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The invisible remains invisible: a study of systems thinking in compulsory school students' descriptions of a wastewater system

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Abstract
This study investigates how ninth-grade students in Swedish compulsory school describe and explain a technological system: the wastewater system. The analysis focuses on students' verbal explanations while illustrating their self-drawn models of the system. Eleven students (aged 15–16) participated through semi-structured individual interviews. Transcripts and models were analysed using Hallström et al.'s (2022) classification model for system understanding and thematic analysis. The results indicate that most students were able to identify the system's purpose, namely, the collection and treatment of domestic wastewater, and describe components such as household outlets, sewer pipes, and treatment plants. However, their descriptions were largely linear and focused on visible components, such as inlets and manholes. Few references were made to energy flows, information control, system boundary, or interdependencies with other systems. Most students' reasoning remained at the Multistructural level; only two demonstrated relational understanding, and none reached an extended abstract level. The thematic analysis revealed that students faced difficulties in understanding temporal processes, feedback mechanisms, and the consequences of system failures, highlighting difficulties in grasping system complexity. The study calls for instruction that explicitly makes hidden structures, interconnections, and sustainability aspects visible in technological systems. It proposes combining student-generated drawings with visualizations, simulations, and structured reflection to promote deeper and more transferable systems thinking in technology education. Although grounded in a Swedish context, the findings and suggested teaching strategies may inform broader educational settings and contribute to strengthening systems thinking as a core competence in technology education globally.

Keywords
Technology education, technological systems, systems thinking, teaching strategies

Introduction
In today's technology-intensive society, technology education plays a crucial role in preparing students to understand and critically engage with the technological systems that permeate daily life. As digital infrastructures, energy networks, transportation systems, and communication technologies become increasingly complex and interconnected, the capacity to analyse, interpret, and make informed decisions about these systems is fundamental. This competence is essential not only for personal agency but also for participation in societal development and the pursuit of sustainable innovation.

At the heart of technological literacy lies the understanding of technological systems: complex networks of components, processes, and flows that function together to meet human needs. These systems extend beyond isolated artefacts or devices and encompass the interactions between multiple components as well as the broader social, economic, and environmental contexts within which they operate. Communication systems, energy supply chains, and transport networks, for example, all depend on integrated subsystems whose coordination determines the overall purpose of the system. To develop meaningful systems understanding, students must grasp both the structure of these systems, their components and organisation, and their behaviour over time, including how they respond to changes and connect with other systems.

Understanding technological systems involves more than identifying visible components. It requires analysing how these components interact together in relation to one another and how systemic processes influence outcomes at multiple levels. This relational perspective enables students to consider the societal and environmental consequences of technology, fostering not only technical competence but also ethical awareness and sustainable decision-making. As Örtnäs (2007) demonstrates, students can describe a range of technological systems from everyday life when supported by pedagogical approaches that foreground the relationships between structure, purpose of the system, and human involvement. According to the same author, students' descriptions of technological systems are significantly enhanced when they engage with images, artefacts, and other forms of visual representation that help to make abstract or hidden system features more accessible. This emphasis on relational understanding, where the focus shifts from isolated components to integrated wholes, reflects a growing consensus in technology education research that systems thinking is essential for preparing students to navigate and critically reflect on the increasingly complex technological world in which they live.

A key aspect of developing this relational understanding is the cultivation of systems thinking, which involves the ability to recognize and analyse how different components within a system interact and influence each other. This aligns with Cabrera and Cabrera's (2015) view of systems thinking as the ability to identify patterns, relationships, and dynamics that shape complex systems over time. Riess and Mischo (2010) define systems thinking as the capacity to move beyond isolated observations and instead perceive systems as dynamic entities where actions in one part may have consequences elsewhere. This approach allows students to see not only the internal interactions within a system but also how technological systems connect to broader societal and environmental contexts.

Voulvoulis et al. (2022) underscore that systems thinking is not merely an educational strategy, but a critical cognitive competence for addressing large-scale sustainability challenges. They argue that it must be scaled up across society to enable systemic change, and that education plays a central role in catalyzing this transformation. Several studies illustrate that achieving this type of holistic understanding is challenging for students.

Research by Lind (2019) and Hallström et al. (2022) shows that students often focus on individual, visible components rather than on the complex interactions and hidden processes that characterize technological systems. Their descriptions tend to be linear and fragmented, with limited awareness of feedback mechanisms, system boundaries, or the role of human agency. This narrow focus restricts students' ability to understand how systems behave as wholes and how they impact the world around them.

To address these difficulties, scholars have highlighted the importance of instructional strategies that help make systemic relationships and dynamics visible and meaningful to students. Visualizations, models, simulations, and artefacts can serve as powerful tools for bridging the gap between students' everyday experiences and the abstract nature of technological systems (Engström & Svensson, 2022; Citrohn et al., 2023; Örtnäs, 2007). Such tools allow students to trace flows of energy, materials, and information, and to observe how changes in one part of a system can generate effects throughout the system. Örtnäs (2007) emphasises that using images and physical representations supports students in identifying structures and roles, while also making it easier to understand the relationships that govern system behaviour.

The importance of systems thinking extends beyond technological competence to include education for sustainable development. Palmberg et al. (2017) argue that students need to understand the complex interconnections between ecological, social, and economic systems to critically examine the role of technology in sustainability. Meadows (2008) similarly describes systems as dynamic and self-regulating, where cause and effect are often separated by time and space. Senge (2006) highlights that perceiving such patterns requires an ability to think systemically, an essential skill for addressing global challenges such as climate change, resource scarcity, and environmental degradation.

