Towards a Student Systems Thinking Inventory

Defining 'Qualities of Knowledge' about Technological Systems

Jonas Hallström, Claes Klasander and Ann Zetterqvist

Assessment of students' technological knowledge is a challenge for teachers. This stems not only from the inherent complexity of technological knowledge but also from the short history of technology education and its assessment practices. Furthermore, technological systems as a curriculum component is complex, under-developed and under-researched. The aim of this study is to investigate 'qualities of knowledge' about technological systems, by constructing and evaluating with students in secondary education a test instrument about water supply and sewerage. The test instrument was distributed to 32 students in a Swedish grade eight class (14–15 year olds), and data analysis was carried out using a qualitative, hermeneutic method. The findings show that the students' qualities of knowledge regarding the overall structure of the systems was quite advanced, but the systems or the societal context were not elaborated upon with any detail. The purpose of the system could be connected to humans and society, but students did not offer a definition of the overall purpose. The flows that the students described were only of matter (water, wastewater) but not energy or information. The system boundary was also elusive, except for waste coming out of the sewer system and other environmental consequences. Thus, the test instrument "worked" in the sense that it was possible to gauge students' qualities of knowledge, especially regarding system structure, but the validity might need to be improved with respect to some system aspects.

Keywords: technology education; technological systems; secondary school; qualities of knowledge; assessment

Introduction

Assessment of students' technological knowledge is a challenge for teachers. This stems not only from the inherent complexity of technological knowledge (Mitcham, 1994; Vermaas, Kroes, van de Poel, Franssen, & Houkes, 2011) but also from the short history of technology education and its assessment practices. Furthermore, technological systems as a curriculum component is complex, under-developed and under-researched. A previous study showed that the learning demands on students from the teachers was low and not at all at the level required by the Swedish curriculum, which presumably has to do with an insufficient understanding of systems even among teachers (Schooner, Klasander & Hallström, 2018). Even though the previous research is rather limited, a few conclusions about students' and teachers' knowledge of technological systems can be drawn. Firstly, both students and teachers are better at understanding structure, input and output of a system than its behaviour, and control mechanisms and flows of information are particularly difficult to grasp. Secondly, students understand systems better when they are scaffolded by e.g. teachers, and thirdly, students develop a deeper understanding of systems as they grow older, especially regarding the included components. Finally, the role of humans in and around a technological system is difficult to comprehend, probably because humans fulfil so many different roles as designers, users and operators and thereby function as crucial but multifaceted components of the system (e.g. Hallström & Klasander, 2017; Koski & de Vries, 2013; Mioduser, Venezky & Gong, 1996; Svensson, 2011; Örtnäs, 2007).

However, there is as yet no agreed upon template for what constitutes qualitatively different knowledge of technological systems, although Svensson, Zetterqvist and Ingerman (2012) did formative research towards this end. The aim of this study is therefore to investigate 'qualities of knowledge' about technological systems, by constructing and evaluating with students in secondary education a test instrument about water supply and sewerage.

Theory, Study Design and Method

When learning about technological systems, some aspects are considered to be more difficult than others. For example, visible components in a system are easier to understand than abstract, invisible phenomena such as feedback loops or system borders, and linear systems are more easily understood than non-linear systems (e.g. Arbesman, 2017; Hallström & Klasander, 2020). In order to further explore how students understand technological systems, we designed test instruments that were built on hypothesized qualities of knowledge about technological systems. A technological system can be defined as a purposeful collection of components or sub-systems, connections and flows between them, and a system boundary that delimits the scope of the system. Based on this definition, the test instruments were constructed to incorporate a broad array of aspects of system knowledge, which relied on theories of technological systems and were supposed to give students opportunities to reflect upon and express e.g. their knowledge of the functions of certain technological systems, how they are delimited, what components they include, what kind of resources that flow through the systems, the systems' relation to their surroundings, the systems' historical development, how the systems are controlled, etc. (e.g. Bijker, Hughes & Pinch, 2012; Hughes, 1983, 2004; Ingelstam, 1996, 2012; Klasander, 2010; Vermaas et al., 2011).

Related to the above characterization of systems, we included altogether four different aspects of technological systems, and in these we hypothesized that different qualities of knowledge could manifest:

1. *System boundary and relation to the surrounding*: describe boundary → relation to the system's surrounding: humans, society, nature and other systems (interdependence between systems) → relate to several other systems and compare systems with similar purposes.

2. *Purpose of the system*: exemplify purpose → relate purpose to humans → relate purpose to society → relate purpose to use of resources (energy, matter, information) → describe how questions about the purpose of the system can be answered on a systemic level (e.g. that it is possible to find several purposes of a system).

3. *System structure and behavior (modelling)*: exemplify components → relationship between components → relate components to system behavior → describe the system using relevant model (e.g. network or cyclical model, hierarchical model, or input/output model) → describe how changes to components/sub-systems influence other components as well as the purpose of the system.

