified into a continuum so that it flows from inadequate conceptualization to full conceptualization. For this, we examined the responses to see whether these can be classified as such. In respect to inadequate conceptualization, as long as one attribute was seen in the students’ responses, it was classified as such. At the upper end of the continuum, we looked for full conceptualization, that is, all seven attributes emerging from the analysis need to be

present. The interval spanning these ends contains other varying conceptualizations of the term.

To further check on the coding of the post-test responses, two undergraduates, both of whom had obtained a distinction in the course from another cohort, were asked to check on the fidelity of the coding process independently for [prevalence of ST attributes in student's responses at post-test, number of attributes for ST seen in students' responses at post-test and the attributes continuum figure. For combinations of attributes, a plus (+) sign was used. They concurred fully with the coding, with their inter-rater agreement being 1.0.

4. Results

The pre-test data (Table 2) showed that students generally had very limited understanding of ST. Their responses were generally short and not elaborated upon. Even those who seemed to have some understanding couched it in somewhat general terms. Briefly, very few students' responses can be classified as being even satisfactory. All the students' responses are shown in Table 2.

The responses show that the students have varying preconceptions about the term 'systems thinking.' Most students seem to have some fuzzy ideas of ST, but their responses were given as short phrases, with no elaboration—and this complicated further analysis. In other words, most of the seven ST attributes, which arose from the data in post-test, did not manifest in the pre-test data. Thus, we focus more on the post-test data to explore students' conceptualization of ST.

Table 3 shows the range of attributes as well as their prevalences in students' conceptualisation of ST at post-test. As can be seen, most students have indicated at least two attributes. Very few students mentioned all attributes in their responses. Sample responses of these are also presented.

A commentary on the classified responses obtained in post-test (Table 3) from the lens of ST is now presented. The table provides a nuanced picture of students' post-test conceptualization of ST by mapping the prevalence of different combinations of seven core attributes alongside representative responses. A striking finding is that only two students (2.90%) demonstrated full conceptualization, incorporating all seven attributes in their responses. These responses are qualitatively rich, integrating elements such as system components, dynamic behaviour, causal interactions, and modelling tools (e.g., causal loop diagrams), and often explicitly referring to reinforcing and balancing effects. For instance, the exemplar responses emphasize how "one variable...can cause impacts...whether it reinforces or diminishes it," reflecting an advanced understanding of feedback-driven dynamics and holistic system behaviour. Such responses approximate canonical definitions of ST and illustrate a coherent synthesis of structure, behaviour, and modelling. Beyond this small group, a larger proportion of students exhibited predominant but incomplete conceptualizations, typically involving five to six attributes. For example, eight students (11.59%) demonstrated six attributes (excluding feedback or boundary), while several others expressed slightly different six-attribute combinations. Their responses frequently included references to interdependence, causality, mapping, and emergent behaviour, often framed in terms of analyzing complex systems or predicting outcomes. Sample responses in this category show growing fluency in ST vocabulary, including notions such as "interconnected relationships," "causal links" and "system behaviour over time." However, the omission of specific attributes—particularly feedback or system boundaries—suggests that while these students can articulate structural and analytical aspects of systems, they are still developing a more complete understanding of system dynamics and delimitation. The largest concentration of responses lies within the moderate and partial ranges, typically involving three to five attributes, indicating that most students achieved only a mid-level understanding of

ST. Notably, combinations such as interconnectedness, causality and mapping accounted for 13.04% while interconnectedness and mapping had 14.49%, representing some of the most common response patterns. These responses frequently foreground the “big picture” perspective, the interconnectedness of variables, and the identification of relationships within a system. For example, students describe ST as “seeing how one variable can affect the rest” or as understanding “interactions between factors.” While such responses indicate meaningful progress beyond pre-test conceptions, they remain largely structural rather than dynamic, with limited engagement with feedback loops, temporal evolution, or system boundaries. This suggests that students are more comfortable identifying relationships than reasoning about how these relationships generate behaviour over time. At the lower end of the spectrum, a smaller but noteworthy group of students demonstrated minimal or fragmented conceptualizations, with responses containing only one or two attributes. Although no student produced a completely null response, some responses were restricted to isolated ideas such as linking variables, broad perspective-taking, or general analytical thinking. These responses lack integration and often fail to distinguish ST from generic problem-solving or critical thinking. Even when causality or mapping is mentioned, the absence of other attributes—particularly feedback and emergence—indicates a limited grasp of systems as dynamic and self-regulating entities. Overall, the distribution of responses in Table 3 reveals a clear gradient of conceptual sophistication, with the bulk of students occupying intermediate levels and only a very small minority achieving full integration of ST attributes. The accompanying sample responses reinforce this interpretation by illustrating how conceptual depth varies not only in the number of attributes included but also how coherently these are articulated. Importantly, the data suggests that students tend to privilege interconnectedness, causality, and mapping—attributes that are more intuitive and structurally oriented—while underrepresenting feedback, system boundaries, and synthesis, which require higher-order reasoning. Thus, although the intervention appears to have expanded students’ conceptual repertoire, their understanding remains uneven, with a persistent gap between recognizing system structure and fully engaging with systemic and holistic integration.

Another commentary on the cognitive transition from linear to systemic reasoning from pre-test to post-test is now presented. Comparison of Table 2 (pre-test) and Table 3 (post-test) generally reveals a clear cognitive transition from predominantly linear and reductionist reasoning toward more systemic and relational thinking, albeit with varying degrees of depth and integration. At the pre-test stage, students’ responses were largely fragmented, generic, and decontextualized, reflecting what may be characterized as proto-conceptual or linear cognition. Many responses reduced ST to general-purpose cognitive skills such as “critical thinking,” “logical thinking,” or “analysis thinking,” without reference to system structure or dynamics. Even when slightly more developed, responses were typically expressed as isolated ideas—for example, “It is about thinking as a whole” or “Thinking to seeing the big picture”—which, while suggestive of holistic intent, lacked operational meaning and did not engage with mechanisms such as causality or feedback. Such expressions indicate that students’ initial understanding was primarily linear and descriptive, focusing on either individual elements or vague notions of aggregation, rather than on structured interrelationships or dynamic processes. In contrast, the post-test responses in Table 3 demonstrate a marked shift toward systemic reasoning, characterized by explicit recognition of interdependencies, causal relationships, and interactions among system components. A substantial proportion of students began to articulate ST in terms of linked variables and cause–effect chains, as reflected in responses such as “seeing how one variable can affect the rest of the variables in the system” and “identify the cause and effect of a situation and how it affects other components”. This shift signifies movement beyond

