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The Role of Technology Exposure in Systems Thinking: Investigating Air Quality Modeling with SageModeler in Diverse Educational Contexts

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Abstract

This study explores the impact of students' prior exposure to technology on their ability to model air quality phenomena using SageModeler, a web-based, open-ended, systems modeling tool designed to facilitate conceptual understanding through dynamic simulations and visual representations of causal relationships. Students used the tool to engage in core modeling practices such as defining system boundaries, establishing causal links, using evidence to build and revise models, and interpreting outcomes to make predictions and explanations. A comparative study was conducted between an urban school, well-equipped with digital resources and where students were familiar with web-based tools, and a rural school with limited computer access and minimal prior exposure to digital modeling. Urban students, who had prior experience with technology-based learning, demonstrated greater ease in integrating multiple variables, refining model relationships, and iteratively improving their models based on simulated feedback. In contrast, rural students initially faced challenges navigating the digital tool but exhibited notable improvements in systems thinking when provided with structured guidance and scaffolding. Findings suggest that while technology enhances modeling practices, exposure and instructional support are key factors in fostering systems thinking across diverse educational contexts.

Keywords: Air quality modeling, dynamics modeling tool, SageModeler, STEM education, systems thinking

Introduction

Navigating a complex system can be challenging; however, cultivating a structured mindset is essential, and systems thinking is an effective strategy to achieve this. Systems thinking encourages basic categorization and step-by-step problem-solving, in which students build initial connections between concepts. This approach encourages individuals to view the entire system rather than merely focusing on its components, thereby fostering an understanding of the connections among different elements. Senge (2006) identifies systems thinking as one of five fundamental disciplines in learning, providing a conceptual framework that enhances clarity regarding overarching patterns and their dynamics. One can gain deeper insights and make more informed decisions within complex environments by adopting systems thinking (Assaraf & Orion, 2010; Ben-Zvi-Assaraf & Orion, 2010; Hung, 2008). Modeling enhances systems thinking by

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helping students identify relationships, test assumptions, and improve their understanding of dynamic systems. However, lacks deep interconnected reasoning, such as overemphasizing memorization over reasoning, making or lacking real-world context to reinforce systems thinking, making it less effective for complex problem-solving (Kunc, 2008; Liljedahl, 2018). The earlier problem discussed highlighted the importance of implementing the Modelling. Modelling serves as specific representations that illustrate how things work, the causes behind various events, and their functions. It aids in illustrating, explaining, and predicting phenomena (Schwarz et al., 2009).

SageModeler is an intuitive tool that empowers students to create and validate their own models with real-world data. The key findings from previous studies indicate that the tool effectively engaged students in environmental responsibility and is valuable for their learning (Bielik, Damelin, et al., 2018; Bielik et al., 2022; Bielik, Opitz, et al., 2018). PM2.5 is a pressing issue that significantly impacts our daily lives. To fully grasp its dangers and the associated environmental concerns, it is crucial for students to first understand the problem in its entirety. This study invites students to model the sources of PM2.5 and its effects using SAGE Modeler. Additionally, it aims to evaluate how students develop their systems thinking skills regarding this important topic.

■ Theoretical Framework

Spoke, Chain and Net Structures

Kinchin and Hay (Kinchin et al., 2000) identify three substructures in concept maps: spokes, chains, and nets, as show in Figure 1. A spoke represents a simple hierarchy with a central concept, while a chain illustrates a progression of concepts in sequence. Conversely, a net reflects a framework where pairs of concepts are interconnected in multiple ways. These substructures indicate the degree of integration of certain concepts within a learner's mental representation of the subject matter. They also determine how a learner's concept map may adapt when faced with new, conflicting information. In a spoke substructure, a learner has recognized various concepts associated with a central idea but may struggle to understand how those concepts interrelate. This can hinder their ability to connect ideas in contexts that do not involve the core concept. A chain substructure often suggests rote memorization, as it typically mirrors the sequence in which concepts were introduced during lectures. Some connections in this structure may be fragile, breaking under new information. Conversely, a net substructure indicates a stronger integration of concepts, making it more resilient to contradictory information than spoke and chain structures. These structures were used as a framework to classify students' model structures as our coding and analysis process. Each student's model was analyzed for the presence of spoke-like (centralized), chain-like (sequential), or net-like (interconnected) relationships, which allowed for assessment of the depth of their systems thinking and conceptual integration.

