A Model for Teaching Systems Thinking

A Tool for Analysing Technology Teachers' Conceptualising of Systems Thinking, and How it is Described in Technology Textbooks for Compulsory School

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This study concerns how technology teachers conceptualize systems thinking and how textbook descriptions of systems can be related to systems thinking. The analysis is conducted using the 'Freiburg heuristic model of systems thinking', which uses four dimensions of systems thinking: (1) declarative and conceptual knowledge, (2) modelling systems, (3) solving problems using system models, and (4) evaluation of system models. It concerns both propositional knowledge and problem-solving skills, which makes it suitable for technology education purposes. Four Swedish technology textbooks, intended for years 7–9 in compulsory school (pupils aged 13–16 years), were analysed. The declarative dimension was present in varying degrees through use of terms and concepts related to systems (component, input, output, etc.). System modelling processes, model use, and model evaluation are absent. An interview with three technology teachers working in compulsory school (pupils aged 7–16 years) rendered similar results. When prompted to describe systems thinking and how it is taught, they talked mainly in conceptual terms (e.g., systems as sets of interacting components). To some extent they discussed pupils' modelling activities, but not how models could be used for problem solving, explanation, or prediction. The teachers also put forward historical perspectives on infrastructure as part of systems thinking. The study suggests that systems thinking in compulsory school could be developed further. The use of system models to understand for example complex environmental problems related to technology use, or perform life cycle analyses is not emphasized, neither by the teachers nor in the textbooks.

Keywords: systems thinking, technology teaching, technological systems, compulsory school, system modelling

Introduction

This paper presents a study of systems thinking in introductory technology education. In compulsory school in Sweden (pupils aged 7–16), technological systems are included in the core content of the mandatory technology subject. The aim is to improve understanding of for example systems' functions and historical development, as well as environmental consequences (Skolverket, 2018). There is however no explicit, clearly described aim to develop systems thinking as a competence. Hallström and Klasander (2020) discuss the capabilities that students should develop when it comes to understanding complex technological solutions and their impacts. They argue that the term *systems thinking* is relevant. We agree, and in this study, we assume that systems thinking is a key competence that is appropriate in the technology teaching context. This is especially true for an educational system such as the Swedish, where there is an explicit intention to integrate environmental studies and encourage a sustainable lifestyle.

The concept of systems thinking has proven to be difficult to grasp. It includes (but is not limited to) understanding a whole as more than a sum of its parts, as well as concepts like feedback and redundancy. It is a way of thinking and understanding that is central within technological system analysis, organisational theory, and studies of ecological systems (von Bertalanffy, 1968; Öquist, 2008). Systems thinking has been discussed in literature about geography and geography education (e.g. Clark & Zeegers, 2015; Riess et al., 2015), biology and biology education (e.g. Riess & Mischo, 2010), organisational theory (e.g. Mingers & White, 2010; Öquist, 2008), studies of sustainable development (e.g. Schuler et al., 2018; Stibbe, 2009), engineering science, technology and engineering education (e.g. Frank, 2000, 2002; Hallström & Klasander, 2017, 2020; Kordova, Frank, & Miller, 2018). Systems thinking is also a concept within the cross-disciplinary field known as 'Science, technology and society' or 'Science and technology studies' (STS) (e.g. Gyberg & Hallström, 2011; Sismondo, 2010).

When teaching, the teacher is guided by content and traditions in his/her own previous teacher education, his/her knowledge about the subject, previous teaching experience and personal interpretations of curricula and syllabi. Textbooks also affect teaching, and often have a strong impact on how learning objectives are communicated (Heikka, 2015; Skolverket, 2019).

Purpose and research questions

The study purports to answer the following questions:

- How is systems thinking included in the technology textbooks?
- How is systems thinking described by technology teachers?

Background and previous research

The term 'system' is used in similar ways in many scientific fields and school subjects. A system can be described as a 'set of elements standing in interrelation' (Bertalanffy, 1968, p. 55) or, in a more elaborated form by Assuraf & Orion (2005, pp. 519–520) as

> A system is an entity that maintains its existence and functions as a whole through the interaction of its parts. However, this group of interacting, interrelated or interdependent parts that form a complex and unified whole must have a specific purpose, and in order for the system to optimally carry out its purpose all parts must be present. […] The interrelationships among the variables are connected by a cause and effect feedback loop […] Yet, the properties attributable to the system as a whole are not those of the individual components that make up the system.

