Paper 71. Systems thinking for sustainable development - what does it mean and how is it formed?

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Abstract

Education for Sustainable Development (ESD) is continuously being developed and discussed in relation to quality, content and skills such as life-long learning, ability to shift perspective and systems thinking in relation to the students' professional roles. Systems thinking, or the ability to think both holistically and in parts simultaneously, can often be characterised by the incorporation of different perspectives in assessing a problem or identifying a measure.

In this contribution, students' development of systems thinking is studied in two courses. The first course is a compulsory bachelor course for building construction engineers with the aim that the students in their future professional role will be able to participate in sustainable decision-making and in society's dialogue for sustainable development. The learning was assessed in a written exam and in a project. In one of the questions of the written exam the students are asked to describe systems.

The second course is a PhD course in sustainable development (SD) with the aim to give the students an opportunity to reflect on the potential impacts of their research and describe their potential contributions to sustainable development in society. The task is performed mainly by a written individual assignment and the students were also asked to generate concept maps of their perception of sustainable development in general, both before and after the course.

The aim of this contribution is to discuss how system thinking in relation to sustainable development is visible in different texts and concept maps generated by the students and reflect on how it develops in different groups of students in relation to learning outcomes and the implications for teaching in sustainable development at Chalmers. Preliminary results show that pre-knowledge and possibilities to reflect together with peers and teachers influence how the skill develops.

1 Introduction

In ESD, skills such as life-long learning, ability to shift perspective and systems thinking are emphasized and there are ongoing discussions on how the skills can be taught and are being used in the students' professional roles. The students often perceive it confusing to think holistically and in parts simultaneously, since it includes interconnecting and incorporating different perspectives and different levels of detail. Such thinking needs practices and good examples. The aim of this contribution is to discuss how systems thinking in relation to SD is visible in different texts and concept maps generated by students and how this thinking develops in different groups of students in relation to learning outcomes and the influence of the students' contexts. The aim is further to describe how systems thinking for SD is constructed to improve ESD at Chalmers.

1.1 Systems thinking

The literature on the development of systems thinking and other competences, such as perspective shifting, is rather limited although such competences have been identified as key competences in student learning for SD (e.g. Svanström et al. 2008, Wiek et al. 2011, UNECE 2011). Systems thinking originates from cybernetics (Weiner 1968) and is characterised by the ability to cognitively interconnect elements and identify causalities and feedback loops. This concept has been applied in both natural sciences (von Bertalanffy 1968, Ingelstam 2002) and social sciences, e.g. for identifying improvement opportunities in organisations (Ingelstam 2002). Flood and Carson defined systems thinking as a way to think of different events or activities by creating structures (Flood and Carson 1993, s.4) and Wiek et al. described it as

"*the ability to collectively analyse complex systems across different domains (society, environment, economy, etc.) and across different scales (local to global), thereby considering cascading effects, inertia, feedback loops and other systemic features related to sustainability issues and sustainability problem-solving frameworks*" (Wiek et al. 2011).

A large body of research discusses how systems theory and causal loop diagrams in systems analysis can be used to illustrate different phenomena, and some do it in connection to wicked problems in relation to SD (Kunsch et al. 2007). Few address how students learn to think in terms of systems or how students make sense of the concept of systems.

1.2 Systems thinking in education

In teaching in higher education, the focus is often on the application of systems theory and systems analysis in relation to e.g. learning in organisations (Espinosa and Porter 2011) or in environmental assessment of products and technical systems using life cycle assessment (LCA) (Tillman and Bauman 2004). Not much has been reported on how students learn systems thinking in higher education, including engineering education. Habron et al. (Habron et al. 2012) studied students in higher education learning in systems thinking in relation to SD by using drawings and other types of graphical representations generated by the students. Feedback from the students was utilized to continuously modify the course. The result of the study indicated that students failed to develop a complex systems thinking. Reasons stated by the authors were that the teachers assessing the students were not prepared for the shift in teaching approach, i.e. student centred learning, disagreed on how to assess the learning and failed to utilise the feedback from the students.

The body of literature on learning systems thinking at primary and secondary school level is larger and focuses on how pupils conceptualize or make sense of systems (Hmelo-Silver and Pfeffer 2004, Svensson 2011). The framework SBF (i.e. Structure, Behaviour and Function) has been used to describe systems thinking in novice and expert sense-making of complex systems, such as an aquarium (Hmelo-Silver and Pfeffer 2004). In the framework, *structure* refers to the elements in the system, *behaviour* to mechanisms within the system, and *function* refers to the role of and outcome of the systems. It was found that novice thinking focused more on the system's structure of elements compared to expert thinking that focused on how the different parts were interconnected and their role in the system. The same framework was used in a study in which pre-service teachers explored complex human functions, such as breathing, aided by computer software (Liu and Hmelo-Silver 2009). The results showed that using a conceptual model to organise knowledge, such as concept maps, was useful in developing systems thinking.

