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Ways of conceptualizing complex systems

A phenomenographic study of upper secondary school students' systems thinking in the context of the Haber process

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Supervisor:	Professor Åke Ingerman
Examiner:	Jörgen Dimenäs
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Abstract

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The question “How do students in an upper secondary school conceptualize complex systems?” was asked. A phenomenographic study was carried out to identify the ways in which this is experienced by the students. The analysis arrived at an outcome space which revealed four qualitatively distinct categories of description of the ways of conceptualizing complex systems and the logical and hierarchical relationships between them. The first two categories could be seen as least complex, delimited and simplified ways and the latter two as more advanced or powerful ways of experiencing complex systems. The findings point towards traits necessary for a system perspective. Some reflections for learning and teaching are also included.

Declaration

The work described in this dissertation was carried out at University of Gothenburg, Sweden and Hvitfeldtska Gymnasiet, Gothenburg between November 2012 and May 2013. Except where otherwise indicated by references, it is the original work of the author and contains no material obtained in collaboration with others. No part of this dissertation has been previously submitted for any award or academic degree at this or any other university.

Signed: Sue Lewis Date: 29 May 2013

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Contents

Part 1

1. Introduction

Why a kappa and an article?

The traditional way of writing a masters dissertation is as a monograph, but I decided to write a kappa and an article instead. This is because firstly, upon completion of the data collection phase of my study and during the early stages of analysis, my supervisor and I felt that I have rich and interesting data that would make a good article. Secondly, from the literature review that I had carried out, there was a scarcity of empirical studies in the field of upper secondary school students' conceptions on complex systems. I would like to think that my study can contribute to the field of understanding how students conceptualize about such systems.

An article is limited to typically 4 000 – 8 000 words and should be concise and to the point. Since this study is part of my masters dissertation, I wanted to expand and justify my decisions regarding the study particularly on the theoretical framework, research design and methodology as well as give a broader coverage of the research field in the literature review. This I have done in the kappa.

Aim of Study

Science and technology education has always supported the study of systems for the reason that 'system theory' is seen to provide a framework for understanding both the natural and human-constructed world (Chen & Stroup, 1993; de Vries, 2005; Koski & de Vries, 2013). In a democratic society, if education is for all, then science and technology education must have a commitment to educating all citizens. To advance such aims, the systems approach is seen as a viable framework to support this. Chen and Stroup (1993) suggested that the system theory *can provide a set of powerful ideas that students can use to integrate and structure their understanding in the disciplines of physical, life, engineering and social science.*

The aim of this study is to shed light on *how* students conceptualize complex systems, in particular *upper* secondary school students. The interest in upper secondary school students lies in that much of the literature reported on students' conceptions on complex systems, in particular in technology, technological systems and processes were conducted on elementary school children (Davis, Ginns & McRobbie, 2002; Koski & de Vries, 2013) and middle school pupils, between the ages 10 to 15 years old (DiGironimo, 2011; Svensson & Ingerman, 2010). There is a scarcity of studies on pre-college pupils or upper secondary school students who can be viewed as the more advanced group of students who have gone through formal education. It is therefore the intention of this study to contribute to the literature and knowledge domain in this area of research.

Another intention of the study is to contribute to the understanding of complex-systems in education. Systems theory and approaches together with rapid advances in technologies are opening up new perspectives and frameworks for both experts and novices to grasp new ideas in both scientific and professional environments (Axelrod & Cohen, 1999; Booth Sweeney &

Sterman, 2007; Hmelo-Silver & Pfetter, 2004; Jacobson & Wilensky, 2006). If students can learn the core ideas of complex systems principles and recognize that these are applicable across widely disparate elements and transfer what they have learnt and develop an appreciation of integrated networks of ideas, this could dramatically transform their perceptions of the world. It can help them make sense of the 21st century with all its trappings of an ever changing and complex world – the rise and fall of the stock market and the economy, the next smart and innovative technological system and the fragility or robustness of the environment. It is the overall aim of this study to contribute to this deepening understanding of how students experience or conceptualize complex systems as encountered in the Haber process.