Despite the relevance of systems thinking for both technological literacy and sustainability, research demonstrates that many students have difficulty grasping system boundaries, feedback loops, and the ways in which users interact with specific operational aspects of the system, such as input-output relationships, control mechanisms, or user interfaces (Koski & de Vries, 2013 Svensson, et al., 2012). Their interpretations often remain at the level of visible, physical components, with limited capacity to analyse abstract aspects such as energy flows or information exchange (Koski & de Vries, 2013). This fragmented understanding hinders students' ability to see systems holistically and to consider the implications of technological choices.

To support the development of systems thinking, several researchers propose the integration of visual and hands-on learning experiences. Engström and Svensson (2022) suggest combining reflective discussions with practical activities such as study visits, technical drawings, and the construction of models and simulations. Citrohn et al. (2023) underline those simulations, in particular, help make invisible system processes visible, allowing students to analyse dynamic behaviours and explore cause-and-effect relationships. Such approaches enable students to move from fragmented descriptions towards integrated understanding.

Visualizations and models also serve as cognitive tools that bridge theory and practice. As Senge (2006) argues, models help students grasp systemic relationships by externalizing abstract ideas in a concrete, manipulable form. Similarly, Örtnäs (2007) shows that using images and artefacts allows students to describe system structures and identify functional relationships more effectively. These findings suggest that integrating visualization strategies into technology education not only enhances conceptual understanding but also supports the development of systems thinking competencies.

The relevance of systems thinking becomes particularly evident when considering the role of technology in sustainable development. Palmberg et al. (2017) highlight those systems thinking enables students to analyse the interconnected nature of environmental, social, and economic systems, thereby fostering a holistic perspective on sustainability. By helping students perceive technological systems as embedded within broader societal and ecological contexts, technology education can equip them with the analytical tools necessary for responsible citizenship and future innovation.

Despite the recognized importance of systems thinking for both technological literacy and sustainability, much existing research has primarily focused on older students or on disciplines such as biology and physics where systems thinking has a longer tradition (Riess & Mischo, 2010). In technology education, students often demonstrate fragmented understandings of systems, focusing on isolated components or outputs rather than integrated structures and flows (Svensson et al., 2012). In contrast, there is limited knowledge about how students in compulsory schooling conceptualize technological systems and how their emerging understanding can be supported within the context of technology education.

This study addresses this gap by exploring how lower secondary students (aged 15–16) describe and conceptualize a technological system, with particular attention to how visualizations and representations can support the development of systems thinking. These students, situated in the final year of compulsory schooling in Sweden, constitute a key educational stage where technology education can strengthen not only interest in technology but also the ability to think systemically about technological processes and their consequences.

The study builds on the idea that relational understanding of systems, seeing both components and wholes as well as flows and interactions, does not develop spontaneously but must be deliberately supported through pedagogy. Drawing on research by Koski and de Vries (2013), Palmberg et al. (2017), Meadows (2008), and Senge (2006), this study examines how instructional strategies such as visualization, authentic contexts, and structured reflection can foster more integrated systems thinking in younger students. In doing so, it responds to the call for empirical studies that investigate how systems thinking can be cultivated in the context of technology education at the compulsory school level.

By analysing students' descriptions of a wastewater management system, the study offers insights into both the strengths and limitations of their emerging systems thinking. It also contributes to a broader discussion on how pedagogical tools and approaches can help students move beyond linear, fragmented understandings towards a more holistic grasp of technological systems and their societal relevance. Ultimately, the study aims to inform the design of technology education that equips students not only with knowledge of technological artefacts but also with the capacity to analyse the complex systems in which these artefacts are embedded.

This study contributes new insights by combining students' verbal accounts and self-drawn models to explore their systems thinking about a technical system. Through the integrated use of a classification model, the SOLO taxonomy and a thematic analysis, the study captures both the structure and content of students' reasoning. This approach foregrounds students' own voices and adds depth to previous research by showing how systems thinking emerges when instruction and representation are closely connected.

Aim and research question

The aim of this study is to explore how compulsory school students express their understanding of technological systems, with a particular focus on their oral and written descriptions as well as their self-drawn models of a wastewater system. By analysing how students describe, explain, and reflect upon the system's purpose, structure, flows, processes, and boundary, the study seeks to identify key aspects of knowledge and characterize patterns in their systems understanding.

The goal is to contribute to a deeper knowledge of how students' understanding of technological systems is manifested, thereby providing didactic implications for teaching aimed at developing systems thinking. The study employs a theoretical classification model in combination with thematic analysis as tools to identify what emerges in students' expressed knowledge.

The study is guided by the following research question:

- What characterizes lower secondary students´ expressed understanding of a technological system, specifically a wastewater system?

Theoretical framework of the study

This study applies the classification model for technological systems developed by Hallström et al. (2022) in combination with the SOLO taxonomy (Biggs & Collis, 1982). The model highlights four key aspects of systems knowledge:

- System boundary and relation to the environment
- The system's purpose
- System structure and behaviour
- Resource flows (material, energy, informational)

Each aspect is analysed using the SOLO taxonomy levels: Unistructural, Multistructural, Relational, and Extended Abstract. This dual framework enables an understanding of both what the students know and how deeply they reason. The framework has previously been used to map progression in students' systems thinking and thus provides an established basis for interpreting the data presented in this article.