linear cause–effect thinking toward multi-variable causality embedded in a network of relationships, a foundational aspect of systems reasoning. Importantly, the frequent co-occurrences of attributes such as interconnectedness, causality, and mapping in Table 3 suggests that students are beginning to structure their thinking relationally rather than sequentially, marking a departure from the pre-test tendency to conceptualize this in isolation. The transition is further evidenced by the emergence of dynamic and temporal reasoning in post-test responses, which is largely absent in the pre-test data. For instance, several responses refer to how systems “change over time,” how variables interact to produce “behaviour,” or how interactions can “reinforce or balance” outcomes. These formulations indicate an incipient understanding of non-linearity and feedback-driven dynamics, even if not consistently or fully articulated across the sample. By contrast, pre-test responses contained virtually no reference to temporal evolution or system-generated behaviour, underscoring the extent of the conceptual shift. The inclusion of modelling language—such as “stocks,” “flows,” and “causal loop diagrams”—in some post-test responses further signals a move toward operationalizing ST, transforming it from an abstract notion into a tool to privilege varying levels of complexity. Despite this progression, the comparison also highlights that the cognitive transition is generally partial and uneven. While many students moved from linear to relational thinking, relatively few achieved fully systemic reasoning that integrates feedback, boundaries, and synthesis. For example, only a small subset of post-test responses explicitly address feedback processes or system regulation, and even fewer incorporate boundary considerations or holistic synthesis of all attributes. This suggests that students often transition first to a “relational-structural” stage, where they recognize interconnectedness and causality, but do not yet fully grasp closed-loop dynamics or system-level integration. In this sense, the cognitive shift resembles a progression from simple linear chains to interconnected networks to (emerging but incomplete) dynamic systems models. Illustratively, a pre-test statement such as “Systems thinking is about how a system works like car or laptop” reflects a concrete and object-based understanding, whereas a post-test response such as “one variable. . .can cause impacts to other parts of the system, whether it reinforces. . .or balances. . .over time” demonstrates a more abstract, process-oriented, and dynamic conceptualization. Similarly, the shift from viewing ST as “critical thinking” to describing it as analyzing “interdependent relationships. . .to predict behaviour” marks a transition from generic cognition to domain-specific systems reasoning. Overall, the comparison between Tables 2 and 3 indicates that the instructional intervention facilitated a reasonable cognitive reorientation, moving students away from reductionist and linear perspectives toward more complex, interconnected, and partially dynamic representations of systems. However, the persistence of gaps—particularly in higher-order attributes such as feedback, boundary delineation, and synthesis—suggests that while students have generally begun to think systemically, their reasoning remains transitional, situated between relational awareness and full systems integration.

Another indication of the conceptualization of ST in students can be seen from the number of attributes seen in their responses (Table 4). Very few students were able to showcase the full complement of attributes. Two students exhibited all seven attributes in their responses while nine students had only one attribute missing. More than half of the samples exhibited about 3–5 attributes in their responses. Sixteen students have two or fewer attributes in their responses. Of concern is that there are students who obtained only one attribute correctly. There were no null responses from the sample.

Table 2. Pre-test data for students' conceptualization of ST.

Naïve	Acceptable to Limited Extent but Not Grounded Canonically	Informed to Some Extent
It is a sort of thinking to see what is there in a system.	Critical thinking	Able to identify causalities and interconnectedness of a system
Systems thinking is about collection of knowledge together to understand a system.	Analysis thinking	Interconnected thinking
Systems thinking involves systematic analysis	Logical thinking	Thinking to seeing the big picture
Understanding about systems	Analytical and clear	Holistic thinking
It is systematic thinking like flow charting	Critical thinking	Systems thinking is understanding how each part of the system affects one another
Thinking fearlessly challenging assumptions	Logical and systematic thinking	Systems thinking is about how a system works like car or laptop
Inquisitive thinking	Insightful thinking	We need to think a question including nearly every relevant element into consideration and analyze the connections and interactions within the whole system.
Rational thinking	It is about thinking as a whole	Examining and modelling a dynamic pattern of behaviours that arise from a number of different variables interacting with each other.
Any forms of behaviour are likely to be from a system, and a system can always be part of another system.	Thinking and looking things at a broad perspective	It is a way to seeing an individual thing but as a part of the system
It is a systematic approach to analyze to predict the outcome of the system.	Looking at various systems around us as there are many factors intertwined.	Systems thinking is about a different point of view to consider more connected relations and related things.
To study Correlation		Bigger picture, all affect one another.
Delays patterns language		Systems thinking is a way of effective thinking to solve a problem, ability to put things together and form a "system."
Addiction. Small Action Big Result. Wrong Goal Direction. Distancing.		Systems thinking is about all the factors should be interconnected and dependent on one another.
Systems thinking is simplifying language		Systems thinking is the in-depth analysis of systems see between possible components.
Systems thinking is a skill used to see clearer understanding to solve a problem.		
It is a qualitative analysis about a system		
"Systems thinking" means looking at different view of a problem and solve it		
Methodical thinking		
It is about causation		
Interconnected.		
Interconnectivity		
A thinking oriented around the existence of concepts of systems		
22 (47.82%)	10 (21.74%)	14 (30.43%)

Note: % do not add up to 100% owing to rounding off.

Table 3. Prevalence of ST attributes in student's responses at post-test (N = 69).

ST Attribute	Prevalence (Number/%)	Sample Responses
1 + 2 + 3 + 4 + 5 + 6 + 7	2 (2.90)	Systems thinking is understanding a system and its parts, and how the system's behaviour is affected by its parts, through the use of dynamic hypothesis and CLDs. Systems thinking to me is about taking on the perspective that almost everything can be seen as a system, and we can study how one variable, no matter how small or insignificant, can cause impacts to other parts of the system, whether it reinforces the phenomenon or diminishes it by balancing. Overall, the study of systems allows us to see the big picture.
1 + 3 + 4 + 5 + 6 + 7	8 (11.59)	System thinking is a method of processing complex data and hypothesising the results. When there are many factors in a system, their interconnected and interdependent relationships are no easy to predict, hence using system thinking will help with the process. By considering how each variable interacts with one another, we can see the bigger picture of how the system will change over time. This is the qualitative analysis. Assigning values to the variables and observing outcome will be the quantitative analysis. Thinking about the world as a whole, rather than its individual bits. It can be applied at any scale: e.g., computer needs a processor, motherboard, RAM, Graphics card to work and each component may have a job, but they must work as a whole to display emerging behaviour. Another example is the global economy. Each country's economic policies do not determine how well the country is in as it is affected by those globally.
1 + 2 + 3 + 5 + 6 + 7	1 (1.45)	It is a sort of thinking that allows people to identify stocks, flows, variables, and constants and see the interconnection and interaction between a set of elements, and thus draw feedback loops, SFD, CLD, etc. to predict the behaviour if the elements over time.
1 + 3 + 5 + 6 + 7	6 (8.70)	It is a sort of thinking that allows people to identify stocks, flows, variables, and constants and see the interconnection and interaction between a set of elements, and thus draw feedback loops, SFD, CLD, etc. to predict the behaviour if the elements over time. System thinking is the analytics of interdependencies of factors that contribute of a specific behaviour in a system. By identifying factors involved, we can account for reasons behind phenomena and also formulate policies for control
1 + 2 + 3 + 5 + 7	4 (5.80)	System thinking is think not just based on basic linear causal relationship but looking how one change in an element might bring about another change in other element might bring about another change in other elements through feedback loops. It makes us think how system interacts, interdependent, and interconnected. Thinking in systems. Expanding our mental models into more complicated models so that we can examine them further through feedback qualitative loops and quantitative analysis to make better and more informed decisions
1 + 2 + 3 + 5	1 (1.45)	Systems thinking is a concept where things are interrelated and connected. Understanding how different factors come together and balances or reinforces each other.

Table 3. Cont.