In a phenomenographic study, secondary school pupils' systems thinking and understanding of societies' technical systems and technical artefacts was studied (Svensson 2011). Svensson argued that to be able to demonstrate systems thinking, the pupils need to identify and describe a number of meaningful relations between different elements that are interlinked to form a whole, for example

- causalities that lead to different effects that the separate parts cannot provide on their own, i.e. emergence,
- interconnect different levels of details, i.e. system levels,
- flows, for example of matter, energy or money

1.3 consequences of changes in the system. Concept maps

A concept map is graphical representations of the cognitive process of assimilating knowledge and is based on Ausubel's theory on meaningful learning. According to Ausubel's assimilation theory, knowledge is created when it is perceived meaningful, new concepts easily can be connected to old concepts, the cognitive structures of knowledge are hierarchical and when knowledge can be differentiated in more structure and detail, i.e. progressive differentiation (Novak 2005). The process of adding more and specific details to a hierarchical structure is called progressive differentiation (Novak 2005) and is formed when a central concept is explained by adding concept of more detail.

Novak used cognitive maps to transcribe interviews on knowledge development in pupils in natural sciences in a longitudinal study for 12 years (Novak 1990 and 2005). Meaningful learning is expressed in concept maps with a high degree of structure, detail and motivated links (Novak 2005, Turns et.al 2000). A concept map's complexity, i.e. links between concepts belonging to different hierarchical levels, and the level of detail describes how students organise their knowledge (Shavelson et. al. 2005, McClure et. al. 1999). A messy concept map, characterised by lots of interconnected concepts and links with apparently no relevance is difficult to assess and interpret. One possibility is that the knowledge is complex, and another that the knowledge is new and not fully assimilated. A third possibility is that the concept map is the result of a messy mind (Turns et.al 2000).

In engineering ESD, concept maps have been used to quantitatively evaluate students' and educators' perception and learning in SD courses (Zanting et al. 2003, Lourdel et al. 2007,2009, Lonzano-Garcia et al. 2008, Segalàs-Coral 2009) by categorising and counting the number of words of different perspectives of the three dimensions of SD: In a case study of 5 universities from different parts of Europe engineering students' development of SD skills such as systemic thinking and critical thinking was evaluated with concept maps (Segalàs-Coral 2009). The results showed that the students' knowledge varied depending on pre-knowledge, the teaching philosophy and the students' societal context. The conclusion was that engineering students in Europe generally focused on environmental and technological aspects of SD. The distribution of knowledge from an engineer in a future society was analysed in 732 concept maps by Shallcross (Shallcross 2010) and was found to dominate in the environmental, technical, societal impacts and values, which agrees well with the study performed by Segalàs-Coral (Segalàs-Coral 2009)

2 Method

The main data set includes concept maps and written answers to exam questions, generated by students in two different courses. The two authors of this paper were teaching in the two courses. Further on systems thinking in SD will be developed by identifying characteristics of systems concepts in a SD context. These characteristics will be used for identifying systems thinking in the data.

2.1 Study objects and details of the analysis

The presentation of the courses will begin with the Bachelor course "*Environment and Sustainable Development*" and be followed by the PhD course "*Challenges and Opportunities of Technology in Sustainable Development*"

2.1.1 Environment and Sustainable development

The Environment and Sustainable development course is a bachelor level course of 7.5 hec, lasting 7 weeks. The number of students was about 120, with two thirds third-year Building construction engineers and one third second-year students in the program Business developer in the building construction industry. Written answers to exam questions were collected from these students.

The aim was, that by the end of the course, the students should be able to understand the global challenges and, in their professional role, be able to discuss and assess technical systems and solutions with a SD perspective. The learning outcomes aimed to make the students aware of the planetary boundaries, the need of stakeholder participation, and the influence of values in decision-making on physical societal planning. The specific systems thinking learning outcomes were to:

- Describe causalities for different environmental problems and their relation to society's use of resources
- Structure and formulate an environmental question in an environmental impact assessment, assisted by systems thinking and system analytical tools

The idea in the course is learning by doing and thinking, applied through in-house and guest lectures within societal planning and building construction, by exercises and a project. The exercises go into depth in one of the aspects discussed during lectures and are often connected to system analytical tools and indicators. The project is a supervised group assignment with both a written report and an oral presentation. The assessment comprise a written exam, the project report and the presentation.