The third aim of this study is to reveal potential traits that students may present towards having a systems perspective or point to signs of complex systems thinking (Boersma, Waarlo & Klaassen, 2011; Hmelo-Silver, Marathe & Liu, 2007; Jacobson & Wilensky, 2006). The study may also uncover what intuitive concepts or pre-concepts or naïve understandings (Booth Sweeney & Sterman, 2007) that students hold about complex systems and hence address them when teaching students about natural and social complex systems like ecology, chemical equilibrium and information systems (which is outside the scope of this present study but a logical follow up study for the future).

Research question

In the light of the aims of the study, the following central research question guided the investigation.

> *How do upper secondary school students conceptualize about complex systems as encountered in the context of the Haber process?*

Following on from the central research question emerged three sub-questions:

- What do upper secondary school students understand of complex systems in terms of their constituent parts in the context of learning about the Haber process?
- What does it mean to understand complex systems in the light of the Haber process?
- What does it take for students to connect seemingly disparate elements as encountered in the Haber process to industrial systems, to pollution, to the economy and to the wider context of the environment and society?

The study is an exploratory investigation into the ways in which upper secondary school students understand, experience, conceptualize or perceive of complex systems. It uses a phenomenographic approach to reveal the qualitatively different ways of experiencing complex systems as encountered in the Haber process, in chemistry. A detail description of the phenomenographic approach undertaken in this study is presented in chapters 3 and 4 of this dissertation.

The researcher

From the outset it is important to locate myself as the researcher in this study. I am a chemist by training having attained a masters in pharmacy (1990) and as a researcher I have attained a doctorate of philosophy in chemistry (Loughborough University, 1993). I have a teaching diploma from Loughborough University (1996). During the period from 1998 to 2010, I taught science including chemistry, physics and biology to lower secondary school students between the ages of 12 and 16 years old and chemistry to upper secondary school students between the ages of 17 to 19 years old. My interest in science and technology education stems from the desire to support students in their learning of difficult concepts in these knowledge domains. In order to be able to support students in their learning it is necessary to understand where they are in their understanding, hence this present study to investigate *how* students conceptualize about a particular phenomenon and uncover what understandings do students have about complex systems.

It is also important to minimize or ‘bracket’ (Ashworth & Lucas, 2000; Marton & Booth, 1997, p. 119), as far as possible, any predetermined views, researcher bias and researcher subjectivity about the phenomenon under investigation. However, bracketing is not intended to exclude my experience in the field being studied nor is my experience necessarily a liability. Instead a researcher’s experience, in accordance with the phenomenographic approach, may be an asset as it could bring about achieving an outcome space that is more meaningful and relevant to the phenomenon being studied (Åkerlind, 2002; Collier-Reed, Ingerman and Berglund, 2009).

2. Research Overview & Literature review

Systems thinking in Science-Technology-Society (STS) Education

The goal for science education is twofold, firstly to develop scientifically literate citizens and to develop students' abilities to act as responsible citizens in a world increasingly affected by science and technology. Secondly, to prepare albeit a minority for science based careers, to develop and inspire scientists of the future (Wellington, 2001). Students need to understand the interactions between science and technology and their society (Mansour, 2009). From this social need arose the STS movement in science education (Solomon & Aikenhead, 1994; Yager & Tamir, 1993; Ziman, 1980). STS focused on the applications and use of knowledge, their relevance to the life of the individual and to society, and the central role of the teacher in curriculum development (Yager & Tamir, 1993). One of the primary objectives of STS education is to present contextual understanding of current science and technology and provide students with the intellectual foundations for responsible citizenship (Waks, 1987, 1989). To this end, system thinking skills are a prerequisite for acting successfully and responsibly in an increasingly complex world (Arndt, 2006). In traditional education students are handed objective facts usually divided according to subject content matter. This knowledge remains isolated and most facts taught and learned are quickly forgotten by these students. A recurring criticism of traditional schooling has been the lack of relevance for students in their everyday lives (Osborne & Collins, 2000; Reiss, 2000). The issue of relevance is at the heart of STS education (Aikenhead, 2005). Most students use simple strategies to reach their goals which usually involve linear thinking but such strategies are likely to fail in more complex systems where multiple causality and feedback loops are involved (Arndt, 2006). Therefore the need for systems perspective is imperative, the ability to link what they have learnt to other subjects and across different contexts and thus integrating what they know into a larger, meaningful whole is essential in order to function in today's complex world (Arndt, 2006; Jacobson & Wilensky, 2006). Such systems thinking skills need to be developed, they cannot be learnt 'naturally' (Booth Sweeney & Sterman, 2007, Hmelo-Silver & Azevedo, 2006) and it has been suggested that this can be developed through STS curriculum in schools (Aikenhead, 2005; Arndt, 2006; Mansour, 2009).