ST Attribute	Prevalence (Number/%)	Sample Responses
1 + 4 + 5 + 6	1 (1.45)	Systems thinking is a way of thinking such that when there are different things come into your mind, you can put them together, find some or many causations between them or even come out with a behaviour presumption based on them. It is like the ability to put things together and form a “system.”
1 + 3 + 5 + 7	3 (4.35)	Systems thinking is about visualising a problem in a system way in which we identify the cause and effect of a situation and how it affects the other components in the system. Systems thinking is about the interdependence of the various involved components in which they need to work together for it to be an effective system. Systems thinking is a concept where things are interrelated and connected. A certain factor can be affected by a multitude of other factors, and all these combined create a system. Thinking of things as individual items may restrict one’s perception of how such things operate in the real world, and systems thinking adds a layer of depth to one’s understanding.
1 + 3 + 4 + 5	4 (4.35)	Systems thinking, to me, is a way of simplifying the constraints in a system and identifying that everything is connected. How important each variable is to contribute to that factor also plays a part but primarily, we must be able to identify each relationship between each variable so we can build a bigger picture of the issue at hand and formulate out a plan that is relevant. System thinking is the mindset to think in systems—to understand and analyse the interconnectedness and interrelations between different variables in a complete and complex system and therefore make use of these connections to anticipate long term situations and device on the most effective polices to tackle this problem.
1 + 5 + 6 + 7	1 (1.45)	A mindset of thinking oriented around the existence of concepts of systems, which are sets of variables that are interconnected and interdependence on one another and may exhibit certain behaviours that are more than the sum of its parts.
1 + 3 + 5	9 (13.04)	Systems thinking is a skill used to see the bigger picture. It helps us to see how one variable can affect the rest of the variables in the system. Using systems thinking, it enables us a clearer understanding and helps us to better strategize the approach we can take or improve if needed. Systems thinking is the understanding of all independent, interconnected and interactions between each factor.
1 + 5 + 6	2 (2.90)	The interconnection between the different variables that simulates the dynamic of an entire system. I understand systems thinking as a form of analytical thinking where practitioners identify and analyse the interconnected and interdependent relationships between the different variables within a system. They then leverage these relationships to predict future outcomes or trends of the different variables and form conclusions about them.
3 + 5 + 6	1 (1.45)	The thought process of thinking non-linearly and considering impacts variables may have on each other (as opposed to cause-and-effect), to a system structure and its behaviour.

Table 3. Cont.

ST Attribute	Prevalence (Number/%)	Sample Responses
1 + 4 + 5	2 (2.90)	It is about thinking of systems as a whole, looking at boundary and things within the system as many interconnected parts rather than individual parts.
1 + 5	10 (14.49)	The interaction between the variables within an ecosystem and the complexities of how often times there are many factors intertwined. Systems thinking involves the links drawn within a system as well as the extension to form relations.
1 + 6	1 (1.45)	A combination of multitude of factors culminating in a sense of interactions in which are in a way interdependent to produce a behaviour over time
1 + 7	2 (2.90)	Systems thinking is the construction of mental models to best illustrate different processes and stakeholders in a system that are interdependent and interconnected with one another. After the model is formed, it is the job of the systems thinker to devise plans and policies to achieve the most optimal leverage on the system to best solve a problem over time. It is to keep an open mind and be able to look at the bigger picture. It is to think meticulously how one system can interconnect and influence other factors and may result in unintended consequences. To solve real world problems, it is extremely important as we hope to minimise risk and look for a balance.
1 + 3	4 (5.80)	It is about identifying what are the factors and how they affect each other. Systems thinking is the process of viewing everything as a system of smaller things that are always interacting with and affecting one another.
5 only	2 (2.90)	System thinking is about the looking things at a broad perspective, separating into different component and analysing the system. System thinking is about the looking things at a broad perspective, separating into different component and analysing the system.
6 only	1 (1.45)	Systems thinking" means looking at different view of a problem and thus identify the behaviours that the system will exhibit.
1 only	0 (0.0)	Not seen in the responses
2 only	0 (0.0)	Not seen in the responses
3 only	3 (4.35)	It is a method to link different factors together. Linking different variable together systematically
4 only	1 (1.45)	Systems thinking involves the links drawn within a system as well as the extension to form relations.

Table 3. Cont.

ST Attribute	Prevalence (Number/%)	Sample Responses
1 + 2 + 3 + 4 + 5 + 6	0 (0.0)	(Not seen in responses)
1 + 2 + 3	0 (0.0)	(Not seen in responses)

Attribute: 1 (interconnectedness/interdependence); 2 (feedback); 3 (causality); 4 (systems boundary); 5 (mapping); 6 (emergent behaviour or behaviour of a system over time); and 7 (synthesis).

Table 4. Number of attributes for ST seen in students' responses at post-test (N = 69).

Number of ST Attributes	Combination of Attributes	Number Students	Total Number Students	% Sample	Conceptualization Category
7	1 + 2 + 3 + 4 + 5 + 6 + 7	2	2	2.90	Full
6	1 + 3 + 4 + 5 + 6 + 7 1 + 2 + 3 + 5 + 6 + 7	8 1	9	13.0	Predominant
5	1 + 3 + 5 + 6 + 7 1 + 2 + 3 + 5 + 7	6 4	10	14.9	
4	1 + 2 + 3 + 5 1 + 4 + 5 + 6 1 + 3 + 5 + 7 1 + 3 + 4 + 5 1 + 5 + 6 + 7	1 1 3 4 1	10	14.9	Modest
3	1 + 3 + 5 1 + 5 + 6 3 + 5 + 6 1 + 4 + 5	9 2 1 2	14	20.29	Partial
2	1 + 5 1 + 7 1 + 3 1 + 6	10 2 4 1	17	24.64	
1	3 4 5 6	3 1 2 1	7	10.14	Inadequate
Total = 69					

Note: ST attributes number is the same as footnoted in Table 3. The plus (+) signs means combinations of these.

Keeping in mind the range of attributes seen in students' responses, we attempted to come up with an 'attributes continuum' for the samples based on Table 3. This can be another way of looking at the students' responses from a holistic standpoint. The continuum spans the interval from inadequate to fully correct. Since at least one attribute is seen in the responses of all the students, the continuum does not start from fully incorrect. Figure 1 shows the attributes continuum for the sample's conceptualisation of ST. From the base to the top, there is a progressive increase in number of attributes seen for ST in the students. At the furthest end of the continuum, all seven attributes are seen. Sample responses are also shown in the continuum.