2.1.2 Challenges and Opportunities of Technology in Sustainable development

The course is a 3 hec course, given twice a year, with about 20 students each time. The overall purpose of the course was to develop the PhD students' ability to reflect on their research topics in relation to SD, and to give insight into the opportunities and challenges of technology, both in general terms and in relation to their research project. There were no prerequisites of earlier studies in SD since the course was designed to introduce SD to students with no previous knowledge.

The intended learning outcomes were: After completion of this course, the students should be able to:

- Describe the importance of understanding the consequences for SD of different technological choices
- Describe their role as individuals and researchers in the context of SD
- Define and describe important ethical, environmental, social, cultural and economic considerations related to their research

The course design included lectures, seminars and an individual assignment. The class met one full day a week for five weeks. The lectures covered different aspects of SD and the lecturers came from different domains of knowledge in academia and in society. Each lecture was followed by a discussion seminar where the topic was further explored, both with and without a teacher present.

In preparation for an individual assignment (essay), the students were asked to interview three different persons. The choice of interviewees was suggested to be: their supervisor, to receive an external perspective, one person unconnected to the PhD student's research project, and one freely selected by the PhD student. The written individual assignment was peer-reviewed during a group seminar halfway through the course and the second draft of the assignment was reviewed by a teacher at Chalmers within the sustainability domain of knowledge. The feedback was intended to further develop the students thinking in relation to their research and the intended learning outcomes. After this feedback the students prepared the final version. The course was evaluated using a questionnaire, and the students were asked to draw concept maps, before and after the course, which are used in this study.

2.1.3 Data

In the Bachelor course, the empirical material was the students' answers to a written exam question. The students were asked to describe systems in 6 different ways on a level that somebody who was unfamiliar with systems would understand and further to provide two relevant examples of how systems would be a part of their future professional roles. By selecting every second answer out of a total number of 113 answers 56 answers was analysed.

In the PhD course, the students made concept maps at the beginning and end of the course. The central concept was SD, which was pre-printed on the evaluation form. Within this study, 27 pairs of concept maps were analysed in order to identify systems thinking and how it developed during the course. Of the 27 concept maps, two maps were disqualified either because the concept map failed to address SD or because the second concept map was less informative than the first and therefore did not show if the student's system thinking had developed. The students had no previous knowledge in how to construct concept maps and had about 15 minutes to produce each concept map.

2.2 Systems thinking for SD and student's sense making

Using system characteristics (Weiner 1968), systems definitions (Flood and Carson 1993, Wiek et al. 2011) and the systems thinking capabilities in relation to technical systems (Svensson 2011) systems thinking in a sustainability context can be interpreted within the framework of the three dimensions of SD. Causalities, feedback loops, emergence, system levels, flows and consequences need to be put into a sustainability context.

Causalities can be expressed as connections between perspectives, including the different dimensions, for example environmental degradation, poverty and economic growth, or biofuels, land use and food. *Feedback loops* can be described within different contexts such as recycling of waste or traffic congestion. Sustainability interpretations of *emergence* are, for example, social welfare systems and environmental problems. In the developed world, economic growth gives the means to create welfare systems through production systems that both create employment by uses of energy and materials producing wastes. *System levels* in a sustainability context can be expressed through discussion using scales, e.g. poverty and environmental degradation, local poverty and environmental degradation may look very different from global poverty and environmental degradation. *Flows* relate for example to energy, matter, information, money, traffic etc. *Consequences* in a sustainability context relate to effects in the different dimensions.

In the analysis of the data, e.g. written exam answers and the concept maps, the characteristics developed above on systems thinking was used. In the exam question, the students were asked to describe systems, not explicitly from a sustainability perspective; it was left to the students to choose how to make sense of systems. The answers were analysed for similarities and differences to identify qualitative differences between the answers in the sense of how systems concepts in a SD were used and also put in relation to the learning outcomes. The SBF framework (Structure, Behaviour and Function) was used to understand how the students made sense of and understood systems (Hmelo-Silver and Pfeffer 2004).

In the concept maps, the systems thinking was analysed based on how the students managed to integrate different characteristics of systems into their maps. How the students choose to make sense of SD can be used as a method to find similarities between the maps. The students' task was to describe SD and not explicitly to express systems thinking for SD. The results from the analysis were also put into the context of Ausubel's theory of meaningful learning (Novak 1990) and to the learning outcomes of the course.