Implications for Systems thinking Development

Systems thinking involves recognizing patterns, establishing relationships between concepts, and integrating information across different domains (Checkland, 1981). The three substructures in Figure 1 correspond to different levels of systems thinking and cognitive complexity.

A spoke substructure is characterized by a central concept with multiple associated ideas branching out, forming a simple hierarchical model (Kinchin et al., 2000). This structure aligns with a fragmented approach to thinking, where learners recognize individual concepts but struggle to integrate them into a comprehensive system (Fielding-Wells, 2016). In the context of systems thinking, this model is analogous to identifying variables without fully grasping their interdependence. Consequently, learners who rely on a spoke structure may find it difficult to adapt their knowledge when faced with complex or contradictory information, limiting their ability to engage in dynamic problem-solving.

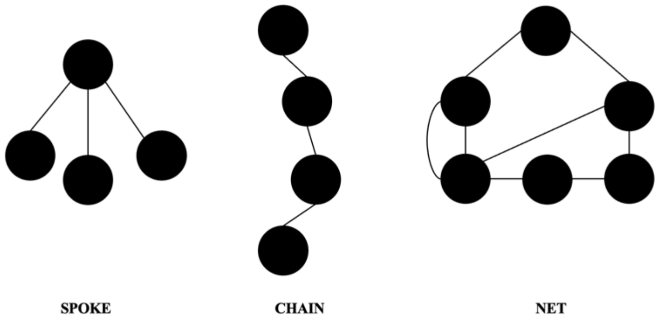

Figure *1*. Illustrate Three Substructures in Concept Mapping

In contrast, a chain substructure represents a linear progression of ideas, often reflecting the structured manner in which knowledge is introduced in educational settings (Kinchin et al., 2000). This model corresponds to sequential thinking, where concepts are understood in a fixed order, making it useful for procedural knowledge but less effective for flexible problem-solving. Systems thinking, however, necessitates adaptability and the ability to see interconnections between ideas (McNeill & Krajcik, 2008). While the chain structure provides a foundation for step-by-step reasoning, it may limit a learner's ability to reconfigure relationships between concepts when encountering novel situations, thus restricting their capacity for deeper cognitive engagement (Evagorou et al., 2020).

The net substructure, on the other hand, represents an interconnected web of concepts, signifying a high level of integration and cognitive complexity (Kinchin et al., 2000). This structure aligns most closely with systems thinking, as it enables learners to perceive relationships, recognize feedback loops, and apply their understanding across various contexts (Makar & Rubin, 2009).

SageModeler Making Systems thinking Visible

Systems thinking is a crucial cognitive skill that enables learners to recognize patterns, establish interconnections, and develop a comprehensive understanding of complex systems. In STEM education, fostering systems thinking can significantly enhance students' problem-solving abilities and conceptual understanding. *SageModeler*, an open-ended, web-based dynamic modeling tool, plays a vital role in making systems thinking visible by allowing students to construct, simulate, and refine their own conceptual models (Bielik et al., 2022). By engaging in iterative modeling practices, learners can visualize relationships between variables, test hypotheses, and revise their models based on feedback, thereby strengthening their systems thinking skills.

■ Methodology

Participants and Protocol

There were two groups of participants: 27 students from an urban school and 9 students from a rural school. The urban students were organized into groups of three, resulting in a total of nine groups. In contrast, the rural students worked individually. The urban students were familiar with using technology, while the rural students had limited experience with it. Both groups were tasked with using *SageModeler* to model the PM2.5 issue during the four-implementation process: 1) Define the issue and create the initial model, 2) Gather additional information, 3) Revise the model, 4) Propose a solution, as shown in Figure 2. The models created by students from both schools were collected and analyzed to assess the frequency of substructures, which are spokes, chains, and nets present in the models. Subsequently, a comparison was conducted to identify the differences in systems thinking between the two schools.