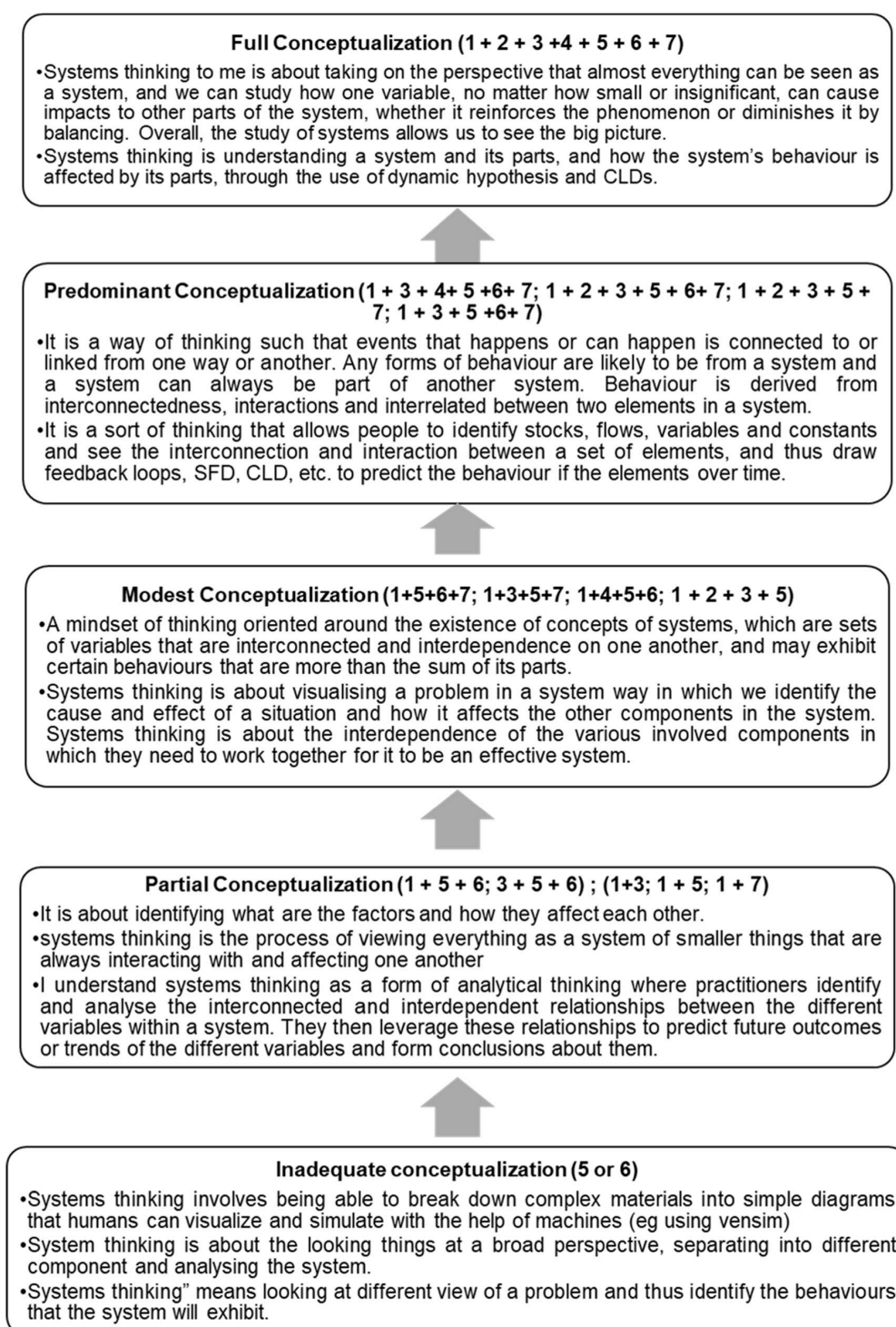


Figure 1. Attributes continuum for students' conceptualization of ST at post-test with sample responses.

The attributes continuum depicted in Figure 1 reveals a clear progression in students' conceptualization of ST, ranging from inadequate to fully developed understanding. At the lowest end, inadequate conceptualization is characterized by minimal engagement with ST attributes, typically reflecting only a single idea such as simple linkage or association. Responses at this level seem to be reductionist and fragmented, indicating an absence of systemic reasoning, causal depth, or recognition of dynamic interactions. For example, a representative response under this category states, "It is a method to link different factors together". Moving along the continuum, partial conceptualization reflects an emerging awareness of systems, with students incorporating two to three attributes—most commonly interconnectedness and basic causality. While these responses indicate a shift toward relational thinking and recognition of the interdependent components, they remain structurally descriptive and lack integration of higher-order features such as feedback loops or emergent behaviour. A typical illustration is: "Systems thinking is the process of viewing everything as a system of smaller things that are always interacting with and affecting one another". At the modest conceptualization level, students demonstrated a more developed understanding by incorporating approximately four attributes. Their responses begin to reflect structured reasoning that integrates causality, interdependence, and elements of system representation. Although these students can describe how components interact within a system and recognize cause–effect relationships, their explanations remain incomplete due to inconsistent inclusion of key higher-order elements such as feedback mechanisms, system boundaries, or synthesis. A representative response notes, "Systems thinking is about visualizing a problem in a system way in which we identify the cause and effect of a situation and how it affects the other components in the system." Further up the continuum, predominant conceptualization reflects advanced but still incomplete ST, typically involving five to six attributes. Students at this level demonstrate coherent integration of structural and dynamic aspects of systems, including interconnections, causality, mapping, and aspects of emerging behaviour over time. Their responses often reference modelling approaches such as feedback loops or causal loop diagrams, indicating a developing ability to analyze and predict system behaviour. However, the absence of one or more critical attributes—most frequently feedback or boundary definition—prevents full conceptualization. An illustrative response states, "It is a sort of thinking that allows people to identify stocks, flows, variables, and constants and see the interconnection and interaction between a set of elements and thus draw feedback loops. . . to predict the behaviour of the elements over time." At the highest level, full (canonical) conceptualization represents comprehensive ST, where all seven attributes—interconnectedness, feedback, causality, systems boundary, mapping, emergent behaviour, and synthesis—are present and coherently integrated. Students at this level demonstrate holistic and dynamic reasoning, articulating how system structure gives rise to behaviour over time and how multiple elements interact through reinforcing and balancing processes. Such responses reflect mature understanding and the ability to conceptualize systems as complex, adaptive wholes. A representative example is: "Systems thinking is understanding a system and its parts, and how the system's behaviour is affected by its parts. . . we can study how one variable. . . can cause impacts to other parts of the system. . . Overall, the study of systems allows us to see the big picture." To sum up, the continuum illustrates a qualitative shift from linear and fragmented notions toward increasingly integrated, dynamic, non-linear and holistic thinking and reasoning. This progression underscores the cognitive complexity of ST, with higher levels requiring the simultaneous coordination of multiple attributes, particularly feedback, emergence, and synthesis.

Yet another way of looking at the span of ST abilities is to see what attributes are occurring as a function of frequency when averaged out over all the responses of the students.

Table 5 presents such an analysis. Attributes 1 (interconnectedness/interdependence) and 5 (mapping) were present in almost all the students' responses while attribute 3 (causality) was present in most of the students' responses. Attribute 2 (feedback) was present in the lowest number of students.

Table 5. Individual attributes of ST seen in students' responses at post-test (N = 69).

Attribute Number for System Thinking	Prevalence of Specific Attribute (Number of Responses)
1 Interconnectedness/interdependence	67
2 Feedback	9
3 Causality	54
4 Systems boundary	20
5 Mapping	65
6 Emergent behaviour or behaviour of a system over time	29
7 Synthesis	27

Based on Tables 2 and 3, threshold concepts [57] that were problematic can be identified by looking for responses and ideas that

- Are initially absent or are poorly articulated in pre-test responses (Table 2);
- Emerge unevenly and with difficulty in post-test responses (Table 3), especially with low prevalence or partial integration;
- Represent transformative shifts from naïve/linear thinking to systemic reasoning.

From this comparison, certain threshold concepts in ST stand out (Table 6). (Please shift this sentence one line below).

Attributes such as interconnectedness/interdependence and mapping are excluded as threshold concepts because they are highly prevalent in post-test responses (67 and 65 respectively) as well as partially evident even at pre-test, indicating they function as foundational or enabling concepts rather than transformative thresholds.