3 Results

3.1 The Bachelor students' systems thinking

The students were asked to explain systems in such a way that somebody unfamiliar with the concept would understand. The students' choice of concepts explaining "systems" varied, but the one concept occurring in all exams was "subsystems" exemplified by technical, natural and social systems as dimensions of sustainable development. Other frequently occurring system concepts are the systems definition and systems properties such as emergence, system boundaries and systems thinking. The answer's quality increased as the students added their own examples to illustrate concepts, mentioned different properties and functions of a system. The examples came mainly from their own domain of knowledge and were applied to activities in relation to technical systems, society and the natural environment relevant to their professional roles.

The different systems characteristics (causalities, emergence, feedback loops, systems levels, flows and consequences) are present in a varying degree in the answers. Simple causalities such as "building a road has an impact on biodiversity" are very common. More complex causalities are often found in how systems are a part of their professional role and then related to societal planning and building construction. The citations below are translated close to the student's own wording.

"*It is important to integrate green areas into the city environment since we can then make use of ecosystem services that comes from cleaning air, natural drainage and possibilities for recreation*"

The interconnection between different systems is often expressed as how the building constructor interacts with technical and organisational systems. System properties such as system boundaries and flows can to a varying degree be identified in the answers. Systems boundaries were easier to identify than flows which were often an implicit part of the system. Below, both are clearly identified

"*..a building construction site is a typical example of an open system with large flows of material coming in to be used in a construction and the left-over material (waste) is transported out of the system to be further used or waste managed*."

Feedback loops were often exemplified with waste management and recycling of material. SD emergence was generally less clearly expressed; the examples used were often taken from different technical systems such as climate installations and cars. The SD examples occurring had been used in lectures. System levels occurred in the answers and then in relation to the transport system:

"*The transport system can be defined by many levels and boundaries. To be able to go to the city from the suburb e.g. a tram, bike or a car is required, which requires a system of roads and rails*."

In connection to consequences, systems thinking was used as a concept to describe systems and as a method to structure, analyse problems and aid in decision-making to avoid sub-optimisation or as some students' wrote: "avoid making mistakes". Common examples used were chemicals in construction material with unknown or uncertain environmental effects. Another example is:

"*A building constructing engineer ought to think about sub-optimisation, for example in constructing infra-structure. It may benefit the technical system to build a railroad or a road but less beneficial to natural systems and the social systems. A building construction engineer needs a holistic perspective of the area to be used for construction so that it doesn't disturb other systems*"

3.2 The PhD students' systems thinking

The systems thinking in relation to SD among the PhD students varied. In 22 out of 25 maps, all three dimensions of SD were present. The maps lacking at least one dimension often focused on different types of technical systems. Maps including causalities in a sustainability context were identified in 17 of the 25 maps. In the maps lacking concepts from all three dimensions of sustainability, causalities could still be identified but were often expressed as a connection to natural systems or production systems. In some maps, unsustainable development was used as an illustration of consequences. The system concept flow was often expressed as economical flows. Aspects less frequently present were emergence and feedback loops. Systems levels could be identified in particular in terms of scales.

A holistic perspective, although not always properly interlinked, was present in most of the concept maps. Some of the causality chains showed links of concepts covering a variety of perspectives in SD. An example of a long causality chain was "*waste and ecology - technology- resources - welfare and poverty – distribution*". Another example is "*justice (connected to conflicts and responsibility) - world politics - society - companies - technology (connected to development and welfare)- resources*" which connects back to justice. In a learning perspective, most concept maps include more concepts after the course than before, but normally the second map's structure is messier than the initial map.

4 Analysis and Discussion

4.1 The Bachelor course

The learning outcomes in the Bachelor course are focused on SD, systems thinking and systems analysis tools. The set of answers analysed show that most of the students have some understanding of systems thinking in a SD context although some students fail to understand the usefulness either in their present context or in their future professional role. The students' answers varied according to the SBF (structure, behaviour and function) framework (Hmelo-Silver and Pfeffer 2004) where there were answers representing different types of sense making in relation to the framework. In the "Structure group", the answers showed pre-knowledge in systems thinking in connection to their own domain of knowledge with a focus on the system's elements. The students' understanding of systems in a SD context was lacking or under development, shown by the focus on separate SD elements but lacking interconnections. The students' focus may imply that their ability to apply systems concepts into a new context, such as SD, requires understanding of how to identify system elements. These students' development of systems thinking probably requires very clear examples on how to "translate" their old understanding into a new context as well as encouragement to experiment with how these elements can be connected.

In the "Behaviour group" the focus in the answers was characterised by the mechanisms within the system. In this group of students, the systems concepts were still explained one at the time but concluded with examples on how environmental issues were put into practice and how that could affect then in their professional work. This suggests that the students made sense of systems by connecting elements of SD, mainly ecological, to what it means to do or get things done in a professional context e.g. how systems affects the student. To improve their understanding and systems thinking for SD, they need to be provided with examples on what the elements are in other dimensions than the ecological and how they are connected to their present understanding. This group also needs to be engaged in dialogues with peers and teachers to be able to develop their thinking.

