DEVELOPING SYSTEMS THINKING FOR SUSTAINABLE DEVELOPMENT IN ENGINEERING EDUCATION

A. Nyström Claesson [1,3], M. Svanström [2]
[1] Chalmers University of Technology, Sweden
[2] Chalmers University of technology, Sweden
[3] anna.nystrom.claesson@chalmers.se

Abstract: Present and future generations of engineering students are facing very different challenges than what engineering students did some 20-30 years back. The ability to appreciate the whole and assess complexity are abilities that become more and more urgent, in order to manage climate change, increased levels of chemicals in society, conversion of the energy system, food and water supply and many other challenges. To be able to act in a relevant way, students need to develop skills such as systems thinking to be able to assess complex systems. Systems thinking has been described as the ability to identify parts, causalities, flows and feedback loops.

Systems thinking is likely a skill that engineering students develop to a varying degree during their university education, especially with regard to complex sustainability systems. In order to be able to improve engineering education in relation to systems thinking, it is important to understand what systems thinking is about and how systems thinking may be developed during the education.

The overall aim of the study is to report on the first part of a study investigating how engineering students from two different programs develop systems thinking for sustainable development during their Bachelor education. In this part of the study, freshmen students (year 1) have been interviewed. The particular aim of this paper is to describe freshmen systems thinking before engaging in a university course on sustainable development. Group interviews were recorded and analysed for the students understanding and use of systems thinking. Students in both groups show evidence of systems thinking but it is intuitive rathter that conscious and they lack a language to communicate about it. However, in one group the students together manage to describe complex systems.

1 INTRODUCTION

I was recently asked to participate in an interview about sustainable development. One of the questions asked was "Is sustainable development expensive?" I needed to make sense of the question before I answered, because I wasn't sure I understood the question, to what the journalist was referring and finally if the journalist was expecting a complex or simple answer. I decided to make a simple answer but with complex content.

Future engineers will need to be able to answer questions that are not well defined, may have many different solutions and be complex in character. Systems thinking has been recognised as an important skill in engineering education, to be able to appreciate the whole in order to assess parts of a system.

1.1 SYSTEMS THINKING

The prerequisites for an successful introduction of systems thinking into a curricula and educational design was studies by Sterling (2004). Sterling describes systems thinking as

"the problematic nexus such as this by increasing the level of abstraction or overview, rather than the reductionist route of examining details and dividing the issue into smaller parts".

System 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).

The literature on the development of systems thinking and other competences, such as perspective shifting, is rather limited although it has been identified as key competences in student learning for SD (e.g. Svanström et al. 2008, Wiek et al. 2011, UNECE 2011). Systems thinking for sustainable development has been described 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).

1.1.1 Systems thinking in education

Research in learning about systems and systems thinking can be found within all educational levels. In a phenomenographic study, secondary school pupils' systems thinking and understanding of societies' technical systems and technical artefacts was studied (Svensson 2010). 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

There are studies reporting on learning systems thinking at primary and secondary school level and how pupils conceptualize or make sense of systems (Hmelo-Silver and Pfeffer 2004). In the SBF (i.e. Structure, Behaviour and Function) framework systems thinking have been used to distinguish different characteristics in in novice and expert sense-making of complex systems (Hmelo-Silver and Pfeffer 2004). In the SBF 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. Another study using the same framework is Lammi et. al.(2013) who studied pupils system thinking in a design process. In common for the studies above is that the problems are delimited and shows systems thinking at different levels in relation to causalities and parts of the systems.

1.1.2 Systems thinking in higher education

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). Engineering education discussed by Seager et al. (2012) in the context of the ability to assess wicked sustainability problems. The ability to appreciate the pluriverse i.e. the multiple descriptions of reality that leads to multiple coexisting realities, is an important part of systems thinking. The characteristics of a wicked problem are that it is difficult to find an appropriate problem formulation, there are compatible solutions and there are competing value systems or objectives. Engineering education has long focused on well-defined problems which is consistent with the epistemology. The character of education in relation to systems thinking for sustainable development varies with epistemology e.g. deterministic or critical realistic (Porter and Córdoba 2009). Porter and Cordoba (2009) also points out the importance to appreciate wicked sustainability problems and make sense of the pluriverse that include different stakeholders and value systems. Systems thinking has also been studied as a threshold concept, e.g. a skill that students need to work with to be able to master (Sandri 2012).