Studies on students' systems thinking and conceptions on complex systems

Complex systems are highly interconnected, dynamic, involving feedback loops and nonlinearity (Jacobson & Wilensky, 2006; Sterman, 2000). According to Senge (1990), system thinking is connected *with seeing the 'whole', understanding the inter-relationships between system elements and identified patterns of change.* According to de Vries (2005, p.25) there are two ways of conceptualizing complex technological systems, firstly as a set of parts working together, the 'physical nature' aspect and secondly by their input, process and output, the 'functional nature' aspect. Ropohl (1999) characterized inputs, states and outputs as matter, energy or information which can occur in time and space. The core of systems thinking in a technological context is the concept of the change with time of physical or social variables like temperature, volume or number of products, variables relating to energy, matter and/or information (Barak & Williams, 2007; Svensson & Ingerman, 2010).

In the literature there is a body of research that examined how students in elementary, middle schools and secondary schools think about complex systems (Assaraf & Orion, 2005; Grotzer, 2003; Hmelo-Silver, Marathe & Liu, 2007; Koski & de Vries, 2013). But many of these studies have focused on complex systems in biology like ecosystems and the cell (Grotzer, 2003; Hogan, 2000; Verhoeff, 2008). There are very few empirical studies on *upper* secondary school students' conceptions on complex systems in chemistry or technology being reported in the literature. I would like to consider two studies in particular that have influenced my own study of complex systems and systems thinking in chemistry.

Firstly, the study by Booth Sweeney and Sterman (2007) looked at how middle school students and teachers think about complex systems in the form of everyday settings involving feedback, stock and flows, time delays and nonlinearities prior to any formal teaching of these concepts. They used an instrument which they called the 'Systems-Based Inquiry (S-BI) protocol to probe students' intuitive models of complex system dynamics like feedback structures and nonlinearities. The study assessed the participants' abilities in three areas namely (i) to recognise recurrent patterns of behaviour in different domains, (ii) distinguish different types of system structures and (iii) make relevant policy recommendations. What they found was that generally both students and teachers exhibited limited understanding of complex natural and social systems but as a group, teachers showed higher levels of system intelligence than students. This study helped me to recognise what some of the systems thinking skills were and how they were manifested in the students and teachers. In my own empirical study I was able to identify some of the traits that surfaced in Booth Sweeney and Sterman's study.

The second study by Hmelo-Silver and Pfeffer (2004) compared expert and novice understanding of complex system in an aquarium system. The study included middle school students, pre-service teachers and aquarium experts. They conducted interviews to elicit participants' mental modes on an aquatic system and used 'Structure-Behaviour-Function' (SBF) theory as a framework for analysis. Their findings indicated that novices' representations focused on perceptually available, static components of the system and experts integrated, structural, functional and behavioural elements in their understanding. The experts demonstrated decentralized thinking, multiple causality explanations and used stochastic and equilibration processes whereas students favoured simple causality, central control and predictability. These findings were consistent with expert-novice comparisons of complex systems thinking in a study by Jacobson (2001) and a later study by Hmelo-Silver, Marathe and Liu (2007). This study was interesting in that it used SBF theory as a framework for analysis. It was useful in my own phenomenographic study to consider whether focal awareness and dimensions of conceptions could follow the structure-behaviour-function themes.