In the "Function group", the focus was on the role and outcome of the system and this group of students used the concept systems thinking as a way to describe and make sense of systems by pointing out all the benefits of using systems, such as giving structure, organisation and knowledge of problems, identifying mistakes and understanding consequences of different actions to avoid sub-optimisation. This group identified the elements of systems and began to build networks of interconnected causalities. Their sense making was probably aided by the possibilities they perceived of improving society within their professional role, as being able to aid decision making and evaluate different options of action. This group of students' systems thinking is developed by engagement in exploring open complex problems, i.e. wicked problems.

4.2 The PhD course

The learning outcomes in the PhD course aimed at increasing the students' awareness of SD in relation to their research and were met in most of the concept maps. The sets of concept maps varied in quality and could be grouped in four different categories of learning. According to Ausubel's theory of learning, meaningful learning happens when knowledge is well structured and detailed.

In many of the concept maps, the students' perception of SD was initially vague, illustrated by few concepts and interconnected more or less with relevant links between the concepts. Generally, after the course, these concept maps had an increased number of concepts but they were still messy in structure and included many links of varying relevance and importance. These students probably employed a learning style of memorising, either due to lack of time or lack of skill of employing different learning strategies (Anderberg 2003). Another possibility is that the students had difficulties making sense of the topic in connection to their own research or that they spent much of their time trying to memorise instead of understanding. They may also have been occupied with sorting information.

In another selection of maps, the students' first maps showed structure and the second were messier. According to Ausubel's theory of learning, this implies that the students have existing cognitive structures (pre-knowledge) in the topic but lack time to sort the knowledge and associate the new received knowledge with the old knowledge. In a third selection of maps, the student's initial map was messy while the final map was structured and contained more concepts. This implies that the students' learning was meaningful and probably instrumental in sorting and organising the already existing knowledge into hierarchies and structures. In the last selection of maps, the students produced structured maps both at the beginning and at the end of the course. The number of concepts and links added were relevant and showed that the student's learning was meaningful.

4.3 Discussion of the results

It could be argued that the results would have been different if the exam question had asked for a description of systems thinking in a SD context. On the one hand, the students with difficulties translating the elements between systems could have made an effort to find relevant examples. On the other hand, the majority of the students already interpreted the question as systems in a sustainability context so it would probably make no difference to the results. The answers selected to be analysed were taken from a pile of exams that was sorted in no-particular order which implies that the distribution between the different types of answers probably reflects the Bachelor course as a whole.

Using the SBF framework (Hmelo-Silver and Pfeffer 2004) to identify different ways of sense making has been useful and it agrees with the findings of Svensson (Svensson 2011). Both studies identify degrees of sense making from lacking or having poor understanding of systems resulting in a systems thinking focusing on the elements of the system to the ability to identify interconnections, complex networks and from that evaluate consequences. To choose the SBF framework for analysis was a starting point for sorting the material and identify similarities and differences and gave valuable input to students' sense making or understanding that can be approached in ESD courses.

The usefulness of concept maps in education is the graphical representation of knowledge which can be used for discussing and structuring knowledge in a learning situation. The approach used to analysing the concept maps was based in Ausubel's teory of meaningful learning, which is based in a constructivist approach to learning (Novak 2005). In the literature there are other methods of analysing concept map that are more quantitative in character, for example Lonzano-Garcia et al. Segalàs-Coral (Lonzano-Garcia et al. 2008, Segalàs-Coral 2009). The differences between the two approaches of analysing the concept maps were that a quantitative approach focuses on *what* has been learnt and qualitative on *how* it is learnt. In this contribution the focus has been on how systems thinking has been learnt, why a more qualitative approach was used.

5 Conclusions

The study combined different frameworks and showed that systems thinking in relation to SD can be identified in texts and concept maps produced by students during their involvement in a course. Depending on the method, i.e. texts or concept maps, the visibility of systems thinking's different characteristics varies. The study indicates that important issues in developing systems thinking is that the new knowledge is perceived as relevant and that the connections to existing knowledge are clear. In the bachelor group, some pre-knowledge of systems appeared to exist. In cases of developed systems thinking, students may have used this knowledge to identify elements of SD to create a new understanding by assimilating new knowledge to old.

The outcome suggests that to improve the students' capability to make sense of systems and develop their system thinking for SD, education needs to provide clear examples of systems elements in SD and how they connect, provide opportunities for dialogue and include open problems in courses.

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