Mingers and White (2010, p. 1148) describe the following four characteristics of systems thinking, based on a management theory view: (1) viewing the situation holistically, as a set of diverse interacting elements within an environment, (2) recognising that the relationships or interactions between elements are more important than the elements themselves in determining the behaviour of the system, (3) recognising a hierarchy of levels of systems and the consequent ideas of properties emerging at different levels, and mutual causality both within and between levels, and (4) accepting, especially in social systems, that people will act in accordance with differing purposes or rationalities.

Frank (2000) lists rules of thumb for the development of technological systems, so-called 'engineering systems thinking laws.' These are elaborated further into a definition of systems understanding put down in a multifunctional definition of engineering systems thinking, which is summarized in eleven categories: (1) understanding the whole system, (2) understanding the synergies of the system, (3) understanding the system from multiple perspectives, (4) understanding the implications of modifications of the system, (5) understanding a new system immediately upon presentation, (6) system complexity level, (7) interconnections, (8) remedies for failures and system problems, (9) analysis and synthesis, (10) don't get stuck on details, and (11) multidisciplinary and interdisciplinary knowledge (Frank, 2002, pp. 1351–1355).

There are technological systems of all sizes and levels of complexity, with different amounts of human involvement. It is often difficult or even impossible to draw a dividing line between 'purely technical' and 'socio-technical' systems. Instead, systems are on a continuum with varying degrees of human participation and influence (Kroes, Franssen, van de Poel, & Ottens, 2006). The general principles for systems and systems thinking (identified e.g. by Frank, 2000; Mingers & White, 2010) are valid for systems of any size or degree of complexity. Well-developed systems thinking enables spotting similarities as well as difference between systems of different size and level of complexity (Assaraf & Orioa, 2005; Frank, 2002).

Furthermore, Gulliksson and Holmgren (2018) emphasize that systems thinking must be supplemented with critical thinking. They describe this as being able to on one's own analyse, reflect, draw conclusions, question and be creative (p. 31). Barile et al. (2018) refer to Stibbe (2009) amongst others and put forward how a system's interconnections provide the key to its function, and how a developed systems thinking allows us to identify these and understand their relevance.

That systems thinking and knowledge about technological systems are among the key competences of technology education is highlighted by numerous researchers, such as Barile et al. (2018), Frank (2000), Klasander (2010), Ries and Mischo (2010), and Svensson (2010). They do however emphasize different aspects of systems thinking. For example Riess and Mischo (2010) describe it as pupils' ability to identify and understand complex, global relations and use methods from systems theory:

> We see systems thinking as the ability to recognize, describe and model (e.g. to structure, to organize) complex aspects of reality as systems. Another important aspect of systems thinking is the ability to identify important elements of the system and the varied interdependency between these elements. Other key aspects are the ability to recognize dimensions of time dynamics, to construct an internal model of reality and to make prognoses on the basis of that model. (Riess & Mischo, 2010, p. 707)

They also put forward the understanding of non-linear relations within systems and that many interactions within a system may occur simultaneously.

Assaraf and Orion (2005) describe how pupils develop systems thinking skills and present an overview of literature concerning pupils' understanding of systems and their systems thinking. Among others, they refer to Senge (1990) who claims that systems thinking practice develop pupils' general skills so that they

> … focus […] on recognizing the interconnections between the parts of a system and then synthesizes them into a unified view of the whole. Furthermore, it deals with recognizing patterns and interrelationships, and learning how to structure those interrelationships into more effective, efficient ways of thinking (Assaraf & Orion, 2005, p. 520)

Hallström and Klasander (2017) study how a group of student teachers describes technological systems. Most respondents described only the visible parts of the systems, and the sub-functions that could be

Table 1. Freiburg heuristic competence model of systems thinking (Riess et al., 2015, p. 18)