Investigating students' conceptions

There's a plethora of investigative studies on students' conceptions in the literature (see bibliography by Duit, 2007). Duit and Treagust's article on conceptual change discussed the development of the notion of conceptual change amongst other things (Duit & Treagust, 2003). They cited a research by Gilbert, Osborne and Fensham (1982) which showed that children were not passive learners and that most students already hold deeply rooted conceptions and ideas that are not usually in alignment with normative scientific views (Mulford & Robinson, 2002; Nussbaum & Novak, 1976; Osborne, 1980). In the 1970s, studies on students' learning primarily focused on investigating students' conceptions at the content level. Since the 1980s, investigations into students' learning moved on to meta-cognitive conceptions (i.e. views on the nature of science and learning) and results from these studies found that students' conceptions were rather limited and naïve. Then there was a growth of studies investigating the development of students' conceptions and conceptual change (i.e. learning pathways from students' pre-instructional conceptions towards the intended science concepts, Duit, 2003). In their article Duit and Treagust also discussed research into students' conceptions in which various theoretical frameworks were applied. In early research Piagetian ideas on stage theory were applied, then emerging theories of cognitive developmental psychology were adopted and later constructivist ideas developed. During the 1980s and early 1990s there was a merger of radical and social constructivists ideas with social cultural orientations which led to a multi-perspective epistemological framework adopted to address the complex process of learning (Duit & Treagust, 1998). Duit and Treagust concluded that developments in the area of conceptual change are essential as research has shown that conceptual change informed teaching is superior to traditional ways of teaching. They argued that developments in teaching and learning strategies are necessary in order to address the complex phenomenon of teaching and learning science.

I want to introduce two studies from the myriad of studies that can be found in the literature on students' conceptions which have impacted on my own research methodology, studies by Svensson, Zetterqvist and Ingerman (2012) and Koski and de Vries (2013).

Svensson *et al* (2012) used a phenomenographic approach to investigate young people's experience of systems in technology. The systems they chose to investigate involved transport, energy and communication as contextualized in relation to bananas, electricity and mobile phones. They interviewed 18 students all aged 15 years old. What was interesting about this study was that it gave insights to the ways in which middle school pupils conceptualize technological systems, a type of complex system. This was useful in that it helped me, in the process of my own interviews, to be aware of what my interviewees were saying. Due considerations were given to whether upper secondary school pupils talked about similar things, to what extent and were they able to go beyond the concrete to the abstract aspects of a system. The methodology that was used in Svensson's *et al* (2012) study was helpful in my own research design. In their study they asked the participants to sketch the system to help visualize and communicate their ideas of the system. I incorporated this in my own interview process but I found that the interview transcripts were sufficiently rich in their descriptions that I did not use the sketches produced by the interviewees. Although used alongside a couple of the interviews it helped me to understand better what the interviewees were describing but for the majority of the interviews the sketches were superfluous. It was also interesting to read the analysis of Svensson's study, where she analysed the empirical data along the lines of structure, function and interaction of a technological system as well as using the analytical tools of structural and referential aspects. This was helpful in my own analysis of the data that I had collected.

The second study by Koski and deVries (2013) was useful in that it gave another research methodology to which students' conceptions could be elicited. It allowed for comparisons and helped with decision making concerning my research design. Koski and de Vries studied elementary school students (8 to 10 years old) and their teacher in a technology class. They used a pre-test for the teacher, then a session to explain systems thinking to the teachers after which they designed a lesson for the classroom. Koski and de Vries also pre-tested 6 of the 27 pupils in the class. Data was collected during a 70 minutes lesson revolving round a washing machine. Then two weeks later in a post-test, the pupils were asked to draw and explain how a bread maker worked. They videotaped the pre-test and classroom activities. Their research design is shown below:

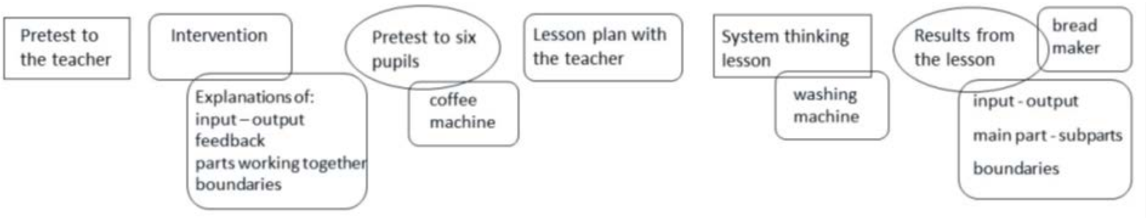

Figure from: Koski, M. I., & de Vries, M. J. (2013). An exploratory study on how primary pupils approach systems. *International Journal of Technology and Design Education*, 1-14.