Table 1. Hallström et al. (2022), Classification model for system understanding the SOLO taxonomy

	SOLO categories			
Aspect/Quality	Unistructural	Multistructural	Relational	Extended Abstract
1. System boundary and relation to the environment	Describes no boundary	Describes boundary	Relates to the system's environment: people, society, nature, and other systems	Relates to multiple other systems and compares systems with similar purposes
2. Purpose of the system	Relates purpose to individuals	Relates purpose to society	Relates purpose to the use of resources (energy, material, information)	Describes how questions about the system's purpose can be answered on a system level (e.g., identifying multiple purposes for a system)
3. System structure and behaviour (modelling)	Provides examples of components	Describes relationships between components	Relates components to system behaviour and describes the system using a relevant model (e.g., network, cyclic, hierarchical or input/output model)	Describes how changes in components/subsystems affect other components and the system's purpose
4. Resource flows in the system (energy, material, information)	Describes material flows	Describes flows of energy and/or information	Describes energy flowing and being used in the system.	Describes information being used in the system for control purposes
	Concrete	Increased level of abstraction →		

Method

Context description

The study was conducted in a Grade 9 technology class (students aged 15–16) as part of a longer teaching sequence aimed at developing systems thinking. The specific instructional context included prior classroom work on general system features, such as components, flows and boundaries, combined with a study visit to a local wastewater treatment plant. This provided an authentic and tangible reference system, already partially familiar to students from earlier grades (4–6), where wastewater had been addressed in technology.

The teaching sequence consisted of introductory discussions, system diagrams, analysis of system purposes and interconnections, and group work on either the wastewater system or other technological systems. Students were encouraged to describe, compare, and critique technological systems from both functional and societal perspectives. The wastewater system served as a pedagogical starting point due to its combination of visible infrastructure (e.g., manholes and treatment tanks) and hidden processes (e.g., flow dynamics and control mechanisms).

Instruction emphasised identifying system elements and describing flows, but paid less attention to feedback, control and interconnections. The SOLO classification and thematic analysis used in this study provide insight into the effects of this instructional focus on students' systems reasoning.

This pedagogical structure was intended to support students in recognising key system characteristics and applying their understanding across different contexts. However, the emphasis on concrete components and stepwise flows may have unintentionally reinforced a linear mode of reasoning, limiting students' opportunities to explore system dynamics and feedback mechanisms.

Data collection

Data were collected through individual conversations with eleven Grade 9 students who chose to continue working with the wastewater system after being given the option to explore another technological system. The aim was to gain insight into how the students reasoned about the system, with a particular focus on their understanding of structure, purpose of the system, and interconnections.

The study places particular emphasis on students' own voices and representations, both verbal and visual. The combination of spoken reasoning and self-drawn system models allows for a rich and situated insight into students' understanding. This approach is relatively uncommon in previous studies, which often rely on written tests or predefined tasks. By foregrounding students' own ways of expressing system reasoning, the study contributes new perspectives to the field of technology education, highlighting how students conceptualize technological systems beyond formal assessments.

Each student brought their self-drawn system model to the conversation. These models served as cognitive and visual tools to support memory, reflection, and articulation of prior learning. The conversations were conducted in a quiet meeting room at the school to foster a relaxed and secure environment (Kvale & Brinkmann, 2014). Each session lasted approximately 30–45 minutes, depending on the individual participant.

To capture both verbal reasoning and students' references to specific components in their drawings, all conversations were audio- and video-recorded. This ensured that gestures, pointing, and visual cues were preserved and could be analysed in relation to the students' verbal explanations. The interviews were semi-structured, starting with open-ended prompts to encourage free expression, followed by more specific follow-up questions aimed at deepening the dialogue and eliciting elaborated reasoning (Kvale & Brinkmann, 2014).

Analysis of data

The analysis combined two complementary approaches: a deductive classification based on Hallström et al. (2022) and an inductive, reflexive thematic analysis informed by Braun and Clarke (2020). This dual approach was chosen to combine the precision of a structured framework with the openness of an inductive method. This dual approach aimed to explore both the depth and quality of students' understanding of technological systems as well as the content and character of their reasoning.

The deductive framework builds on Hallström et al.'s (2022) extended use of the SOLO taxonomy (Biggs & Collis, 1982), integrating four analytical dimensions: "Level," "Structure," "Modality," and "Generability" to enable a more nuanced categorization of students' knowledge. "Level" refers to the complexity of understanding and is aligned with the SOLO taxonomy levels (e.g., unistructural, multistructural, relational, extended abstract). "Structure" assesses how coherent the reasoning is; "Modality" captures the form of expression (oral, written, or visual); and "Generability" evaluates whether students can apply their knowledge in broader or novel contexts.

This tool enabled the analyses not only of the types of knowledge, situated, conceptual, procedural, or strategic (de Jong & Ferguson-Hessler, 1996), but also of the quality and transferability of that knowledge. The model is particularly relevant when studying learning progression, as it considers students' ability to relate system components to each other and to broader contexts (Hallström et al., 2022).

The classification focused on four central aspects of technological system understanding: (1) system boundary and relation to the environment, (2) purpose of the system, (3) system structure and behaviour, and (4) resource flows. Each student's reasoning was assessed qualitatively for these aspects and assigned a SOLO level. Statements were first broken down into meaning-bearing units, which were coded and sorted under the relevant system aspects. The identification of each aspect was guided by operational definitions developed in the early coding process. For instance, statements indicating what the system is "meant to do" were sorted under "purpose," while references to elements entering or leaving the system, such as water, sludge, or energy, were coded as "resource flows." Descriptions involving connections between parts or sequential stages (e.g., "first the water goes here, then it goes there") were categorized as "structure and behaviour." Finally, indications of where the system begins or ends, or how it relates to its surroundings, were classified as "system boundary and relation to the environment." This consistent coding procedure ensured analytic clarity and intersubjective reliability across student accounts.