Competence dimensions	Sub-capability 1	Sub-capability 2	Sub-capability 3	Sub-capability 4
Dimension 4: Evaluation of system models	Determining the structural validity of system models	Determining the performance validity of system models	Determining the validity for the application	Determining the uncertainty of a forecast
Dimension 3: Solving problems using system models	Assessing the need for using a system model for processing the present problem	Assessing the type of system model (e.g. quantitative vs. qualitative) which is required to process a problem	Giving explanations, making predictions, and designing technologies based on qualitative system models	Giving explanations, making predictions, and designing technologies based on quantitative system models
Dimension 2 modelling systems	Determining system elements, interactions, subsystems, system boundaries, system hierarchies and the model purpose	Understanding and reflecting on a complex system with the help of a text field or a word model	Reading and understanding qualitative system models. Constructing influence diagrams	Reading and constructing quantitative system models
Dimension 1 declarative/conceptual systems knowledge	Basic knowledge of systems theory (system concept, system structure, system behaviour, sub-systems)	Knowledge of areas that can be considered as systems (also knowledge of simple and complex systems)	Knowledge of system hierarchies (e.g. cell, tissue, organ, organism, population, biocenosis, eco-system, biosphere)	Knowledge of properties of complex systems (structural and dynamic complexity, non-linearity, emergence, …)

attributed to those parts. They showed no or only trivial understanding of how components make up larger systems. Some respondents did have a rudimentary ‘systems thinking’, expressed by describing how information, energy, or matter was transferred through the system. Only a small minority showed any understanding of the systems’ control mechanisms. The roles played by human beings were commonly omitted. Hallström and Klasander (2017) emphasize how three complementary perspectives are necessary to understand technological systems: components, systems, and system’s interaction with the outside world. In a subsequent article, Hallström and Klasander (2020) suggest pedagogies for teaching and learning about technological systems and thus systems thinking: (1) *an interface pedagogy*, starting with the interface between the supposed system and the human beings using it, (2) *a holistic pedagogy*, starting with a technological system and move from that wholeness and successively identify important sub-systems and components, (3) *a historical pedagogy*, following the historical change of a technological system and identify important structures, subsystems and components, and (4) *a design pedagogy*, analysing existing systems, and include making, or prototyping, technological systems of appropriate complexity.

Theoretical framework for the analysis: a model for systems thinking

With aim to define systems thinking and link it to technology education we adopt the systems thinking model presented by Rosenkränzer et al. (2017). They describe systems thinking as a multi-dimensional concept, and how knowledge within the area can progress: from simple to complex, from qualitative to quantitative. The model shares many characteristics with the descriptions of systems thinking presented above but places a greater emphasis on the creation and use of system models. Rosenkränzer et al. (2017) summarise the different dimensions of systems thinking in a table, the so-called ‘Freiburg heuristic competence model of systems thinking' (hereafter referred to as the 'Freiburg model'; see table 1). The model identifies four dimensions of systems thinking: (1) declarative and conceptual knowledge, (2) modelling systems, (3) solving problems using system models, and (4) evaluation of system models.

The Freiburg model includes general knowledge of system concepts as well as the ability to create, use and evaluate system models. Understanding and using models of systems (physical, symbolic, mental, mathematical, text-based) are inevitable parts of systems thinking, as many systems are not available for direct study. The Freiburg model was developed to describe the knowledge and knowledge development of student teachers in geography and biology. It has been used in other areas as well, for example by Schuler et al. (2017, p. 195) who used it to analyse teaching about sustainable development in higher education. Rosenkränzer et al. (2017) stress that it is important for teacher students to reach the higher levels of systems thinking (dimensions 3 and 4). Only those who reach those levels can use models to make in-depth analyses of systems and discuss for example sustainable development in relation to their complexity and dynamics. The Freiburg model was developed for use in higher education, to analyse the systems thinking of student teachers. One must keep in mind that the systems thinking related to the uppermost levels (competence dimensions 3 and 4; sub-capabilities 3 and 4) presented in textbooks for compulsory school could not be on par with that of a student teacher. The quantitative models must be of a much simpler kind, as the pupils cannot be expected to have any in-depth knowledge of mathematical or statistical methods. Nevertheless, the Freiburg model provides a useful framework for describing learning of systems thinking even among teenagers.