In considering the design of Koski and de Vries' study (2013), I found that the need to use a concrete technological artefact like a washing machine or bread maker quite limiting for my study of upper secondary school students. But it was appropriate for their study as they were looking at elementary school pupils who perhaps lack the ability to communicate their ideas verbally and needed to draw as well as to focus their attention on something concrete. The idea of a pre-test and post-test was considered but discarded early on during the research design phase. This was because in my study I wanted to find out what it means to understand complex systems and how a complex system is constituted by learners. I was less concerned with finding out whether teaching could influence the way students conceptualize complex system (although this could something to consider for future research).

Significance and Scope of the study

Why do we need to know how upper secondary school students conceptualize complex systems or what they say when they talk about complex systems? Why is investigating students' system thinking important? Previous studies carried out by other researchers have mainly targeted primary and lower secondary school students (Assaraf, & Orion, 2005; Davis, Ginns, & McRobbie, 2002; Ingerman, Å., Svensson, Berglund, Booth & Emanuelsson, 2012). There are also numerous studies that investigated undergraduate students' conceptions of technology (Carew and Mitchell, 2002; Dori & Belcher, 2005; Booth, 2001). This present study will bridge the gap of what is known about primary and lower secondary school students' understanding and university students' understanding of complex systems. Another significance of this study is to use the insights gained to enable identification of the interdisciplinary nature of complex systems and map the variation in ways of conceptualizing such systems. These categories of description are not showing how individuals perceive a phenomenon, but as a collective it points to potential ways in which individuals can perceive a phenomenon. This will form an important contribution to understanding how knowledge is constituted and how abstract concepts are related to each other on different levels and as a whole, within a complex system which will be an important part of developing science-technology-society (STS) perspective in education. As our society becomes increasing dependent on science and technology, it is more important now than ever for our students to embrace a system perspective. One of the possible ways to develop this is through development of curricula activities and materials for students as well as professional development for teachers. However before we can get to this stage, previous research has shown that responsible curriculum development draws from and is shaped by students' conceptions and misconceptions (Duit & Treagust, 2003). Hence this study will start the process at a basic level, probing students’ conceptions of complex systems.

The scope of this study is limited to a particular group of students in a particular upper secondary school in the Gothenburg region. Nonetheless, the limited number of ways and the variation in which a phenomenon can be experienced by a group, as portrayed by a phenomenographic approach, should give a comprehensive understanding of what students understand of complex systems.

3. Theoretical Framework

Why Phenomenography?

My research questions revolve around the questions of '***how***' and '***what***' students understand about complex systems in the context of the Haber process. The investigation delves into 'How do students conceptualize complex systems?', 'What do they understand about…?' and 'What does it mean...?' it is not about asking '***why***' students understand the way they do. One of the aims of the study is to reveal the range and variation of ways in which students experience complex systems.

Phenomenography is a research approach that is adapted *for mapping the qualitatively different ways in which people experience, conceptualize, perceive and understand various aspects of, and phenomena in, the world around them* (Marton, 1986, p.31). It is precisely for this reason that the phenomenographic approach is most suitable for investigating students' conceptions.

The phenomenographic approach distinguishes itself from other qualitative research methods in that the focus is on the perceptions or understandings of the participants of the study, i.e. the students, it is not what the researcher perceives thereby taking a second order perspective. A phenomenographic study seeks to uncover what the participant holds in 'focal awareness', what is 'figural' and what aspects of the phenomenon experienced is most significant to the participants (Marton & Booth, 1997, p. 78, 100). Phenomenography also recognises that a person can hold more than one conception of a particular phenomenon and their relationship with the phenomenon can and sometimes does change in the course of the interview process, as various aspects are brought to the fore and others recede to the background or periphery of their awareness at a particular time (Marton & Booth, 1997, p. 149).