Individual analysis documents were created for all eleven students, combining quotations from the conversations with descriptions of their self-drawn system models. These documents provided a multi-layered view of each student's understanding, allowing for the integration of visual and verbal elements in the analysis. This enabled interpretation of how verbal and visual expressions interacted, an important consideration in previous studies (Lind, 2019; Örtnäs, 2007). The documents formed the basis for a synthesized results table, where each student's SOLO level per system aspect is presented. The table offers a systematic overview of individual differences and common patterns across the group.

In parallel, a thematic analysis was conducted across the entire dataset, spoken comments and drawn models combined, to identify recurring themes in how students reasoned about system structure, purpose, and boundary. Unlike the deductive approach, this analysis treated the student group, seeking to uncover shared ways of thinking and expression.
The thematic analysis complemented the classification by making visible the students' conceptual framing of systems thinking. It allowed for the identification of recurring focal points and reasoning strategies that were not constrained by pre-defined categories. This contributed to a richer picture of students' understanding by highlighting how they expressed

relationships, boundaries, and functions in their own words and representations.
The two approaches were thus mutually informative: the classification offered a structured account of students' performance across defined aspects, while the thematic analysis captured more nuanced reasoning patterns and meaning-making processes.

Together, the two analytical strategies, classification and thematic analysis, provide a comprehensive understanding of both what students expressed about technological systems and how well-developed their reasoning was. While the classification model offers structured insights into levels of understanding, the thematic analysis highlights recurring patterns and varying levels of system understanding, particularly in how students focus on components, flows, and purposes, while systemic relationships and feedback mechanisms remain underdeveloped. This combined approach strengthens the study's relevance for developing teaching strategies that promote systems thinking in technology education, with particular importance for education for sustainable development (Koski & de Vries, 2013; Engström & Svensson, 2022).

To enhance the credibility and transparency of the analysis, several measures were taken. The coding process was iterative and reflexive, with initial codes developed independently and then reviewed in relation to both theoretical constructs and empirical patterns. Throughout the analysis, analytical memos were used to document coding decisions and emerging interpretations. The SOLO classifications were discussed within the research team to ensure consistency and intersubjective agreement. In the thematic analysis, constant comparison was applied to verify the coherence of categories and to distinguish between surface-level similarities and deeper conceptual patterns. These strategies support the analytical trustworthiness and ensure that the findings are grounded in the data.

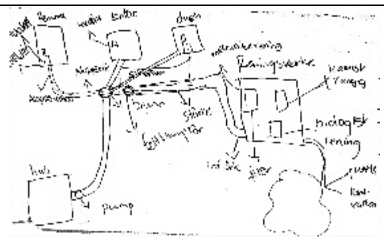
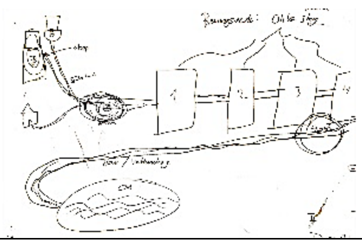
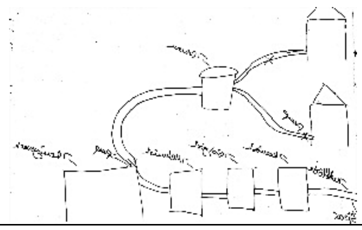
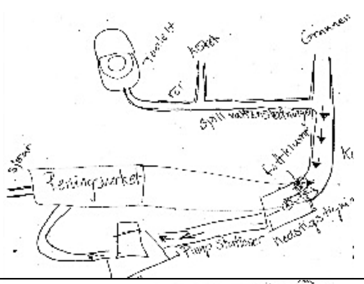
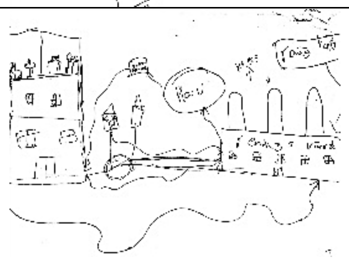
Research ethics and trustworthiness

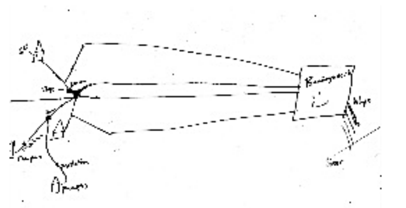
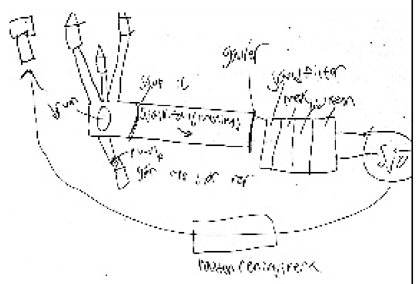
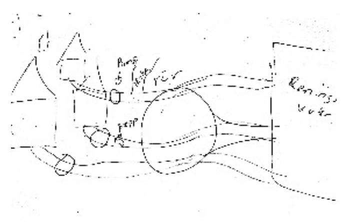
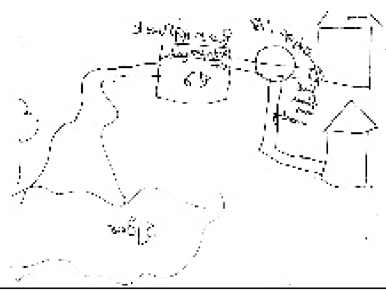
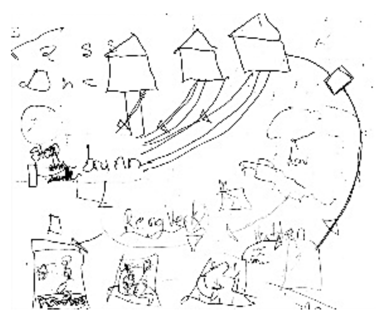
The study was conducted in accordance with the guidelines set out in the Swedish Research Council's publication *Good Research Practice* (Vetenskapsrådet, 2024) to ensure adherence to sound ethical research practices and trustworthiness. Informed consent from the participants was central, and before participation began, everyone received detailed information about the purpose of the study and the nature of the data that would be collected. Participants were given the opportunity to ask questions and express any concerns before they provided written consent to participate. Only individuals who were 15 years of age or older were included in the study. To protect participants' privacy and safety, they were informed that their participation would be anonymous, and that personal information would be handled confidentially. No names or identifying details were used in the reporting or in any other contexts not directly linked to the study. Furthermore, participants received clear information about their right to withdraw from the study at any time without any negative consequences.