2 METHOD AND RESULTS

2.1 Data collection

2.1.1 The YouTube clip and the Literature review

The interview was based on the students discussing a YouTube clip concerning recycling of electronic scrap in India and development of wind farms in Morocco. The 10 minutes long clip was produced by the EU and is called "*EU goes green: together towards sustainable development*". In this study, the reported part of the clip is the electronic waste problem in India which also forms the bases for further analysis. The students spent most time discussing this part which gives a richer material to analyse.

In the YouTube clip, the problem described was a wicked sustainability problem that included poverty, health and environmental issues and illegal recycling activities. The recycling of the electronic waste was done by the poorest people, with crude to none technology and it was illegal since it was not done in the context of a firm's business activity. To recover the precious metals, the electronic circuits were manually manipulated with screwdrivers, hammer and heated in the open on open flames. At the same time it exposed both workers and the environment to heavy metal hazards. The intervention and ambition from EU was to create green jobs by educating some of the waste recyclers in business administration and recycling technology. The EU also assisted these recyclers to start a firm so their business became legal.

The data bases used in the literature review was mainly ERIC and to some extent Google scholar. The keywords were combinations of sustainable development, sustainability, systems, systems thinking and higher education.

2.1.2 Selection of students and the Interviews

The participating students came from two different B. Sc programs, Chemistry and Physics, where none of the students had been taking a sustainability course at the university previous to the interview. Out of 4 semesters in a year, the students were on their first term and second semester courses. The number of students volunteering to participate was in total 18, divided equally between the two programs. In the study gender was not an issue but the number of female and male students reflected fairly the ration in the programs. In the chemistry group 5 out of 9 students were female and in the physics group 1 out of 9.

The students were recruited during a break of a lecture. In presenting the project they were informed about the project's goal, what was going to happen during the interview and how the results were going to be used. In the chemistry group the response was very immediate and 10 students volunteered to join and in the physics group the process was almost equally easy. Between the recruitment and the interview, 1 student from the chemistry group and 1 student from the physics group resigned participation. For the interview each group was further divided in two. The two chemistry groups were interviewed in the beginning of November and the two physics group in the beginning of December. The interviews took place after the regular course hours. In the preparations of the transcription of the materials and to be able to recognise the student's voices on the recording, the students were asked to introduce themselves by name, their perception of sustainable development and previous sustainability courses in earlier education before coming to the university.

The pre-knowledge in the chemistry group was rather high and the majority of the students had taken sustainability courses or it had been a part of the curriculum during their secondary school. To characterise the knowledge by Biggs (1999) it was multi structural e.g. that the knowledge is still quantitative, but include details and also misconceptions. After the interview the students were asked about their perception of their knowledge level in relation to their fellow students in their class. They perceived themselves to be representative and argued that the majority of students in the class had applied to the B.SC Chemistry program out of an interest for sustainable development.

The pre-knowledge in the Physics group was much more diverse and in this group there was a minority of students that had participated in sustainability courses during secondary school. On a group level, their knowledge could be characterised as Uni structural (Biggs 1999), e.g. one dimensional and lacking parts of knowledge. One of the students had more pre-knowledge than the rest and this was due to the profile of the school and program he had attended. The physics group were also asked if they perceived themselves to be representative members of their class. The group thought so since the main reason they applied to the B.Sc Physics program was because they were interested in physics.

After watching the YouTube clip, the students were asked to structure the problems described in the clip and to their aid they had a white boards and white board markers. During the interview the students discussed what they saw in the clip and made a structure. The recorded interview lasted between 60-120 minutes.

2.1.3 Understanding the data

The analysis of the data was based on the student's general understanding of the problem, perspectives and also the systems components present in their discussion. In the results and analysis the interviews forms the skeleton in understanding the students thinking since the students' drawings were rather incomplete.

The interpretation of the students' understanding of the problem was done in a number of steps that is described in Sandelowski (1995). The initial step includes an overall impression of the discussion, reoccurring themes and then look for systems components and their context. Of particular interest are systems components such as the ability to identify parts, causalities, flows, systems levels and feedback loops. The context where the systems components are used will be analysed from the perspective if the use is deliberate or just happened as a result of the occurring conversation.

2.2 Results

The students' perception of the management of the sustainability problems presented in the film was diverse. Below the results on how the different groups interpreted the film is reported and also what systems components could be identified in their dialog.

2.2.1 Group 1 Chemistry students

The students' dialog focused on their understanding about strategies on how to change hazardous jobs into "real jobs" rather than to just prohibit the recycling activities. The dialog included win-win scenarios for both the individual recycler and for society such as better health for the recycler and a cleaner society. The intervention from the EU, with knowledge and money, made the change possible. A legal business was a guarantor of better recycled waste prices, security and working conditions. It was also a prerequisite for a better quality of life for the recyclers, with food for the family and educations for the children. Poverty as a concept was rarely used in their dialog but there was a long dialog on child labour in connection to the family situations. The example used was a single mother with seven children where the oldest child became the main family supporter at a rather young age, due to the need of survival and the lack of social systems such as daycare for the younger children.