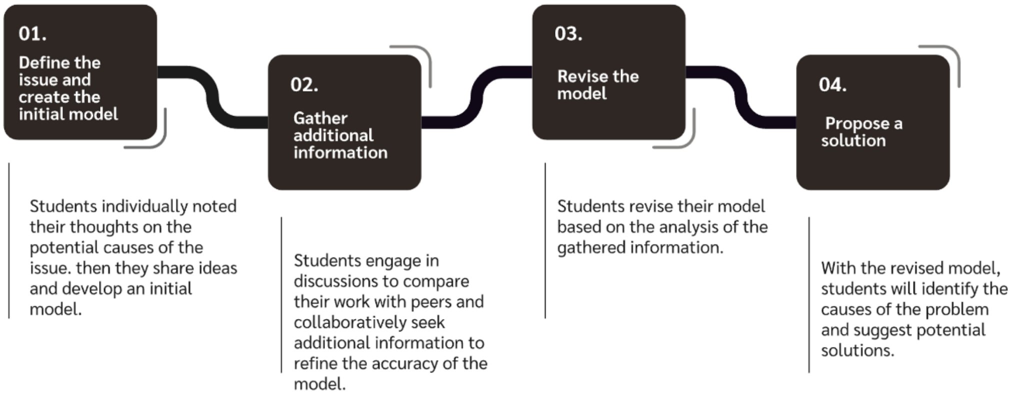

Figure *2*. The Four-implementing Process

Data analysis

This study analyzed the final PM2.5 model developed by students using frequency-based analysis. The research methodology included developing a coding scheme based on the theoretical framework established by Keppens and Hay (2008). The analysis focused on six parameters to evaluate students' systems thinking using SageModeler

Node – The number of nodal terms identified in the SageModeler model that signify relational meaning.

Max Depth – The number of nodal terms in the longest chain of the map that are linked with relational meaning.

Surface Linkage – The number of linkages that represent one-way connections.

Closed Linkage – The number of substructures that illustrate closed figures in relational meaning.

Tree-like Structure – The number of substantial substructures (with four or more nodes) that exhibit branching patterns from the core chain.

The definitions and visual representations of these parameters are illustrated in Figure 3. These measures were used to evaluate the structural complexity of students' models, distinguishing between relational depth and surface-level learning.

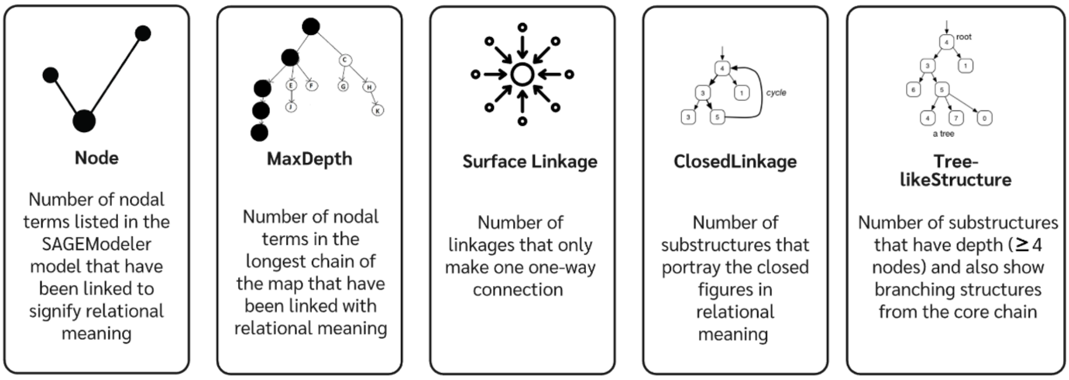

Figure *3*. The Parameters Used in Sagemodeler Map Data Extraction

■ Findings

The comparison between the rural and urban school

The comparative analysis between rural and urban school groups revealed distinct patterns in their systems thinking models. As shown in Figure 4, rural students demonstrated a higher number of total nodes (20.00) compared to urban students (16.375), suggesting a tendency to include more concepts in their models. However, despite having more nodes, rural students exhibited slightly shallower chain relational thinking, as indicated by their maximum depth score (3.22), which was only marginally higher than the urban group (3.125). This suggests that rural students' models may include more disconnected concepts rather than deeply integrated ones.