4. *Resource flows in the system (energy, matter, information)*: describe flows of matter → describe flows of energy and/or information → describe energy that flows and is used in the system → describe information that is used in the system for control purposes (cf. Hallström & Klasander, 2017; Schooner et al., 2018; Svensson et al., 2012).

The above four aspects of technological systems knowledge can be seen as crucial elements of a solid understanding of technological systems, and in this sense they are not ordered hierarchically but they are rather complementary.

Within each aspect, however, there is an increased complexity of knowledge, of which some but not all knowledge may be needed for a higher order understanding of technological systems. We thus define 'qualities of knowledge' as stages or phases of an increased complexity of systems knowledge (cf. de Jong & Ferguson-Hessler, 1996; Friege & Lind, 2006). This way of describing increased knowledge depth or complexity, has certain similarities with the SOLO taxonomy (Structure of the Observed Learning Outcome). It also describes knowledge qualities in the sense of increased complexity and focus on quality, from unstructured to generalizable knowledge – unistructural, multistructural, relational and extended abstract (e.g. Biggs & Collis, 1989; cf. also Wilson, 2009).

The test instruments for investigating the increased knowledge complexity – the qualities of knowledge – contained some 20 different contexts, and in each test item there were between two and five sub-questions. The contexts focused on, for instance, water supply and sewerage, the national electrical grid, cars and road transport, smartphones, elevators, GPS or electric ovens. The instruments were thus varied regarding different types of technological systems, and also the distribution of present-day and historical examples. We also included different "starting points" for the examples of systems. One of the starting points is the interface between the supposed system and the human beings using it, for example, a toilet, a smartphone or an ATM machine. Another starting point is a fairly well-known technological system, e.g. the railway system, and then one moves from that wholeness and successively identifies important sub-systems and components. A third starting point is following the historical change – forwards from a prior point in time, or backwards from now – of a well-known and agreed upon technological system (Hallström & Klasander, 2020).

For this paper, one particular test instrument about water supply and sewer systems was employed (see Figure 1, the House). The test instrument the House was designed with four sub-questions supposed to give the students opportunities to fill in answers showing different qualities of knowledge of the wholeness of the freshwater and sewerage systems centered on the House. Table 1 outlines what technological systems aspects were focused in the four sub-questions of the test instrument.

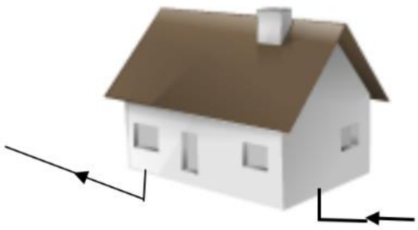

Figure 1. Image of The House, used in the test instrument to visualize and scaffold the students when answering the sub-questions

Table 1. Outline of sub-questions (a-d) and included aspects of technological systems knowledge (1-4) of the student test instrument about water supply and sewerage systems.

The sub-questions in the test instrument the House	*Built-in aspects of technological systems knowledge in the test instrument*
a) What is the freshwater system for? What important needs of the inhabitants of the house can the system fulfil?	2. Purpose of the system
b) What is the freshwater system for? What important needs of society can the system fulfil?	2. Purpose of the system
c) How does the freshwater system work? Start with drawing a simple image of the freshwater system. Exemplify with some parts of the system that you think are important and describe how these work together.	1. System boundary and relation to the surrounding; 2. Purpose of the system; 3. System structure and behaviour (modelling); 4. Resource flows in the system (energy, matter, information).
d) Does the freshwater system impact on the environment? If so, how?	1. System boundary and relation to the surrounding

Data collection and data analysis

To try out the test instrument with school students we contacted teachers connected to a national network of technology educators, in order to see if they were interested in participating in this project. Through word of mouth we eventually got a positive response from a secondary school in a mid-sized Swedish city, so the sampling method was basically so-called snow-ball sampling. The test instrument about technological systems was subsequently distributed in a grade eight class (14-15 year olds) at this school, consisting of 32 students. Altogether 14 copies of the test instrument the House were thus filled in by all 32 students in this secondary class; the students worked in pairs or in groups of three. The gender distribution was even, 17 girls and 15 boys.

The analysis, coding, and categorization of the collected data were performed based on the Swedish transcripts. Excerpts that were included as particularly illustrative examples were translated into English by the authors. A hermeneutic, qualitative method of analysis was employed when coding and categorizing the data, that is, single texts were related to the whole body of texts, the built-in aspects and the systems context in a reciprocal, re-interpretive way (cf. Ödman, 2007). Since a minor part of the empirical material was also made up of the students' drawings of components and systems, often with textual comments, we also employed so-called iconotextual analysis. This is a hermeneutic analysis of the drawings by themselves or together with textual comments (cf. Axell, 2015). We roughly followed the structured phases for qualitative coding and categorization proposed by Braun and Clarke (2006), alternating inductive and deductive stages, in relation to aspects of technological systems and qualities of knowledge. The presented findings constitute the collective picture of the students' conceptions of various aspects of the water supply and sewerage systems.