The group structured the problem with the main systems components recycling, green jobs, chemical components, health investment and legal/illegal business. There were clear relations between environmental hazardous business activities, money and green jobs and they presented causalities for rare chemicals from a resource perspective. The causalities for the health and environmental perspective were less developed. They talked of two flows: money and material and they discussed the recycling activity on both a local and a global scale. On the global scale, the discussion concerned “who was taking care of the recycled components”. The feedback loops concerned the effects of the EU intervention and how the system had changed.

2.2.2 Group 2 Chemistry students

The dialog in the second chemistry group focused on how education could improve the recyclers work conditions. They observed that the recyclers belonged to the lowest levels in the caste system and discussed how education could be perceived as an obstacle to the poorest in order to improve quality of life. The EU intervention, with money, was understood as a way to improve working conditions by educating an already skilled workforce in cleaner recycling technology within the framework of a legal business activity. This was perceived as a bonus for the individual recycler and an improvement of the local area.

The group structured their problem around the elements recycling, environmental investment, health and environment, legal business, green jobs and consumption. There was a clear relation between consumption and waste and also heavy metals with health and environment. In their dialog the causalities were found in between the concepts occupation, education, culture (caste system) and quality of life. The flows discussed were money and waste. The students returned to the questions about where the electronic waste originated and discussed the waste flow from both a local and global perspective. Present feedback loops concerned the effects of a legal business on black markets.

2.2.3 Group 3 Physics students

This group of physics students discussed the YouTube clip in the context of a technical problem in the western world. Their rational was that it was a matter of overconsumption and a lack of technological knowhow of disassembly that prevented the western world to take care of their own waste. In relation to where the waste was recycled, the group reflected about the need of work opportunities in India and the more efficient technology in western society. The focus was mainly on the waste flows and less on the local problem with the hazardous recycling of electronic waste. The group managed to cover the main aspects of the YouTube clip, but the discussion often led into a technological direction. The perceived main objective with the intervention of the EU was to take care of the flows of hazardous chemicals by improving the recycling technology in the local area.

The main elements brought up by this group were poverty, recycling, EU, metals, fumes-into-air and over consumption. There was a clear relation between diminishing global waste flows and work opportunities in India. The flows discussed were waste and money in relation to overconsumption and the lack of interest, due to lack of market, in product design in relation to disassembly. The discussion was mainly conducted on a global scale but with impacts on local conditions and the main feedback loop was the discussion of change of responsibility for the waste flows.

2.2.4 Group 4 Physics students

The discussions in this group focused mainly on how to start a company that could improve the quality of life of the recyclers and how it would be possible to find markets for recycled computer components. The group discussed the YouTube clip from mainly economic perspective and how legal companies may compete with black markets. To recruit recyclers to the legal business was perceived as easy since the working conditions were better than in the illegal black markets. Another important perspective was to improve the recyclers’ health. By reasons of interest of some students, the environmental perspective was almost missing since this was early on delimited from the discussion. The intervention of the EU was mainly to level out the competition to the legal businesses from the black markets.

The main systems elements present in the groups' discussion were education, companies, market, health, black market, and the EU. The relations discussed were between the legal companies and black markets and poverty, education, health and quality of life. The recycling activity's relation to health problems was the main causality in the group's discussion. The flow of money both globally and locally was also discussed in the context of who would sponsor company educational activities in relation to the poor recyclers. The main feedback loop concerned the creation of good working conditions and health.

3 DISCUSSION

3.1 Understanding the problem

The general impression of the groups systems thinking was that it was intuitive knowledge or even common sense thinking. In none of the groups was systems concepts used in an informed way or used to facilitate the discussion. In the group of 18 students, the ability to appreciate the whole was diverse according to Seager's (2012) where the group represents different aspects of the plurivers.

The two chemistry groups had similar perceptions of the whole and the dialogs were richer in content, details and perspectives. They also shared the same overall value system where the environment had a central role. In the YouTube clip the boundaries of the problem is local and focus on recycling scrap, but both the group expanded their perspective to reflect over the origin of the waste. Their understanding of the problem was probably facilitated by their understanding of Sustainable development.