Moreover, rural students exhibited a greater number of surface linkages (8.33) compared to urban students (5.625), reinforcing the notion that their models relied more on superficial connections rather than deeply structured reasoning. This pattern may reflect a surface-level approach to modeling. Students respond to uncertainty or unfamiliarity with modeling tools by incorporating many ideas without fully connecting them. Their lack of prior exposure to structured, systems-based instruction likely contributes to a focus on quantity over conceptual depth. Additionally, limited experience with diverse data sources and modeling practices may cause rural students to rely more heavily on familiar, real-life scenarios rather than engaging with broader or more abstract system concepts. In contrast, despite including fewer nodes, urban students demonstrated more structured relational thinking, as evidenced by a higher proportion of closed and tree-like structures—indicating stronger internal linkages and deeper integration of concepts.

Both groups exhibited similar values for closed linkages (1.33 for rural and 1.25 for urban) and tree-like structures (0.89 for rural and 0.875 for urban), suggesting that deeper structural reasoning was equally present in both groups. However, the overall greater number of connections in rural students' models may indicate a preference for surface learning, in contrast to urban students who displayed a more balanced approach with stronger internal linkages between concepts.

In summary, the analysis highlights distinct differences in systems thinking approaches between rural and urban school groups, with rural students incorporating more concepts but relying on surface-level associations, whereas urban students demonstrated a more structured and interconnected approach to model development. The frequency comparison between both groups is visually represented in Figure 4.

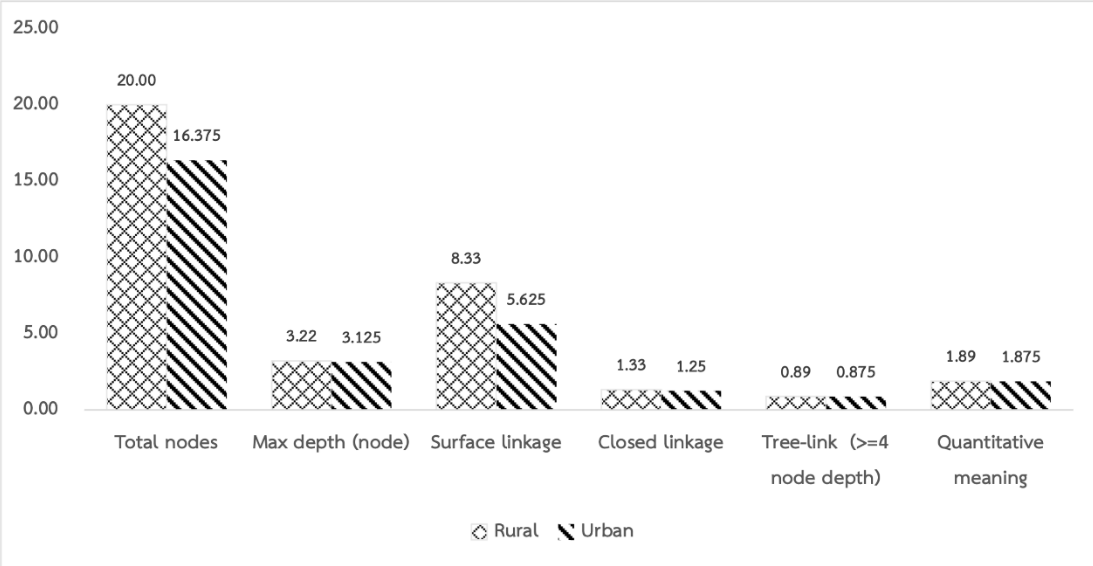

Figure *4.* The Bar Graph Illustrates the Frequency between Two Participant Groups

■ Discussion

The findings of this study indicate notable differences in the conceptual modeling approaches of rural and urban student groups. Rural students demonstrated a higher number of nodes in their models (20.00) compared to urban students (16.375), suggesting a broader recognition of concepts related to the PM2.5 phenomenon. This result implies that rural students were more aware of various factors influencing PM2.5, reflecting a wider scope of conceptual understanding. However, despite their greater number of nodes, rural students' maximum depth score (3.22) was only slightly higher than that of urban students (3.125), indicating that their conceptual connections remained relatively shallow. This suggests that while rural students identified multiple variables, their understanding of how these variables interrelate was limited, leading to a more superficial grasp of systematic relationships (Schwarz et al., 2009).

Conversely, urban students demonstrated a lower number of nodes but exhibited stronger relational thinking. This indicates that although urban students recognized fewer variables, they were better at establishing deeper connections among them. Their ability to create more complex and structured models suggests a more integrated comprehension of the PM2.5 system, likely facilitated by exposure to structured learning environments that promote deep, critical thinking skills (Ben-Zvi-Assaraf & Orion, 2010; Hung, 2008).