Table 6. Threshold concepts noted in undergraduates' conceptualization of ST.

Concept	Empirical Evidence (Tables 1 and 2)	Prevalence/Difficulty in Articulation	Conceptual Transformation Required	Threshold Characteristics (Justification)
Feedback (closed-loop thinking)	Absent in pre-test; least mentioned attribute post-test (9 responses)	Very low prevalence and articulation.	Shift from linear causation to recognizing reciprocal, circular interactions within systems.	Feedback is a key threshold concept because it shifts students' conceptualization from linear cause–effect reasoning to recursive, circular causality, which is often counterintuitive and difficult to internalize.
Systems boundary	Not evident in pre-test; low representation post-test (20 responses)	Low prevalence and articulation	Diffuse “holistic” thinking to explicit delimitation of system scope. Reframing boundaries as constructed and flexible, rather than fixed or given.	This concept is transformative as it requires students to critically determine what to include or exclude in a system, challenging the assumption that systems are fixed and instead revealing them as constructed and context-dependent. It requires judgement, ontologically transformative (redefines system vs. environment) and discipline-specific gateway for modelling.

Table 6. *Cont.*

Concept	Empirical Evidence (Tables 1 and 2)	Prevalence/Difficulty in Articulation	Conceptual Transformation Required	Threshold Characteristics (Justification)
Emergent behaviour (behaviour over time)	Absent in pre-test; moderate occurrence post-test (29 responses)	Moderate uptake and articulation	Transition from focusing on isolated events to understanding patterns and behaviours that arise over time through the interdependent interactions of system components.	Transformative (whole $\neq$ sum of parts), integrative (requires feedback and causality), threshold-like liminality (partially grasped but inconsistently applied). The concept of emergence is troublesome because it requires understanding that system-level non-linear emergent behaviour patterns arise from interdependent interactions and feedback processes over time, not from individual components alone, demanding a departure from reductionist thinking.
Synthesis (integration of ST attributes)	Not visible in pre-test; full integration seen in only 2 students ($\approx 2.9\%$)	Very low prevalence; persistently difficult	Fragmented attributes to coherent, systemic understanding. Moving from fragmented and individual attributes of ST concepts to integrating them into a cohesive, holistic understanding of system behaviour.	Synthesis represents capstone threshold concept by requiring students to integrate multiple systems thinking elements into a coherent whole, moving beyond isolated understanding to holistic reasoning (signals stable conceptual shift).
Causality (non-linear/systemic)	Minimally and simplistically expressed in pre-test; widely present post-test (54 responses)	High prevalence but often linearised	Shift from simple, direct cause–effect reasoning to appreciating complex, non-linear relationships involving delays, feedback loops, and indirect effects	Foundational threshold and acts as a gateway concept enabling understanding of feedback and emergence. Non-linear causality is transformative as it disrupts simple, direct cause–effect assumptions and introduces complexity, delays, and indirect effects that are often difficult for learners to grasp.

5. Discussion

The study sets out to explore undergraduates' conceptualization of the term 'ST,' as articulated in their own words. In the process, we also sought to see what are the key attributes of ST that surfaced in their written expressions. This was both before and after they had undergone a course on ST on energy systems.

The pre-test results (Table 2) reveal how students initially conceptualized ST before formal instruction. A good proportion of the responses (47.8%) fell within the naïve category, offering definitions that are simplistic or fragmented, such as equating ST to flowcharting or describing it merely as “a sort of thinking to see what is in a system.” These responses indicate minimal engagement with systemic complexity and a tendency to focus on isolated elements or basic problem-solving. Approximately 30.4% of the responses are informed to a certain extent, demonstrating limited understanding through references to concepts like interconnectedness, holistic thinking, and the examination of dynamic patterns. While these students acknowledge relationships and broader perspectives, their interpretations lacked rigorous application of systemic principles. The remaining 21.7% provided definitions that are acceptable but not canonically grounded, employing terms such as critical thinking, logical and systematic thinking, and insightful thinking, which suggest an appreciation for complexity but fail to incorporate essential constructs like feedback loops, boundaries, and emergent behaviour. Collectively, the data indicates that although 78.3% (Table 2) of the students moved beyond naïve views, their conceptualizations predominantly em-

phasize big-picture thinking and interconnectedness rather than the deeper analytical and integrative dimensions required for mature ST. In other words, most of the seven ST attributes, which arose from the data in post-test, did not manifest in the pre-test data. That is, reductionist thinking is basically at work at pre-test.

The post-test data shows the results of the intervention, that is, after the course on ST on energy systems. The students have now shown modest enhancements in their understanding of ST. From pre-test to post-test, there is, overall, progression in ST attributes seen in their responses but to varying extents. While this can be regarded as evidence of increase in cognitive complexity in their responses [58], it is not uniformly spread across all samples. That is, individual differences exist across the responses [59].

When assessing the range of attributes present in students' conceptualization of ST, it was fortuitous that the content analysis with deductive coding at post-test unpacked seven key attributes in the responses—interconnectedness/interdependence, feedback, causality, systems boundary, mapping, emergent behaviour or behaviour of a system over time and synthesis. That is, none of the students' responses elicited attributes that were not present in this set. Overall, our findings support the stance that ST is a challenging type of thinking, and, in this respect, our findings are in line with what others have reported in various contexts [44,60,61].

A unique feature of this study is the framing of the 'attributes' continuum, based on the overall responses. The continuum spans the range from inadequate conceptualization to fully correct conceptualization. Examination of this continuum can give us a snapshot of the overall state of ST in the sample of students. As can be seen, the 'attributes' continuum becomes more sophisticated when progressing up vertically. At the lower end, there are a few students who display a very small number of attributes, while in the middle section, there are more students who exhibit 4–5 attributes. Very few students displayed the full range of attributes, as can be seen at the top end of the continuum. What this means is that the sample displays, overall, modest ST abilities. It can be seen from the examples of full conceptualization that these students were able to relate all seven components of ST, that is, they can see the big picture such as understanding of its components, and how the behaviour of a system is generated by reinforcing and balancing feedback loops operating in a system. On the other hand, responses that border on inadequate conceptualization indicate very few attributes of ST. These students indicated only one or two attributes, and missed other key ones pertinent to mapping causation and feedback loops. Other examples of inadequate conceptualization indicate that students thought ST is to consider the correlation and order of different events and linking different variables together systematically. Here, students missed the idea that ST begins with understanding causation but not correlations, although correlations can be established by studying the emerging behaviour of different systems variables generated by feedback loops operating in a system. Looking at the examples of partial conceptualisation, these students employed two to three attributes and viewed ST as a form of analytical thinking for identifying and analyzing the interconnected and interdependent relationships between different variables within a system, leveraging these relationships to predict the behavioural trends. Under modest conceptualization in the continuum, students were able to indicate four attributes to support their conceptualization about ST that it involves visualizing a problem as part of a system, identifying cause-and-effect relationships, and understanding how these affect other components. These students also emphasized the interdependence of various elements, which must work together for the system to function effectively. Under predominant conceptualization category, students were able to indicate 5–6 attributes to define ST as a way of thinking that enables people to identify stocks, flows, variables, and constants, and understand the interconnections and interactions between elements to

create feedback loops and causal loop diagrams (CLDs) and predict the behaviour of these elements over time.