Results

To provide an overview of the students' visual representations of the system, the content of their drawn models is summarized in Table 2. This table serves as a complement to the subsequent analysis, as the models in several cases constitute an important part of the students' system expressions.

Table 2. Students' Models of the Wastewater System and Their Content Focus

Student	Drawn models	Alt, text	Explanatory caption
Anna		Model with a pump station lifting water from a lower to a higher level.	Focuses on a pump station handling elevation differences; illustrates technical solution but few system connections.
Diana		Model with purification steps; the word 'sludge' between steps, 'gravity flow' indicated.	Highlights sludge handling and gravity flow; emphasises the purification plant as the hub but lacks links to other systems.
Fredrik		Model of pipes with three purification steps and a misplaced pump.	Illustrates mechanical, biological, chemical purification but misplaces pump where gravity flow is needed, example of 'deep but wrong'.
Hamid		Model with household perspective, blockage in pipes and solutions.	Emphasises operational problems (blockages) and user behaviour rather than system structure.
Aida		Model with toilet → fat lump → pump station → purification plant → lake.	Technically detailed; connects household, operational points and environmental goal, clear purpose focus.
Mia		Model of apartment building with circular flows via purification plant and sea back to the house.	The only model explicitly illustrating a circular flows boundary within the system, introduces system circularity.

Mary		Model with sloping pipes illustrating continuous gravity flows.	Emphasises pipe inclination and constant flows; lacks technology for elevation differences or system links.
John		Model with three houses → pump well → purification boxes → purification plant → sea.	Typical linear model 'household → pump → purification plant → sea'; contrasts with Mia's circular model.
Angelina		Model with multiple houses, blockage symbols, pump, sludge well and purification plant.	Everyday image emphasizing operation, hygiene and environment, student perspective on purpose and maintenance.
Sara		Model with house → pump well → purification plant → open channel to lake.	Simple linear model with a stop/warning state; illustrates unistructural level.
Ryan		Model with simple flows and text about fat in pipes.	Illustrates simple flows direction and fat problems; few technical details but clear everyday connection.

Part 1. Classification of System Understanding According to Hallström et al (2022) and the SOLO Taxonomy

Table 3 summarizes the results and illustrates how the students' expressions are distributed across the four aspects of technological systems and the levels of the SOLO taxonomy. The table provides an overall picture of the variation in the quality of knowledge and enables comparisons between different forms of expression and levels of understanding.

Table 3. Students' qualities of knowledge about a wastewater system according to the SOLO taxonomy

	SOLO categories			
Aspect/Quality	Unistructural	Multistructural	Relational	Extended Abstract
1. System boundary and relation to the environment	Describes no boundary Angelina, Sara, Ryan.	Describes boundary Anna, Diana, Fredrik, Hamid, Aida, Mia, Mary, John.	Relates to the system's environment: people, society, nature, and other systems Diana, Fredrik, Hamid, Aida, Mia, Mary, John	Relates to multiple other systems and compares systems with similar purposes
2. Purpose of the system	Relates purpose to individuals Angelina, Sara, Anna, Ryan, Diana, Fredrik, Hamid, Aida, Mia, Mary, John	Relates purpose to society	Relates purpose to the use of resources (energy, material, information) Diana, Fredrik, Hamid, Aida, Mia, Mary, John	Describes how questions about the system's purpose can be answered on a system level (e.g., identifying multiple purposes for a system)
3. System structure and behaviour (modelling)	Provides examples of components Sara, Angelina, John, Fredrik, Hamid, Aida, Mia, Mary, John, Ryan	Describes relationships between components Anna, John, Fredrik, Hamid, Aida, Mia, Mary, John, Ryan	Relates components to system behaviour and describes the system using a relevant model (e.g., network, cyclic, hierarchical or input/output model) John, Fredrik, Hamid, Aida, Mia, Mary, John, Ryan	Describes how changes in components/ subsystems affect other components and the system's purpose
4. Resource flows in the system (energy, material, information)	Describes material flows Angelina, John, Sara, Ryan, Diana, Fredrik, Hamid, Aida, Mia, Mary, Anna	Describes flows of energy and/or information	Describes energy flowing and being used in the system. John, Sara, Ryan, Diana, Fredrik, Hamid, Aida, Mia, Mary. Anna	Describes information being used in the system for control purposes
	Concrete	Increased level of abstraction →		

Summary of classification results

The classification shows that many students demonstrate multistructural reasoning when describing the purpose of the system and its structure and behaviour. They are often able to identify several components or steps but have difficulty connecting these into a coherent whole. Aida and Diana stand out by showing relational understanding, where the function of the system is described in relation to its components.