Methods for data collection and analyses

The ensure the usefulness of the Freiburg model when analysing systems thinking in compulsory school, we applied it to two technological systems that are commonly used as teaching examples in Sweden: Internet (for pupils aged 13–16) and the storm-water system (for pupils aged 10–12). See tables 2 and 3.

A group of three technology teachers (for pupils aged 7–10, 10–13, and 13–16 respectively) participated in a thematic group interview (Dahlgren & Johansson, 2012), which lasted for approximately one hour. The interview was conducted according to the ethical directives of the Swedish research council (Vetenskapsrådet, 2017). During the interview, one researcher was guiding the discussions with a few questions about how to define technological systems and what knowledge about them that is important in technology education, but it was mainly a discussion between the respondents. The session was recorded and transcribed verbatim. The number of teachers is limited, wherefore the results are not possible to generalise to the whole population of technology teachers. As the teachers work in different schools and with pupils of different ages, it should however be possible to get an overview of common ideas concerning systems thinking within the larger group.

The transcript was analysed, using a thematic method adopted from Braun and Clarke (2006). Statements and standpoints were classified and characterised using the Freiburg model's dimensions and sub-capabilities.

In addition to the teacher interviews, we conducted a content analysis of textbooks, using the method of Boréus and Bergström (2018). All relevant content about technological systems was divided into their smallest common units. Thereafter the content units were categorised in relation to the Freiburg model. All four currently available comprehensive technology textbooks intended for use in lower secondary school (pupils aged 13–16) in Sweden were studied: *Titano teknik* (Fridh, 2017), *Spektrum teknik* (Karlsson & Brink, 2017), *Puls teknik* (Sjöberg, 2012), *Teknik direkt* (Svensson et al., 2018).

Table 2. The Freiburg heuristic model of systems thinking applied on the Internet.

Competence dimensions	Sub-capability 1	Sub-capability 2	Sub-capability 3	Sub-capability 4
Dimension 4: **evaluation of system models**	Compare a block chart of a home network with the real equipment	As 1, but with numerical figures describing the network's capacity with different number of clients	Discuss how the models in 1 and 2 can be used.	Can we be sure that that the prediction in dim. 3, s.-c. 4, is correct?
Dimension 3: **solving problems using system models**	Realising the usefulness of a system overview when finding what is wrong with a home network (which wire is which etc.)	Discussing the advantages and drawbacks of detailed vs. overview block charts for error checking in a home network	Determine what internet users in Sweden would experience if the main Atlantic cable was disabled	How much will an individual user of the home network be affected if another client is connected?
Dimension 2 **modelling systems**	Identify components in a chart of the Swedish part of the internet	Identify crucial components and possible bottlenecks in a chart of the Swedish part of the internet	Draw block chart of home network (wireless LAN)	Numerical descriptions of network efficiency
Dimension 1 **declarative/conceptual systems knowledge**	Client, server, router, DNS, local area network (LAN)	Individual computer, local network, operator data network, internet	Individual computer, local network, operator data network, internet	Scalability, collaboration overload, network identification, security issues of large systems

Results

During the group interview, the teachers mentioned the notion of a system as a set of parts, and that the whole is different from the parts numerous times. Using the Freiburg model's categories, we find that many of their statements belong to dimension 1 ('Basic knowledge of systems theory'), sub-capability 1. They repeated statements about components, structure, and behaviour. When prompted to describe what systems thinking is and how it is taught in school, they talked mainly in conceptual terms (along dimension 1). They dealt with both complex and simple systems, as well as systems hierarchies (sub-capabilities 2 and 3): 'We discuss the car and its different sub systems' and 'very complex systems things, and subsystems that are smaller.' To a limited extent they mentioned pupils' modelling activities, but not how the models could be used for problem-solving, explanation or prediction. On a few occasions, one of the respondents argued for the need for modelling, related to dimension 2 ('Modelling systems'): 'One needs to see it from above, to see how everything depends on each other' and 'We must help the pupils with modelling to understand how the system is built.' One of the teachers argued for the need to see the system in real life and make some comparison with the taught system. Such statement could be interpreted as (very weakly) related to dimension 4 ('Evaluation of system models'). Occasionally, one of the teachers stressed how 'technological systems can solve problems' and how 'humans always have solved problems with technological systems.' The respondents also stressed historical perspectives on infrastructure as part of systems thinking, which is not included in the Freiburg model.