Research Ethics and Validity

Throughout the research process the ethical principles for research were followed by informing the participants about the purpose of the study and about their right to consent and to discontinue their participation should they wish to. Furthermore, the participants were informed about their participation being anonymous, and that the data would not be used for anything other than research purposes (Swedish Research Council, 2017).

The validity of the study was ensured by carefully trying out the questions in several stages, with several actors contributing to the validity at each stage. Our results can only be seen as representative of the 32 students, although we hope to generate more general inter-subjective validity through them (Larsson, 2005).

Findings

Our findings from the analysis of the students' answers to all four sub-questions (a-d) in the test instrument the House are here presented with respect to the four aspects (1-4) and the qualities of knowledge.

System boundary and relation to the surrounding

Only two groups of students (N=5) implied a system boundary so in that sense most students did not express an elaborated quality of knowledge. However, at the same time both these two groups misconstrued the connection between the water system and the sewerage system because they both suggested that the wastewater from the house goes to the wastewater plant and then directly back into the freshwater system. In reality, the purified wastewater is discharged into a nearby waterway and has to be purified again in a freshwater plant before it is fed back into the water supply system.

Purpose of the system

When it comes to describing the purpose of the water system we looked for if and how they described this in respect to the individuals in the house and to society. Almost every group wrote that the purpose was to provide water to houses and society (fire brigades, public swimming pools, factories etc.) Less than half of the groups wrote about a purpose in terms of leading away water from houses, even less from parts of the city (drains, wastewater, sewage). Some indications on such purposes could, however, be found in their drawings, although not explicitly. One observation from the analysis of the students' answers is that they focused on giving examples on what the incoming water should be used for. All groups mentioned washing, almost every group mentioned food preparation, half of the groups mentioned heating and the few who mentioned a purpose of leading away water wrote about toilets. On a societal level the examples were broader and fairly equally distributed between water used for fire brigades, hospitals, swimming pools, production companies, shops, heating, refuse collection, water towers, schools and flooding. All of these were mentioned between one and four times in total. In summary, most groups focused on the input of water to houses and cities, rather than output. The examples given were richer on the societal level.

System structure and behaviour

Regarding the most basic knowledge about a system's structure and behaviour, all student groups except for two groups (N=4) could exemplify components and specify relationships between components in the water system. However, the next stage of specifying how the components relate to the behaviour of the system was less well understood among the students; here they were either vague about the relationship between components and the system as a whole, or they described too small a part of the system. All in all, fewer students managed this stage than the previous (22 out of 32).

The next stage, describing the system using a relevant model, was something that more students managed than the previous one, although there were many incomplete models or downright misconceptions. All students except for three student groups (N=6) completed the task of providing a system model, of which one was a verbal model and ten were visual models (cf. Gilbert, 2004). Below is an example of a verbal model/analogy:

> A water system works like the blood system. […] The heart is like a water tower that keeps the pressure up all the time. The capillaries are like the system that pumps water (T10-3).

Of the visual models all but one, were input-output models, but only a few of them were also of a more complex network kind, such as the one below (Figure 2, T10-7).

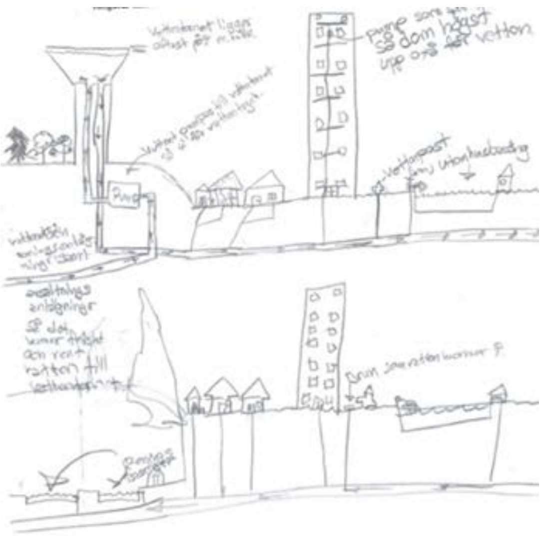

Figure 2. Example of a system drawing that shows visible components as well as pipe networks under ground.

This was also the only student answer deemed to reach the more elaborate last knowledge quality, to describe how changes to components/sub-systems influence other components as well as the purpose of the system. Thus, most of the models were basic such as of the input-output kind but lacked the more intricate descriptions of networks of components, and there were also some misconceptions such as the one below (Figure 3, T10-13) where the wastewater plant feeds directly back into the freshwater system.