In the aspects concerning system boundary and resource flows, the responses are generally less developed. Some students, like Sara and Ryan, mention where the system starts and ends, but without relating it to other systems or broader environmental contexts. Flows of energy and information are seldom addressed, and no student reached the extended abstract level in any of the aspects.

Overall, the analysis reveals a variation in both the number of aspects each student touches upon and the depth of their reasoning. While some responses are limited to listing components or steps in a process, others begin to explore relationships between components and link the system to societal or environmental concerns. Still, most descriptions reflect a linear understanding of the system, typically moving from household to treatment plant to nature. Few students describe systems as networks or refer to feedback mechanisms, and there are very few mentions of interactions with other technological systems. These findings highlight the need for instruction that supports students in moving beyond surface-level descriptions towards a more connected and dynamic view of technological systems.

Shading in Table 3 indicates the SOLO level of students' expressions. Light grey corresponds to *unistructural* responses, where students mention isolated aspects of the system. Medium grey represents *multistructural* reasoning, where multiple components are described without connections. Dark grey is used for *relational* expressions, in which students integrate components into a functional whole. Very dark grey indicates *extended abstract* responses, where students reason beyond the immediate context. White cells indicate that no relevant expression was found for that aspect.

Part 2: Thematic Analysis

Themes were identified through an inductive and iterative coding process. Each theme highlights patterns in how students articulated their understanding of the wastewater system.

The overall purpose of the system

Students commonly described the system's purpose as transporting and treating wastewater to protect human health and the environment. This understanding was typically framed through an input–output perspective, in which contaminated water is moved from households to a treatment plant and then released back into nature.

Aida stated: "We have the wastewater system because otherwise the sewage water goes to lakes and the sea and pollutes them so that it leads to eutrophication and too many nutrients and proteins in the water." Similarly, John described: "The purpose of the system is to provide a clean environment and health." These responses emphasise the system's value based on its outcomes, rather than its internal structure or broader connections.

Most students conceptualised the system as a linear and unidirectional flow, emphasising removal over circulation or reuse. While household sources of pollutants, such as toilets, dishwashing, and laundry, were often mentioned, students did not describe links to other infrastructures, such as drinking water supply or energy recovery from sludge. The system was primarily perceived as an isolated solution to a hygiene-related problem.

The central role of a subsystem – the wastewater treatment plant

The treatment plant was frequently identified as the core of the system. Although students occasionally referred to it as a subsystem, their descriptions often assigned it a central, even dominant, role. Other components, such as pipes and manholes, were typically seen as passive conduits.

Many students described treatment stages, mechanical, biological, and chemical, but with limited technical detail. Angelina explained: "The purpose of the sewage system is to clean the water and remove poo and pee from the home; otherwise, one would have to take it out to the trash oneself, and it would smell, and people would get sick." This reflects a view of the system as a solution to a domestic problem, grounded in everyday experience.

However, few students elaborated on issues like energy use, system-wide coordination, or environmental impacts beyond the local context. The treatment plant was largely viewed as a standalone unit where pollution is processed in a stepwise manner, without connections to broader ecological or technical systems.

The depiction of the system's structure – linear flow

Students described the wastewater system as a series of sequential components. The flow from household to treatment plant was presented as a straightforward path, with little emphasis on interdependencies or networked structures.

Mia said: "I have drawn the entire sewage system with all the pipes and the wells." Her description indicates an understanding of the system as a linear assembly rather than a dynamic whole. Similarly, Anna noted: "There are pumps for the houses that are located lower down, which can pump up the sewage water." This illustrates a problem-solution logic, but without broader system reasoning.

While some students referred to subsystems, such as sludge management, these were often seen as just additional steps, not as components with internal processes or feedback mechanisms. Diana said: "Then there are subsystems in the system too, and that is the sludge management system[...]" but did not elaborate further.

Students frequently attributed maintenance issues to individual user behaviour. Fredrik explained: "Through education and awareness, one can try to reduce the number of unnecessary objects being flushed down the drains[...]" and Hamid added: "There can be blockages[...] and then you fix it yourself[...] Otherwise, the men who work with the pipes come and fix it." These responses suggest a localized understanding of problems, rather than one informed by system-wide design or operational load.

Overall, the system was perceived as a linear arrangement of components, rather than a network with dynamic flows and regulation.

Transport and system boundary

Students described wastewater transport primarily as passive flow via gravity, occasionally supported by pumps. Aida explained: “The wastewater from the apartments or houses always goes downward, so that the flow will work even when there is a power outage.” Diana similarly noted: “The wastewater moves forward through the pipes; they are sloped like this, so it flows by itself down there.” These statements reflect a surface-level understanding of physical conditions, without reference to flow dynamics, pressure, or energy dependence.

Some students acknowledged the role of pumping stations in overcoming elevation differences, but did not reflect on power supply, redundancy, or failure scenarios. John said: “The larger pipes go downward using gravity, but in the houses that are lower down, the water moves upwards with the help of a pumping station.”

System boundaries were usually defined spatially, from household to nature. Diana expressed this clearly: “The wastewater systems start in the home and end out in nature with clean water.” Few students mentioned feedback, loops, or integration with other systems.

A few students touched on potential system connections. Mia said: “When you flush, air goes down and gets pressed down[...] that also has something to do with the ventilation system.” Aida noted: “They take all the fertilizer to the fields.” These ideas hint at systemic thinking but were not developed further.

Challenges such as pharmaceutical residues, industrial discharges, or stormwater inflow were largely absent from student reasoning. Descriptions focused on visible components and straightforward movement, suggesting a limited understanding of system-environment interactions.