The distribution of responses across the different ST attributes (Table 4) offers insights into how students conceptualize ST. The high prevalence of interconnectedness/interdependence (attribute 1: 67 responses) and mapping (attribute 5: 65 responses) suggests that students primarily view ST as the ability to identify relationships among components—indicating a strong foundation in structural and relational analysis. Causality (attribute 3: 54 responses) also ranks highly, showing that many students understand systems in terms of cause–effect dynamics, which reflects logical and analytical thinking. However, the low recognition of feedback (attribute 2: 9 responses) and systems boundary (attribute 4: 20 responses) points to a more limited grasp of dynamic and contextual aspects of systems, such as how systems self-regulate or where their limits lie. Moderate responses for emergent behaviour (attribute 6: 29 responses) and synthesis (attribute 7: 27 responses) suggest that while some students are beginning to engage with more complex and integrative aspects of ST, these concepts are not yet central to their conceptualizations.

In terms of individual ST attributes, the one related to feedback featured minimally in students' written responses—only nine. Previous studies on ST in certain contexts have reported that students have considerable difficulties in cognizing this attribute [62–64], and, in this respect, our findings are not surprising. This suggests that the attribute on feedback is a higher-order ST skill to cognize. Not all phenomena or systems can be modelled directly through feedback loops as it depends on the level of complexity of the system under study. Recognizing and understanding interconnectedness and interdependencies (cause-and-effect relationships) to identify feedback loops is core to ST [7,14,25]. However, even educated adults without ST training tend to lack skill in this ability [65]. While inability to think about ST in terms of closed-loop thinking for identifying the feedback loops can be seen as low-order skill, ability to map and characterize feedback loops with increasing accuracy represents a higher-order ST skill [18,19]. These challenges are well documented, with learners typically performing better on structural or causal descriptions than on closed-loop reasoning or boundary judgments [66–68]. However, in line with the key aspects of ST that the students were taught, 65 students indicated ST attribute as mapping out interconnectedness/interdependencies in a system and 50 students mentioned causality as an attribute of ST (Table 4). This shows that most of the samples were able to recognize that ST essentially involves understanding interdependent cause-and-effect relationships among variables for developing feedback loops. It is gratifying that almost all students had no issues in indicating the attributes of interconnectedness/interdependence and mapping in their responses.

The attribute related to system boundary elicited the second lowest number of mentions in students' responses. That it is a challenging task to demarcate the boundary of a system is also noted by Flood & Carson [69] and Sandri [57]. Many systems are complex in nature, and identifying the boundary can often be a judgment call. Identifying a system's elements defines its boundary. Students with an idea about the system's boundary can realize that the closer an element is to its other key components, the more likely it should be included in the system of interest. This aspect of ST enables students to include the structure of the system and interconnected components within the boundary when looking at it holistically [65,66]. One of the responses covers this idea: 'ST involves analysis of interconnected, interdependent, interconnected elements within a topic of interest'. However, a system's boundary can be expanded by identifying additional exogenous variables that interact with the system, and by determining which of these variables are relevant enough to be incorporated into the system under study. It is to consider the behaviour and cause and effect of elements for a larger system as opposed to the behaviours of each part

independently. With this attribute of ST, students will be able to create an initial mental visualization of the system that contains most of the relevant elements and minimizes those out of the boundary.

It must be recognized that complexity is a key consideration for application of ST in a domain [47,70,71]. While most complex issues can be modelled using ST, the range of attributes that need to be harnessed is variable and may not be circumscribed by all the seven attributes that we have used in our study. There is also the possibility that since we were using a multi-disciplinary cohort of students, there may be some discipline-specific aspects that could have come in the way of students' expression of their understanding of ST. For example, especially among students from law, business and social sciences enrolled in the course, it may not be that easy for them to extract aspects from their discipline that allow for modelling using ST, and this could have also come in their way of demonstrating a holistic understanding of ST from a general perspective that goes beyond course aspects. In view of the small sample sizes for the different disciplines, we did not attempt to do an analysis of their responses according to students' disciplines.

A question can be asked on why only seven attributes of ST emerged, overall, when assessing students' responses. There are three key reasons for this: (a) ST is a complex construct that comprises several attributes; even in the literature, there is no consensus on the number of attributes that comprise ST; (b) the students in this study attended an optional course on ST where they encountered these and other attributes—that is, they were not majors in ST, for which it would be appropriate to assess them on more attributes; and (c) examination of the students' responses did not indicate anyone who has indicated an attribute beyond what was generated through the analytical approach used.

The question arises as to the efficacy of the intervention as the sample sizes were different at pre-test and post-test as well as different forms of qualitative analyses were used to classify the respective responses. We would argue that the intervention was reasonably effective. The pre-test responses have a rather low baseline; that is, the variance was within small limits and not spread out. Also, among the seven ST attributes, very few feature here. In contrast, the post-test responses show more cogency in terms of ST, especially using the vocabulary of ST in the written responses and predominance of the seven ST attributes to varying extents. Compared to the pre-test, the post-test responses show, overall, a higher level above the earlier baseline and also greater variance but in a canonical sense to some extent. Since the findings reflect changes at the cohort level rather than confirmed progression at the individual level, matched pair comparisons are not necessary to explore the effectiveness of the intervention. The conceptual leap, where students generally transitioned from use of rather simplistic vocabulary to express their conceptualisation at pre-test to the use of ST-informed vocabulary at post-test further supports the overall efficacy of the intervention when viewed through a cohort lens rather than at the individual level.

As the data show that only 2.9% of students achieved complete conceptualization, questions arise as to whether the intervention can genuinely be regarded as effective, or whether this relatively low success rate points to the need for a more substantial reconsideration of the teaching strategy. Our argument is that in any educational intervention, it is unrealistic to expect all students to achieve the highest levels of improvement. When examined via a broader lens, it can be seen that 45.7% of the students achieved improvements (5–7 attributes) that can be described as located in the following interval: full, predominant and modest. To us, this is still an improvement from pre-test levels and cannot be discounted. Thus, we would argue that the intervention can be considered to be reasonably effective. The 45.7% indicates that ST is a higher-order attribute that poses some issues when it comes to full conceptualization; this is also supported by the literature in other

contexts. The teaching strategy is well in order as all students across the two cohorts have cleared the course proper; the fact that some students have not responded in depth to the open-ended question does not negate the overall effectiveness of the intervention (which is the course) but is more linked to individual differences in answering the open-ended question, which was not part of the course proper and made clear to them that it was only for research purposes. Significantly, while the coding of the responses at pre-test reflects more of a deficit stance, the different coding of responses at post-test indicates that responses are aligned with ST aspects but to varying extents. In other words, the reasonable effectiveness of the intervention as well as the novel ways of interpreting the data have contributed to the strategic positioning of our study, and this is a contribution to the ST literature.