> *". . . we are not trying to look into the [person's] mind, but we are trying to see what he or she sees, we are not describing minds, but perceptions; we are not describing the [person] but his or her perceptual world (Johansson et al., 1985)".*

It is the relationship between the person and the phenomenon that is investigated. Thus phenomenography can be differentiated from phenomenology in that the former is focused on the person's experience of the phenomenon and the latter on discovering the essence of the phenomenon itself (Marton & Booth, 1997, p. 117; Marton, 2000, p.103).

> *". . . the main strength and promise of phenomenography lies in a rigorous, empirical exploration of the qualitatively different ways in which people experience and conceptualize various phenomena in, and aspects of, the world around us. The approach aims to identify variation in experience of a phenomenon (Marton, 2000, p. 103)".*

Hence by focusing on variation (i.e. the differences, critical aspects), phenomenography allows for the exploration of the array of experiences and conceptions of a particular phenomenon. This will in turn allow for a deeper understanding of the relationship between the person and the phenomenon under investigation.
The section below gives a detail discussion of the underpinnings of the phenomenographic approach.

Phenomenography

From a phenomenographic perspective, *learning is shifting from not being able to do something to being able to do it as a result of some experience* (Booth, 1997, p.136). The sort of conceptualizing or experiencing that phenomenography is mostly concerned with is the *coming to see something in a certain way as a result of undertaking learning tasks that are met in educational settings* (Booth, 1997, p. 136). Therefore from this perspective, learning is depicted as the internal relationship that is constituted between the individuals and the phenomenon and is nondualistic in character (Marton & Booth, 1997, p. 122).

Key features and assumptions of the phenomenographic approach

Epistemological stance

The phenomenographic stance is that knowledge is seen to be relational; it is constituted as an internal relation *between the learner and the phenomenon to be learned, between the knower and the known, the learner and the learned* (Marton & Neuman, 1989; Marton & Booth, 1997; Booth, 2008). Marton and Booth (1997, p.13) described that

> *Gaining the most fundamental knowledge about the world is tantamount to coming to experience the world in a different way…*

Marton and Neuman (1989) described experience as it *always takes someone to do the experiencing and something to be experienced; the experience comprises a relation between them.* The descriptions of experience are not psychological nor is it physical, it is the ways in which people experience a particular phenomenon and the ways in which the phenomenon is experienced by the people (Marton & Booth, 1997, p. 122, 163).

Constructivism, with its roots in cognitive psychology sees mental modes and material actions as the main source of knowledge and that the individual creates his own world that is subjective and divorced from the real world (Marton & Neuman 1989; Marton & Booth, 1997). As a point of departure the phenomenographic stance is there is *only one world, but it is a world that we experience, a world in which we live, a world that is ours* (Marton & Booth, 1997, p.13).

Ontological stance

Phenomenography adopts a *nondualist* ontology. That is there is no separation between the 'inner' (mental modes) and the 'outer' (acts and behaviour) nor is there a subjective world (inner mind) nor an objective world (the existence of reality independent of human experience). There is just one world, *the world is not constructed by the learner, nor is it imposed upon her; it is constituted as an internal relation between them* (Marton & Booth, 1997, p. 13, 163).

Phenomenographic research points to empirical data collected from a chosen sample for which the phenomenon studied is relevant. It points to individual learning but when the data is pooled for analysis, the results lie across the whole data source and is above the individual level and is focused on the collective level (Booth, 2008).

Methodological assumption

An assumption of phenomenography is that there is a limited number of qualitatively distinct ways in which people experience phenomena they meet in their everyday lives and in the case of student learning, this is restricted to study-related contexts (Booth, 2008, Marton, 1986, p.31; Marton & Booth, 1997, p. 122). The approach is inductive, is focused on the relational nature of human experience and adopts a second order perspective (Marton & Booth, 1997, p.122). The researcher is interested in what the participants have to say about the phenomenon under investigation, to describe the phenomenon experienced as it is described to her by the participants, thereby taking a second order perspective. The result of a phenomenographic study, the outcome space denotes the distinct ways, in its range and variation, in which people experience a particular phenomenon.