As all four studied textbooks are intended for use in the same subject for the same group of pupils, studying according to the same curriculum, there are many similarities. All the books mention various

Table 3. The Freiburg heuristic model of systems thinking applied on the storm-water system.

Competence dimensions	Sub-capability 1	Sub-capability 2	Sub-capability 3	Sub-capability 4
Dimension 4: **evaluation of system models**	What parts and components of a real rain/storm-water system are represented in the model? Does the model correspond structurally to reality?	Compare the model with the realty, including studying a real system. Find a system, study its structure, flows etc. Does the model correspond generally to reality?	Discuss how to use the model of the rain/storm-water system to simulate conditions in reality with aim to solve problems with overflowing, pollution etc.	How well does the model of the rain/storm-water system correspond to the reality, for predicting problems?
Dimension 3: **solving problems using system models**	Reflect over overflowing- and environmental-, and other problems due to rain/storm-water and drain-water realise that the water must be diverted and treated into a rain/storm-water system.	Deciding the size of the rain/storm-water system, what components, methods and parts are needed, and how detailed the system is needed to be processed.	Use the model and make conclusions about how water volumes are handled in the system and use the model to suggest changes to the rain/storm-water system. About components, methods how many and how they are structured.	Use the model and make conclusions about how water volumes are handled in the system and use the model to suggest changes to the rain/storm-water system. Based on calculations and measurements.
Dimension 2 **modelling systems**	Identify components and interactions in an ordinary rain/storm-water system. Also interactions with humans and with environment.	Describe how water is led to the system, describe the system in plane and in profile, how and why the rain/storm-drain-water flows.	Draw the system, use appropriate symbols.	Make numerical descriptions of drainage areas, estimate flows, calculate the amount of water that is contained within the system.
Dimension 1 **declarative/conceptual systems knowledge**	Storm water drains, storm water pipes, percolation, and runoff.	Drainage system, pump station, roof water system.	Roof water → drainage system → storm water system.	Water volumes, flow capacity in pipes, flooding capacity, …

types of technological systems. To what extent they are discussed *as systems* varies considerably, though.

Sjöberg (2012) highlights the ability to recognise technological systems: (1) to analyse and explain how technological functions are combined and work together, and (2) to determine what to include in a certain technological system. Throughout the book, phenomena that are systems or components in systems are described. Their characteristics are however not described in system terms. The systems are overshadowed by the individual artefacts. Approximately one third of the book deals explicitly with technological systems. Terms such as system border, component and infrastructure are introduced. The reader learns that systems are characterised by the flow of energy, matter and/or information, and that individual components store, process, or control. Included system models are simple block charts. In Freiburg model terms, the systems thinking expressed by Sjöberg (2012) is dominated by dimension 1, sub-capabilities 1 and 2. Sub-capability 3, 'system hierarchies', is described to a limited extent. Dimension 2 of the Freiburg model is also visible in the book, but only sub-capability 1 ('Determining system elements …'). The provided models are all very simple and the lack of detail make understanding difficult. Pupils' own system modelling is not discussed at all; dimensions 3 and 4 ('Solving problems using system models' and 'Evaluation of system models') are absent. None of book's the exercises are connected to the provided system models.