Discussion

The aim of this study was to explore lower secondary school students’ understanding of technological systems through their descriptions of a wastewater system, using the SOLO taxonomy combined with Hallström et al.’s (2022) four aspects of system understanding and thematic analysis. The findings illustrate that students primarily express a linear understanding of the system, focusing on visible components and sequential processes, while connections between subsystems, feedback loops, and inter-system relationships are limited.

This study adds to previous research by combining classification, SOLO levels and thematic analysis to offer a more complete picture of students’ systems thinking. The approach highlights not only what students understand, but how they express and organise that understanding. By attending to both verbal reasoning and visual representations, the study provides new perspectives on how students engage with technological systems in school, and how teaching can support that development.

As shown in **Table 3**, most students were placed at the **multistructural level**, particularly regarding system structure and purpose. This aligns with the theme *“Linear flow”*, where students described the system as a simple sequence from household to nature. Similarly, their focus on visible components and isolated subsystems, such as the treatment plant, reflects a fragmented understanding, with few references to energy flows, feedback, or interconnections.

Students demonstrate basic knowledge of the system's components and purpose of the system, but their understanding of system integration, dynamics, and feedback remains underdeveloped**.** Students demonstrate basic knowledge of the system's components and purpose of the system, but their understanding of system integration, dynamics, and feedback remains underdeveloped. This pattern has been recognised in earlier research, where students' reasoning about systems often centres around isolated elements rather than dynamic interrelations (Palmberg et al., 2017; Riess & Mischo, 2010).

The classification places most students at the multistructural level of the SOLO taxonomy, where multiple system components are described but rarely connected into a coherent whole (Hallström et al., 2022; Koski & de Vries, 2013). The thematic analysis confirms this pattern: students tend to describe the system as a simple flow from household to treatment plant to nature. While key components are correctly identified, their interrelationships, feedback loops, and invisible processes such as energy flows or system monitoring are rarely addressed (Meadows, 2008; Senge, 2006).

A key finding is that many students seem to conceptualize the system in a stepwise fashion, where each stage is treated as independent rather than interconnected. This compartmentalized view suggests that students struggle to visualize how changes in one part of the system can affect the whole, or how flows of material, energy, and information are maintained across boundaries.

Although the teaching sequence included both visualisation tasks and a study visit, it may not have provided sufficient opportunities for students to work actively with systemic relationships. The instruction placed emphasis on identifying system components and describing the sequence of flows, but did not explicitly support reasoning about feedback, control or cross-system interactions. This could partly explain why many students remained at the multistructural level. Rather than indicating a lack of conceptual ability, their reasoning may reflect how systems thinking was framed and made visible in the classroom context. By triangulating classification, SOLO levels and thematic analysis, this study provides an integrated view of students' system understanding that goes beyond prior research. While earlier studies have reported similar challenges in fostering students' systemic reasoning (e.g., Riess & Mischo, 2010; Palmberg et al., 2017), this study contributes by combining multiple analytical lenses and providing detailed insight into how these limitations are expressed in students' own reasoning.

One important observation is that while students often associate the system's purpose with environmental and health protection, their reasoning seldom extends to circular processes, long-term effects, or system interdependencies (Palmberg et al., 2017). Subsystems, such as sludge management, are described in isolation rather than as part of a larger network (Lind, 2019). The lack of attention to feedback mechanisms or reciprocal relationships indicates that students' system understanding is often static rather than dynamic. For instance, sludge management is rarely linked by students to agricultural reuse or energy recovery systems, even though these connections are central to sustainable wastewater treatment. Similarly, pumping stations or monitoring systems are almost never mentioned, despite their key roles in regulating flows and connecting different parts of the infrastructure. This suggests that subsystems are not only seen in isolation but also disconnected from broader technological and societal systems, such as farming, energy production, or digital control networks.

Moreover, system boundaries are typically framed as a linear path from household to nature, with limited references to connections with other infrastructures such as ventilation systems or agriculture (Hallström et al., 2022). Students rarely mention how the wastewater system interacts with or depends on broader urban systems, such as energy provision, governance, or circular economy initiatives. This linearity reflects what other studies have identified as a common pattern in young students' system reasoning, where input–output thinking dominates while feedback, regulation, and cross-system relations remain unexplored (Riess & Mischo, 2010).

These findings point to the need for instruction that not only supports the identification of system components but also explicitly highlights system dynamics, hidden processes, and interconnections. Without such pedagogical scaffolding, students risk remaining at a surface level of understanding, unable to transfer or apply systems thinking to other technological or sustainability contexts.

To support the development of systems thinking, instruction should therefore move beyond concrete, linear descriptions towards more integrated, dynamic perspectives. Visualizations, comparative system analyses, and authentic examples can play a key role in this progression (Engström & Svensson, 2022). Additionally, explicit discussions about how real-world systems rarely function in isolation, but instead are embedded within wider societal and environmental contexts, could help extend students' understanding. However, it is also important to acknowledge that students' linear representations may not solely reflect a lack of understanding, but rather a developmental stage in their systems thinking. As such, these representations can serve as valuable starting points for pedagogical interventions that gradually introduce complexity, interconnections, and feedback. The combination of classification and thematic analysis in this study provides valuable insight into how such instructional approaches could be targeted to foster more advanced reasoning.

The findings suggest that instructional design should support the transition from descriptive to integrative reasoning by scaffolding students' attention to system boundaries, feedback mechanisms, and interdependencies. Practical strategies may include comparative analysis of different systems, model-based reasoning, and explicit reflection tasks where students consider the consequences of changes in one part of the system. These approaches could strengthen students' ability to engage with complex technological and socio-ecological systems, aligning with goals in education for sustainable development.