The high prevalence of interconnectedness/interdependence (Attribute 1: 67 responses) and mapping (Attribute 5: 65 responses) suggests that students primarily conceptualize ST as the ability to recognize relationships and trace linkages among components—indicating a respectable foundation in structural and relational analysis. Causality (Attribute 3: 54 responses) is also well represented, demonstrating that many students can articulate cause–effect chains and begin to engage with dynamic interactions within systems. While explicit references to feedback as a standalone concept (Attribute 2: 9 responses) appear limited, this does not necessarily indicate a lack of understanding. Rather, students’ relatively strong performance in mapping and causal loops implies that elements of feedback thinking may be implicitly embedded within their reasoning. In other words, students appear capable of constructing and conceptualizing feedback loops when engaged in relational and causal mapping, even if they do not explicitly label these processes as “feedback.” The lower recognition of system boundary (Attribute 4: 20 responses) suggests some limitations in defining system scope and context, while moderate responses for emergent behaviour (Attribute 6: 29 responses) and synthesis (Attribute 7: 27 responses) indicate that more complex, integrative dimensions of ST are still developing. Nevertheless, the alignment between high responses in interconnectedness with moderate representation of causality and feedback dynamics provides evidence that the intervention has generally been effective in fostering foundational skills necessary for appreciating feedback loops. Thus, despite the low frequency of explicit references to feedback terminology, students generally demonstrate a meaningful and functional grasp of feedback-related thinking through their recognition of causal relationships and system interactions. This suggests that the intervention has successfully supported the development of applied feedback conceptualization, even if explicit articulation of the concept remains an area for further strengthening. The findings not only support the existing literature [13] but also aligns with the other cited literature, for example, ref. [64].

While there are a few ways of assessing students’ ST skills—for example, use of multiple-choice questions [72], use of scenarios [13,66], and pre/post-tests with a formal intervention [73], we chose to focus on just an open-ended question. There are a few advantages in using such an approach: (a) it allows students to express themselves in their own words on their understanding, thereby revealing how they make sense of complex ideas through personal meaning-making; (b) it is a fast approach to get some useful data; (c) it allows us to unpack their understanding of ST by just scrutinizing their responses in their own words, thus offering rich qualitative insights; and (d) testing burden is minimized (about 15 min each for pre-test and post-test), which can generally be done within curriculum time. As mentioned earlier, there are some studies in the science education literature that have used such an approach to probe students’ understanding of concepts in certain topics [48–50]. But we have not come across a study in the ST literature that has used such an approach.

Another novel aspect of our study is the generation of threshold concepts. We comment further on this here. The findings summarized in Table 6 highlight a consistent pattern: key ST concepts—feedback, system boundaries, emergence, synthesis, and non-linear causality—function as threshold concepts because they require significant conceptual transformation and are persistently difficult for learners. Feedback (closed-loop thinking) emerges as a foundational yet problematic concept. Students tend to default to linear cause–effect reasoning, making it difficult to recognize circular causality and reinforcing/balancing loops. The required transformation involves shifting from event-based thinking to dynamic, loop-based reasoning. This aligns with threshold characteristics of being transformative and troublesome, as understanding feedback changes how learners interpret system behaviour. Systems boundaries are similarly challenging due to their abstract and subjective nature. Learners often assume boundaries are fixed rather than constructed for analytical purposes. The conceptual shift involves recognizing boundaries as flexible, purpose-dependent decisions that shape system interpretation. This concept is integrative, as it connects multiple system elements, and irreversible, once learners appreciate how boundary choices influence understanding. Emergent behaviour (behaviour over time) requires learners to move beyond static snapshots to dynamic patterns. Difficulty arises in linking structure to behaviour, particularly in anticipating long-term consequences. The transformation here involves temporal reasoning and pattern recognition, reinforcing the transformative and integrative nature of this threshold concept. Synthesis (integration of ST attributes) represents a higher-order threshold concept, where learners must combine multiple systems ideas into a coherent whole. The difficulty lies not in individual concepts but in integrating them simultaneously. This reflects the cumulative and bounded characteristics of threshold concepts, marking progression towards more holistic ST conceptualization. Causality (non-linear/systemic) is consistently identified as one of the most problematic areas. Learners struggle with delays, indirect effects, and multiple interacting causes. The conceptual shift involves abandoning simple linear causation in favour of complex, networked causality. This transformation can be deeply troublesome but ultimately leads to closed-loop thinking by fundamentally altering reasoning patterns. Overall, the findings suggest that these concepts are not merely difficult but represent epistemological shifts in thinking. Their threshold nature is evidenced by their persistence as learning bottlenecks, their integrative role across ST, and their transformative impact on learners’ understanding. Collectively, they indicate that teaching ST requires pedagogical approaches that explicitly support conceptual change, rather than incremental knowledge acquisition.

A key contribution of this study can be seen in its novel analytical approaches, which have not been reported before. These can be alternative approaches for assessing the state of ST in students. A conceptualization continuum was developed to categorize student responses from inadequate to full understanding, revealing that only a small fraction demonstrated proper conceptualization of the term ‘ST’ by integrating all the expected attributes. Additionally, attributes prevalence tables were used to systematically capture the presence and depth of key ST elements across responses. These tools move beyond traditional assessment metrics, offering richer insights into students’ cognitive engagement and conceptual clarity. Such approaches, though they may be critiqued as deficit stances, have the advantages of determining what attributes are not present, what attributes are present, and what combinations of the attributes are present [64,65]. This can be useful when interventions are conducted to improve students’ ST skills.

It could be argued that there seems to be a mismatch between the intention of applying a comprehensive ST framework to participants’ outputs and the course emphasis on system dynamics, which is one aspect of ST. The primary intention of both the course design and the pedagogical approach was to develop participants’ ST capabilities in a comprehensive

and holistic sense. While system dynamics (SDs) was emphasized within the curriculum, this emphasis should be understood as a pedagogical vehicle rather than a conceptual limitation. SD served as a methodological extension of ST, rather than a narrowing of scope. Accordingly, the use of a comprehensive ST framework in analyzing participants' responses remains consistent with the study's overarching objective of capturing the breadth of ST competencies developed throughout the course.

In summary, the contributions of this study to the ST literature are as follows:

1. It explored the ST conceptualizations of a multi-disciplinary cohort of undergraduate students. To the best of our knowledge, we have not come across another study that has used such samples.
2. It explored students' conceptualization of ST through just one open-ended question. To the best of our knowledge, we have not come across another study in the ST literature that has used such an approach.
3. The analysis approaches we have used have not been reported before in the ST literature to the best of our knowledge.
4. The findings show that, overall, the undergraduates have a range of conceptualizations of ST—this is, after attending the course on ST involving energy systems. Prior to the start of the course, their conceptualization of ST was rather limited.
5. An interesting aspect of our data analysis is the framing of the 'attributes' continuum.
6. While the instructional design aimed to develop broad ST competencies (both qualitative modelling through CLDs and quantitative through SFDs and simulations) the course progression moved from foundational ST concepts—such as CLDs (feedback structures)—to a stronger emphasis on SD modelling using SFDs for analyzing energy-related scenarios and projects. This pedagogical emphasis may have influenced participants' responses and how they articulated their conceptualisation of ST, potentially foregrounding SD over other dimensions of ST in some cases.
7. The course on energy systems based on ST curriculum could have shaped the interpretation and generalizability of the findings. Its approach is designed and characterized by inherently interdisciplinary and application-oriented domain, situated at the intersection of scientific, technological, economic, social, and policy considerations. It is specifically designed to help students understand the complex behaviour arising from non-linear interdependent interactions among multiple system actors and factors, including economic, political, environmental, and technological dimensions. As such, it provides a natural context for teaching and learning of ST tools and concepts, and application to model energy-related problems. This context would not have influenced the pre-test responses but could have influenced the post-test outcomes. Students engaging with real-world energy policy scenarios, case studies, and modelling tasks are likely to demonstrate contextualized forms of ST, which may differ from those elicited in more abstract or purely theoretical disciplines. The applied and project/problem-based nature of the course may have facilitated the expression of relational and dynamic reasoning, particularly when supported by structured tools such as CLDs, which are one of the modelling constructs in SD. However, irrespective of the discipline, key attributes and constructs of ST remain fundamental to its conceptualization. In addition, the relatively short duration of the intervention (two weeks), undertaken alongside other ongoing modules, is an important consideration. While the findings suggest that meaningful shifts in students' representations of ST can generally occur and typically develop over extended periods of practice and reinforcement, it needs further research to verify this assertion.