Svensson et al. (2018) include a chapter titled 'Technological systems.' Systems are also discussed in other chapters. The need for models and modelling to understand large technological systems is identified. The need for systems thinking to grasp the complex issues of sustainable development is also mentioned. A section focuses on the information, matter or energy that flows, and the components which store, transform or control. System-related terms like component, black box and flux or flow are introduced in the system chapter, but used sparingly in the rest of the book. Autonomous vehicles are described in a non-systemic way. Another example are bridges, which are described in terms of geometries and materials. That they are components in transportation systems is not mentioned. In the autonomous vehicle and bridge cases, not one single box in the Freiburg model can be ticked, even though the systemic character of the phenomena is obvious. The explicit attempts to introduce systems thinking is reserved for the systems chapter. In dimension 1, Svensson et al. (2018) cover sub-capabilities 1 and 2 to some extent, with lists of terms that are explained and many examples. Attempts to describe the concept of feedback-based control are made. System hierarchies are not discussed at all. Some modelling concepts are introduced, and model use is discussed. We learn that models are used to describe and analyse large systems that are difficult to get an overview of, as well as small and embedded systems. How models are used beyond the textbook context is not mentioned at all. In dimension 2, Svensson et al. (2018) do not get beyond sub-capability 2 ('understanding and reflecting …'), despite the best intentions. Dimensions 3 and 4 are absent from the book. Limitations of models are not made explicit anywhere in the text and no problems are solved using them. The exercises and questions provided deal only with model creation, not with model use or evaluation.

Compared with the other books, Fridh (2017) has a stronger focus on industrial processes, electronics, and machinery. There is no chapter dedicated especially to systems theory or the study of systems. The word 'system' does not even occur in the book's index. Small as well as large systems are however to be found throughout the book, even though they are not identified as such. System models in the form of block charts are common. None of the field specific terms are used, and the relation between model and reality is not discussed. As of this, Fridh (2017) does not really support the development of systems thinking, as described by the Freiburg model.

Karlsson and Brink (2017) show the lowest level of systems consciousness of the four books. Most chapters deal with everyday technologies such as electricity, a veterinary hospital, electronic payments and virtual currencies, the mobile telephone etc. There is an apparent focus on modern technologies, which either are parts of large technical systems or rely on large technical systems for their function. Nevertheless, the system perspective is never made explicit. There are no sketches or block charts showing components and their interaction in large systems. Systems terms such as 'component' and 'sub-system' are absent. Karlsson and Brink (2017) do not support the development of systems thinking as described by the Freiburg model.

Discussion and conclusions

The Freiburg model was originally designed for the analysis of systems thinking among geography teacher students. In this study, we have applied it to textbook representations of technological systems and teachers' descriptions of how said systems take place in their teaching.

The teachers describe how they teach about systems along similar lines as those described by Hallström's and Klasander's (2020) different pedagogies. The commonly emphasise the *holistic pedagogy*, concentrating on the system as an aggregate of parts or sub-systems, or the *historical pedagogy*. Models (physical) are built to get an overview, but nobody mentions using them for problem solving. In the Freiburg model's terms, the teaching almost exclusively concerns the first dimension, 'Declarative and conceptual systems knowledge'. The teachers express a view of systems thinking that is limited to having an overview of the system, knowing components, sub-systems, and how they are connected. Modelling or model use are not seen as subject content on their own merits, just as ways to gain the overview.

The textbooks express attitudes similar to the teachers'. Two of the books use models to explicitly provide overviews of different systems. They do however neither explain how models could be used for analysis and problem-solving, nor the nature of models, their creation, and limitations. If the teachers' attitudes have been influenced by the textbooks or the textbook authors have been affected by actual teaching practices is not known (see Heikka, 2015; Skolverket, 2019).

The conclusion is that systems thinking obviously is represented in a very shallow way in both Swedish technology textbooks for lower secondary school and in the interviewed teachers' classrooms. A system is treated as a structure of components in interaction and described using certain special terms. Systems and systems thinking is not explicitly connected to social or environmental issues (compare Gulliksson & Holmgren, 2018). Control problems, explanation and prediction of systems' behaviours, or the modelling process are not addressed. This is in stark contrast to the Freiburg model's systems thinking, where interpretation, creation, and use of models are described as fundamental parts.

Future studies

The Freiburg model for system thinking provides a structure that we believe could be used for both planning and evaluation of teaching. The model's structure describes a possible learning progress, from low level competence dimensions and sub-capabilities to higher. It provides a structure for learning to recognize and describe a technological system, as well as to use system models for structuring complex aspects, analysing important elements, solve problems, and evaluate the model in relation to the real world. In a future study, we intend to examine possible uses of the Freiburg model when teaching about technological aspects of complex environmental problems and sustainable development.

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