Another key distinction was observed in surface linkages, where rural students had a significantly higher count (8.33) compared to urban students (5.625). This finding suggests that rural students were more inclined to create one-way, surface-level connections, potentially focusing more on identifying elements rather than deeply analyzing their interactions. Some of exemplary evidence is shown in Figure 5. Surface learning, characterized by memorization and limited conceptual insight, may indicate a less advanced approach to modeling tasks. This could stem from a lack of exposure to critical thinking frameworks or systemic analysis approaches in rural education (Bielik et al., 2022).

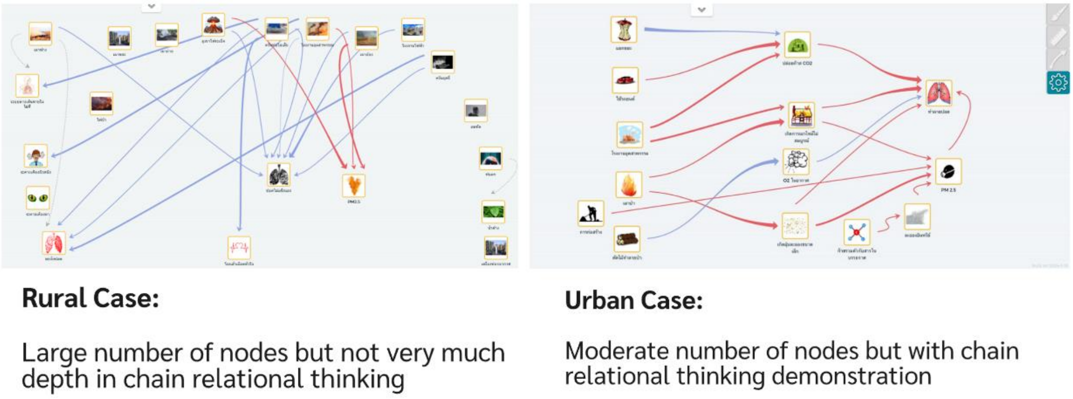

Figure *5.* Example of Rural Student's and Urban Student's Sagemodeler Maps

Despite these differences, both rural and urban groups exhibited similar numbers of closed linkages (1.33 vs. 1.25) and tree-like structures (0.89 vs. 0.875). This suggests that, in terms of structural complexity, both groups had some understanding of relational systems concerning PM2.5. However, the rural group's tendency toward higher surface linkages highlights the need for fostering deeper relational thinking in educational strategies, particularly in rural settings. Encouraging conceptual integration and systematic modeling techniques in rural classrooms could enhance students' ability to construct more meaningful and interconnected representations of complex systems. For example, rural teachers can provide guided questioning strategies during model-building activities, which prompt students to explain the reasoning behind each connection they make. Additionally, integrating real-world data sets and encouraging students to revise their models in response to new information can help shift their focus from isolated facts to dynamic system relationships.

Ultimately, these findings underscore the importance of promoting interconnected and deeper thinking approaches, particularly in rural areas where tendencies toward surface learning are more pronounced. Educational strategies should prioritize relational understanding and cognitive engagement to equip students with the skills needed to develop comprehensive conceptual models (Liljedahl, 2018; Schwarz et al., 2009).

■ Suggestion

As this research is in its early stages, the findings represent an initial exploration of systems thinking development within a short-term study. To enhance the effectiveness of systems thinking approaches, future studies should incorporate more structured and long-term learning interventions.

One potential improvement is the integration of guided learning instructions, which could facilitate a more structured progression in conceptual development. Through step-by-step scaffolding and scenario-based exercises, students could gradually refine their ability to recognize key concepts and establish deeper interconnections. By encouraging students to construct closed loops of interconnected variables, educational interventions could help them transition from surface-level associations to comprehensive, system-based reasoning.

Ultimately, the goal is to cultivate systematic thinkers who can independently construct, analyze, and refine complex models, thereby improving their ability to navigate and understand intricate real-world phenomena. Future research should explore the long-term impact of systems thinking interventions across diverse educational contexts, ensuring that students from all backgrounds benefit from deeper, interconnected learning experiences.

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