The theoretical frameworks adopted in this study have been useful in addressing the research questions. The first framework on constructivism was in operation when

students leveraged their prior knowledge to answer the open-ended question. The second framework on ST was in use when we evaluated students' responses for evidence of ST. By combining constructivist learning theory with ST frameworks, the responses to the single open-ended question provided a constructivist lens into students' cognitive structures, while the ST tradition offers a benchmark for evaluating the depth and coherence of their responses. This dual-theoretical approach enables a nuanced understanding of students' mental models and identifying gaps in their ST understanding. Seen through these theoretical lenses, the pattern observed in the students' responses at post-test—from predominantly recognizing interconnections and causal links toward more limited engagement with feedback, boundaries, and synthesis—mirrors the developmental continuum described in the literature, wherein learners typically acquire structural and relational insights before mastering dynamic, integrative, and reflexive aspects of ST.

6. Implications

Our study shows that students commonly articulated interconnectedness and mapping, but fewer demonstrate feedback reasoning, boundary judgments, or synthesis. This pattern is consistent with contemporary evidence that ST is difficult to assess and to teach in short bursts, and that integrative, framework-guided designs are needed to expand students' cognitive reach from structure to function to dynamic outcomes [64,65,74,75]. In addition, transferability of ST skills and learning is increasingly recognized as a core indicator of ST, particularly when students engage in real-world, scenario-based modelling tasks such as the construction of causal loop diagrams (CLDs) in unfamiliar contexts [75]. This underscores the importance of designing authentic, real-world scenarios that enable educators to assess ST not merely as domain-specific knowledge, but as a transferable and generalizable mode of thinking. When instruction explicitly integrates structured modelling practices, students are better positioned to recognize underlying structural similarities between contexts and adapt their reasoning accordingly. Thus, the attributes-prevalence tables and conceptualization continuum in this study provide practical, low-burden lenses for instructors to locate where students are along the ST spectrum and to target instruction toward higher-order skills. Further implications are as follows:

1. The sample here largely highlighted ST attributes such as mapping out interconnectedness/interdependencies and causality with a conceptualization that ST fundamentally involves understanding cause-and-effect relationships to develop feedback loops. This generally aligns with the intended intervention and learning outcomes of the course mentioned earlier. However, while this indicates students made good progress with these attributes, some attributes of ST appear in low frequencies, which suggests that there is still room for improvement in achieving a fully comprehensive and holistic understanding of ST through further interventions.
2. ST and SD skills are recognized as essential 21st-century competencies in various educational curricula [40]. While our study indicates that the undergraduates have room for improvement in fully comprehending ST skills, it also suggests that fostering these skills in pre-university or school students may require even more work.

7. Limitations

Our study is constrained by the following limitations:

1. The ST conceptualization of students in this study represents those of a multi-disciplinary cohort. Care should be taken not to extrapolate this on a disciplinary basis.
2. The findings represent those from two cohorts of students. The findings from the data cannot be extrapolated to those from other cohorts.

3. The ST conceptualization of students was assessed based on their responses to an open-ended question. It should be noted that there are other approaches for assessing ST. So, our findings are restricted to this context.
4. ST is a multi-faceted construct that spans several attributes. However, for this study, the seven attributes which emerged at post-test were adequate for the purpose of exploring the students' conceptualization.
5. The conceptualisation of students' ST skills in this study should not be taken as an index of sophistication of their ST abilities; this would need their further articulation or assessment in more robust contexts.
6. The generic ST conceptualizations of the students, as uncovered from their responses to the same open-ended question, represent their state of conceptualization of this construct before and after they have undergone the course related to energy systems.
7. The pre-test and post-test numbers are different for the reasons stated earlier; matched pair analysis was also not done for the reasons mentioned. We kept all the responses so as to preserve the uniqueness of the 'as obtained' data. Since we are not doing a robust statistical analysis or matched pairs comparison but more of qualitative analyses, we felt that the chosen approach is not unreasonable. However, it remains a limitation of this study.
8. Though the study sought to explore students' conceptualisation of what is meant by the term 'ST', we deliberately used the term 'understanding' in the instrument so that students can comprehend it easily. It is a given that the terms 'conceptualization' and 'understanding', though sharing commonalities, are quite different from a science education research perspective.
9. We acknowledge that there might be some subjectivity involved in the classification of the pre-test responses owing to the nature of the coding used. We do not see this as an issue as we are looking at the intervention from a broad lens—and it is clear that the post-test responses are richer from a ST perspective than the pre-test responses.
10. The brevity of the responses at both pre-test and post-test means that unpacking further insights into the students' conceptualizations was not possible. Also, just because they have used the ST attributes in their responses to varying extents in the post-test does not necessarily mean they have in-depth understanding of these terms; this would need further ascertaining.
11. Interviews after post-test could have provided richer insights into the students' conceptualization of ST as well as their understanding of the attributes present in their responses. However, this could not be done as the university examinations were in the following weeks, and it would be long semester holidays after that, when they would not be available for follow-up on their written responses.

8. Conclusions

The study sought to explore undergraduates' conceptualization of what ST is through a simple open-ended question. While their level of ST is rather limited at pre-test, that at post-test is mixed. While very few students exhibited the full spectrum of ST attributes at post-test, there are others who exhibited only one attribute. Feedback and systems boundary are less frequently mentioned although they are familiar with these terms while working on modelling exercises, which might indicate that these concepts, while important, are more challenging to grasp and articulate clearly. The number of students who exhibited a good number of attributes is rather modest.

The most prevalent attributes were interconnectedness/interdependence and mapping, with causality also prominent—an essential component for conceptualizing interdependence within a system. Attributes such as emergent behaviour and synthesis ap-

peared moderately, indicating partial engagement with dynamic and integrative aspects. The intervention's reasonable effectiveness, together with novel data interpretation, positions this study as a meaningful contribution to the ST literature. In addition, the core attributes or concepts—feedback, system boundaries, emergence, synthesis, and nonlinear causality—function as threshold concepts, as they require deep conceptual shifts and remain persistent learning challenges. Thus, both the integrative and transformative nature of these concepts suggests that they would represent epistemological changes rather than simply difficult content.

Overall, students' conceptualizations emphasize structural clarity and non-linear relationships, while revealing gaps in understanding of feedback mechanisms, boundary setting, and holistic integration—critical elements of mature ST. Despite differences in numbers at pre-test and post-test, analysis at cohort level (rather than individual tracking) shows the overall conceptual shift from generally baseline thinking to use of ST frameworks to varying extents across these test intervals.

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Data Availability Statement: Data will be made available upon request with exceptions to privacy or ethical restrictions.

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