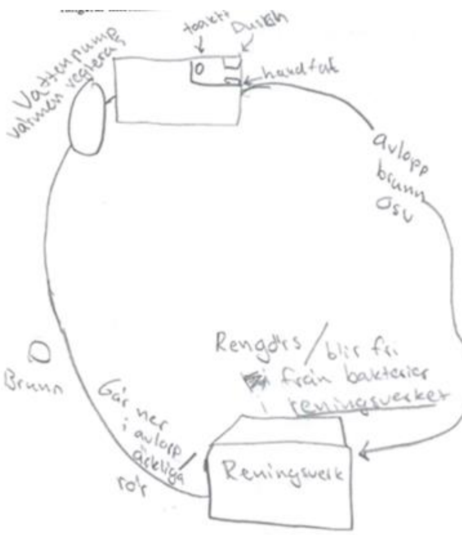

Figure 3. Example of a system drawing depicting a closed loop between the water and sewer systems.

Resource flows in the system

Not surprisingly, most students described flows of matter in the form of water. They described in words and/or pictures how the water flows from the water plant and water tower through pipes to the house, and some also depicted how wastewater is discharged from the house and goes to the wastewater plant.

The students did not however, describe flows of energy or information nor how these flows are used in the system, with one exception. A couple of students correctly observed that hot water carries energy, although it is unclear if they mean hot water input into the house (in which case, this really comes from district heating systems) or within the house (from e.g. a home heating system):

> The water system exists for us to be able to reuse the water again and again, and even be able to control the temperature. That is, get heating to the taps, etc. (T10-13).

Concluding Discussion

The teacher of the participating students divulged that the students had not been taught about the water systems in houses or society. One student wrote: "This was the first time I heard the word 'water system'". In the textual answers and drawings, we could however see that the students had been educated about how a water tower works and how it distributes pressure in a system. We suppose that this might have been more a part of previous science teaching than technology. Students were also presumably taught about environmental pollution within science (d) but not very much about the technological aspects of systems (a-c).

Especially regarding the purpose and resource flows of a system, the students often did not reach higher levels of understanding, which we interpret is either because the teaching was not advanced enough or that our probes, the test items, did not allow them to express such understanding. For example, we only asked about "the water system" not "the water and sewer systems", while the figure in the test instrument shows arrows for both input and output (see Figure 1) and the students sometimes referred to sewerage in their answers.

When the students answered, for example, the question about the purpose of the water system for the individual they often exemplified by mentioning activities (take a shower, drink water, flush the toilet...), but they did not explicitly write about the purpose and main function of the water system. Our position when interpreting the student answers is thus parallel to the teacher's because we both try to identify if the student has shown his or her understanding of the purpose, etc. of the water system as a whole.

In conclusion, the students showed quite advanced qualities of knowledge regarding the structure of the system, and some students could draw quite detailed systems near the house with freshwater plants and water towers. However, the systems within the home were not elaborated upon with any detail, nor was the wider societal context. The purpose of the system could be connected to humans and society but students did not offer a definition of the overall purpose. The flows that the students described were only of matter/water, not energy or information, so there was no notion of the driving forces or control of the systems. The system boundary was also elusive, except for waste coming out of the sewer system and other environmental consequences. All in all, this study thus confirms much of previous research (e.g. Hallström & Klasander, 2017; Koski & de Vries, 2013; Mioduser, Venezky & Gong, 1996). Thus, the only one of the four aspects of technological systems in our study that seems to have "worked" is number 3, although students generally did not reach the most advanced qualities. In aspects 1, 2 and 4 students never reached beyond the less advanced knowledge qualities. In this sense, even regarding these qualities of knowledge, our study largely confirms earlier studies.

So what, finally, is the verdict on the test instrument and the qualities of knowledge? On the one hand, they do work in the sense that the student answers in this study could be categorized in terms of these qualities of knowledge. On the other hand, they might be less valid for measuring a presumed progression in systems thinking and technological systems understanding, since it is a small sample. In the course of this study we also encountered certain limitations that we need to address when continuing this project. There may be reason to rethink the validity of certain questions in the test instrument, because, for example, d) asks about how the system affects nature but not the other way around. Furthermore, no student could exemplify the general purpose of the system whereas many could relate the purpose to humans and society, which calls for further attention to this test item in relation to qualities of knowledge. There may thus need to be more precision in the test instruments. But most of all, another conclusion can be drawn: to reach higher or more complex qualities of knowledge students need to be taught more about technological systems by their teacher (cf. Booth Sweeney & Sterman, 2007); the students of this study had had minimal systems education. When continuing this project, we thus need to find school students that actually have encountered systems content in their technology education.

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