Conceptions

Conception is the unit of description in phenomenography (Marton & Pong, 2005). The aim of a phenomenographic approach is to investigate the qualitatively different ways in which people understand a particular phenomenon or aspect of the world around them. The different 'ways of understanding' or *conceptions* are represented as categories of descriptions and further analysed with respect to their logical relationship between the categories to form an outcome space, which is how the result of a phenomenographic study is presented. A 'conception' has also been called 'ways of conceptualizing', 'ways of understanding', 'ways of seeing', 'ways of apprehending', 'ways of experiencing' and so on. The reason for so many synonyms is that although none of them corresponds completely to what is meant they all contribute to a certain extent and so one can discern and focus upon conceptual features (Marton, 1992, p.261; Marton & Pong, 2005). A conception can be characterised as composed of a referential aspect (the meaning) and a structural aspect (the features discerned and focused upon by the subject). In phenomenography, conception is viewed from an experiential perspective consisting of an internal relationship between the person and the phenomenon studied (Linder, 1993; Marton & Booth, 1997, p. 122).

Categories of description

The categories of description are a collection of conceptions that have emerged from the empirical data and grouped together according to their similar meanings. The set of categories can be seen on one hand as being constituted by the empirical data but also constructed or developed by the researcher as she carries out the analysis process. The aim of a phenomenographic approach is to describe the phenomenon under study through a limited number of categories of description, that is to say as few categories should be developed as is feasible and reasonable for capturing the critical variation in the data (Marton & Booth, 1997, p. 125). The categories of description presented are usually derived from a smallish sample of a chosen population for which the phenomenon of interest is studied so it can never be claimed to form an exhaustive description. But what it can claimed is that the set of categories is complete in describing the range, variation and distinct ways in which that particular population at a collective level experience, perceive or conceptualize about the phenomenon studied. The set of categories and the logical relationship between them denotes the outcome space. This research approach takes its point of departure in individual conceptions and relates it across the entire data source at the collective level.

Outcome space

The outcome space is a representation of the final results of a phenomenographic study. The outcome space comprising of the categories of descriptions depicts the qualitatively distinct and different ways of experiencing or conceptualizing the phenomenon under study and the logical relationships between them. It can be presented as text, table format or diagrammatically.

Phenomenographic interview

The phenomenographic interview falls in between the two extremes of qualitative research interviews, namely structured interviews and totally unstructured interviews (Bryman, 2008, p. 193, 438). An in-depth semi-structured interview is used to open up for discussion as many aspects of the phenomenon as is possible and relevant. The interviews are carried out in such a way as to bring the interviewee and the interviewer into a discursive dialogue around the phenomenon or aspects of the phenomenon under study from different directions, approaching it from different concrete or potential contexts (Booth, 2008).The aim of the interview is to reveal the qualitatively different ways of conceptualizing or experiencing the phenomenon studied, to discover what constitutes the phenomenon for the interviewee and against what background this comes to the fore and is discerned by the interviewee. It is also the aim of a phenomenographic interview to capture the variation in peoples' conceptions of the phenomenon studied. It is not focused on the person, the context of the study nor the phenomenon but on the *relation* between the person and the phenomenon studied. This relation is constituted between the person and the phenomenon studied and the phenomenon with the person experiencing it (Marton & Booth, 1997).

The phenomenographic interview uses an interview guide or protocol, where a number of conversation openers or entry points for discussion are prepared. The questions asked may not follow the exact order as outlined in the interview guide nor are all the questions necessarily asked. The focus of the interview is to allow the participants a great deal of leeway to respond. The interview is not based on a set of relatively rigid pre-determined questions and prompts to be slavishly followed but open and discursive in nature. In this way the interviewer is able to ask questions that were not included in the interview protocol and follow up on interesting lines of thought identified by the interviewees and seek further elaboration or clarification. Usually most of the questions in the interview guide will be asked and a similar wording will be used from interviewee to interviewee. This is important to ensure that the interview is focused on the *same* phenomenon so that the range and variation in the participants' conceptions can be captured and revealed.