By combining a structured classification model with a reflexive thematic analysis, this study contributes methodologically by illustrating how quantitative indicators of system understanding (e.g., SOLO levels) can be complemented by qualitative insights into students' reasoning processes. This dual approach may be particularly valuable in educational research on complex cognitive domains, such as systems thinking, where both breadth and depth of understanding are important to capture.

Limitations

This study has some limitations that are important to acknowledge. It was conducted in a single compulsory school in Sweden with a relatively small group of eleven students. While the intention was to gain in-depth insights into students' systems thinking, the limited sample size and specific teaching context mean that the findings should not be generalised without caution. The results provide indications of patterns in students' reasoning but cannot be assumed to represent wider populations without further studies across different schools and contexts.

The students had previously encountered the wastewater system through classroom instruction and a study visit. These experiences likely shaped how they described the system in the interviews, and while this was part of the intended design, it also makes it difficult to separate what stems from prior teaching and what reflects students' independent reasoning. Despite the structured instructional approach, many students' responses remained at the unistructural or multistructural level. This may reflect the complexity of systems thinking but also points to challenges in making abstract system aspects visible and accessible in teaching.

Furthermore, the analysis draws on a combination of students' verbal reasoning and self-drawn models. This allowed for a rich interpretation of their understanding, but it also involved interpretation by the researchers—particularly in the classification of reasoning levels using the SOLO taxonomy. Although efforts were made to ensure consistency and transparency, a degree of subjectivity remains. The use of two analytic frameworks strengthened the analysis but also introduced interpretative complexity, especially in borderline cases of classification.

Finally, the study focused on one specific system. The wastewater system was chosen because it is both concrete and complex, but it is unclear whether students would reason in the same way about other systems, such as those involving digital infrastructure or energy flow. While this system provided a relevant context for exploring flows and boundaries, other systems might evoke different conceptual challenges. Future studies could explore how students' systems thinking develops across different types of systems and instructional designs.

Implications for teaching

The study illustrates that lower secondary students can develop an emerging understanding of technological systems when teaching highlights concrete components, flows, and functions. However, this understanding is shaped by what is made visible in instruction. Students tend to grasp what is concrete, like pipes and treatment stages, while abstract or systemic aspects remain hidden. This underscores the importance of deliberate instructional choices that reveal both the visible and invisible dimensions of technological systems.

To foster more coherent systems thinking, teaching must address not only the content of systems but also how systems operate as interconnected wholes. This involves emphasizing structures, processes, relationships, and system behaviours that may not be immediately apparent (Meadows, 2008; Senge, 2006). Many students illustrate a basic, linear understanding of systems. Instruction should therefore highlight network structures, feedback loops, energy and information flows, and links to other societal and ecological systems (Palmberg et al., 2017).

One effective strategy could be to have students compare multiple system models, for example, linear and circular wastewater systems. Such comparative analysis can help make system structures explicit and encourage students to question simplistic or fragmented representations. Engström and Svensson's (2022) teaching model, which combines visualisations, authentic experiences, and reflection, offers practical strategies for making both visible and invisible system aspects accessible. Drawing on students' everyday experiences, such as prior visits to treatment plants, can also help ground abstract concepts in familiar contexts. Moreover, sustainability aspects can be integrated by illustrating circular flows, such as the transformation of sludge into fertiliser or biogas, thus making resource use and environmental impacts more tangible.

Hallström et al.'s (2022) classification model supports both planning and assessment by identifying which system aspects students grasp and which need reinforcement. By combining this with the SOLO taxonomy, teachers can plan for progression from unistructural and multistructural levels towards relational and extended abstract understandings. Formative assessment that explicitly targets students' ability to connect system components, identify feedback, and reason about broader system implications could help guide this progression.

The findings indicate that many students remain at the multistructural level, where system components are identified but not yet coordinated into a holistic understanding. To support progression towards relational and extended abstract reasoning, instruction needs to scaffold students' ability to connect components, functions, and flows within and beyond the system. One approach is to engage students in structured comparisons between systems, where common patterns such as flows, boundaries, and feedback can be discussed. Whole-class modelling activities, using teacher-led visualisations, can also support the identification of interactions and causal relationships between components. Furthermore, Engström and Svensson's (2022) model highlights the value of combining visualisation, authentic contexts and reflective tasks to support students in articulating system relationships. Hallström et al.'s (2022) classification model can be used formatively to identify which system aspects are present in student reasoning and to guide instructional focus. Teachers may support students' movement up the SOLO taxonomy by drawing attention to system dynamics, inviting predictions, and encouraging reasoning about system-level consequences. Together, these strategies can support a shift from fragmented descriptions to more coherent, transferable understandings of technological systems.

Finally, systems thinking should be embedded across the technology curriculum rather than treated as an isolated competence. Early and continuous exposure to systems concepts, increasing in complexity over time, can help students build transferable knowledge and cognitive strategies for analysing diverse technological systems (Riess & Mischo, 2010; Voulvoulis et al., 2022). This progression is crucial for preparing students not only to understand existing technologies but also to critically engage with future sustainability challenges.

In conclusion, fostering systems thinking in technology education requires targeted instruction that makes systems visible, highlights interconnections and dynamics, and situates learning within real-world sustainability contexts. Through this, students can be supported in developing deeper, relational, and dynamic understandings that extend beyond surface-level knowledge and contribute to responsible technological citizenship.

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