The physics group had different perceptions of the whole and did not introduce the same level of detail in their dialog. When a student perceived that he or she did not understand, they asked the group to explain. The explanations were delivered in both cases by students with more pre-knowledge than the others and helped the group to continue the discussion. In general, the content, level of detailed and the number of perspectives introduced in the discussion were low. The overall value system in the physics groups was more divers and was more focused on technology and the people in society. The systems boundaries were in one of the physics groups as inclusive as the chemistry group while the other physics groups made a rather early delimitation of the problem.

3.1.1 Comparison between year 1 students

Systems thinking was present in both programs but none of the program's participants knew how to use the systems concepts. The students were freshmen and introducing systems thinking is often done at the university rather than in secondary school, which explains that lack of familiarity among the students to the terminology of systems thinking. The pre-knowledge of sustainable development in the chemistry group probably contributed to rather similar understandings of the problem, compared to the physics groups where the understanding was rather different between the groups. In general the level of details and the number of perspectives introduced in the discussion in physics group were lower than in the chemistry group. In the physics group when a student perceived that he or she did not understand, they asked someone to explain in the group to be able to continue the discussion. These type of explanations were never necessary in the chemistry group and is probably explained by the pre-knowledge in the group. The overall value system in the physics groups was different than in the chemistry group. The overall value system focused more on technology economy in society. The systems boundaries were in one of the physics groups as inclusive as the chemistry group while the other made a rather early delimitation to of the problem.

4 CONCLUSIONS

The study of the freshmen, show evidence of systems thinking. The students lack the language to efficiently communicate and express their thinking. Their perspective on the system is influenced by how they understand a wicked sustainability problem and their pre-knowledge. In the study the chemistry students mainly described the problem as an ecological economic issue where society was the benefiter and the physics students described the problem as a technological economic problem.

References

Biggs J. (2001), The reflective institution: Assuring and enhancing the quality of teaching and learning", Higher Education, 41,. 221-238

Sandelowski M., 1995, "Focus on qualitative methods. Qualitative Analysis: What it is and how to begin", *Research in nursing & Health*, vol 18, pp. 371-375

Sandri O., J., 2013, "Threshold concepts, systems and leanting for sustainability" Environmental education research. 19(6), 810-822

Bertalanffy, L. von, General Systems Theory; New York, Georg Braziller 1968

Espinosa A., Porter T., Sustainability, complexity and learning: insights from complex systems approaches, *The learning organization* vol. 18, pp. 54-72, 2011

Habron G., Goralnik L., Thorpe L., Embracing the learning paradigm to foster systems thinking, *International Journal of sustainability in Higher Education*, vol. 13, pp. 378-393, 2012

Hmelo-Silver C. E., Pfeffer M. G., Comparing experts and novis understanding of a complex system from the perspctive of structures, behaviours and functions, *Cognitive Sciences*, vol 28, pp127-138, 2004

Ingelstam L., System - att tänka over system och samhälle, Energimyndigheten, Energimyndighetens förlag 2002

Liu L., Hmelo-Silver C. E., Promoting Complex Systems Learning through the use of Conceptual Representations in Hypermedia, *Journal of Research in Science Teaching*, vol 46, pp. 1023-1040, 2009

Svanström, M.; Lozano-García, F.J. & Rowe, D, Learning outcomes for sustainable development in higher education. *International Journal of Sustainability in Higher Education,* 9:3, 339-351 (2008).

Svensson M, "Att urskilja system – didaktiska dimansioner i grundskolan", Dissertation, Educational science, University of Linköping, 2010.

Tillman A-M., Baumann H., "The Hitch Hiker's guide to LCA-An orientation in life-cycle assessment methodology and application", Studentlitteratur, Lund, 2004

Turns J., Atman C. J., Adams R., Concept maps for engineering education: A Cognetively Motivated tool supporting varied assessment functions, *IEEE Transactions in Education*, 43(2), 164-173, 2000

UNECE (2011). *Learning for the future: Competences in Education for Sustainable Development.* Economic Commission for Europe, Committee on Environmental Policy. ECE/CEP/AC.13/2011/6.

Wals, A.E.J. & Blaze Corcoran, P. (2006). Sustainability as an outcome of transformative learning. Education for Sustainable Development in Action, Technical Paper No. 3. In Holmberg, J. & Samuelsson, B.E. (Eds), Drivers and Barriers for Implementing Sustainable Development in Higher Education, Unesco, Paris.

Wiek A, Withycombe L, Redman CL (2011). Key competencies in sustainability: a reference framework for academic program development. *Integrated Research System for Sustainability Science. Sustainability Science*, 6(2):203-218