In summary the phenomenographic interview is in a sense structured in that there are prepared conversation openers or entry points in varying contexts to open up the interview. But it is open in that the interviewee has the opportunity to turn the conversation in a number of different directions whether expected or unexpected thus allowing the interviewer to follow up or pick up on things said by the interviewees. It is closed in a sense that the interviewer will eventually bring the interview back on track and focus on the phenomenon under study.

Phenomenographic analysis of data

The aim of the analysis is guided by the research question(s) of the study and aimed at revealing the variation in the ways of experiencing the phenomenon studied. The researcher takes a second order perspective and seeks an understanding of what is conceptualized of the phenomenon studied from the interviewees' descriptions of what it means to them. Usually it starts with a search for meaning or variation in meaning across the interview transcripts. At the same time constant comparison between the similarities and differences of aspects of the data generated constituting the structural relationships between meanings is being constructed. In the early stages of the process, iterative reading of the transcripts was approached with openness to possible meanings and then later on becoming more focused on emergent aspects that were interesting and pertinent to the phenomenon under study. The whole process involved constant reading and re-reading of interview transcripts, continuous sorting and re-sorting of data, group and re-grouping of selected interview excerpts according to similarities and differences (Marton & Booth, 1997, p. 133). As a result tentative categories emerged and through a process of further discussions with other phenomenographers, refinement and adjustment in the light of the empirical data, the categories of description are stabilised and defined. Further analysis can take place using the analytical tools of referential and the structural aspects. The structural aspect denotes the specific combination of features that have been discerned and focused on and the referential aspect, the global meaning of the object conceptualized (anything delimited or attended to by the subjects) (Marton & Pong, 2005). However it must be recognised that both the referential and structural aspects of a way of experiencing a phenomenon are intertwined and are used as analytical tools to further understand the categories of description.

The final result of the analysis process is represented in an outcome space which denotes the qualitatively different ways of conceptualizing a particular phenomenon and the relationship (logical and usually hierarchical) between them.

4. Research design & Methodology

Why upper secondary school students?

The sample population chosen for the study was not an opportunistic or random sample. Upper secondary school students were selected for the study because they represented the more advanced group of secondary school students. Numerous studies on complex systems (Booth Sweeney & Sterman, 2007; Hmelo-Silver & Pfeffer, 2004; Levy & Wilensky, 2009) have shown that core system concepts are difficult concepts and counterintuitive to students and hence not easily 'learnt' (Hmelo-Silver & Azevedo, 2006). For my study I wanted to interview upper secondary school students because this particular group of students would probably be more likely to show advanced thinking skills than elementary or lower secondary school students. These advanced students would be more likely to be able to articulate more clearly how they go about experiencing a complex and abstract phenomenon in chemistry.

Empirical setting

The setting of this study is in an upper secondary school, *gymnasiet*, in Gothenburg, Sweden. The school offers both the Swedish curriculum as well as the International Baccalaureate (IB) diploma programme. The IB diploma programme is a two year pre-university programme (IB2 and IB3) designed to give students a strong academic foundation, and prepare them for life as global citizens as stated in the IB organization mission statement (http://www.ibo.org/mission/). One of the characteristics of this upper secondary school is that it was one of the first schools in the Gothenburg region to offer the IB programme in 1989 and since the start the school's results have been well over the world average. In the last three years, the school's average is 33 points compared to the world average of 29.5 points out of a maximum of 45 points.

Another characteristic of this upper secondary school is that most of the students enrolled in the IB programme have at some point in their education been educated abroad and taught by teachers who had received their training and education abroad as well.

The participants

The participants for the study were all students of the IB3 chemistry course and taught by the same chemistry teacher. The students were between the ages of 18 and 19 years old. The sample consisted of 16 students all from the same class taking IB3 chemistry. There were 11 boys and 5 girls. 10 of the students were Swedish, 3 were native English speakers, 2 were Asian and 1 from Nigeria but all the students had lived and studied in Sweden for at least two years.

The Haber process

The Haber process was chosen as a starting point for talking to students about complex-industrial systems. This is because in almost every upper secondary school chemistry curriculum, the Haber process is quoted as an excellent example of chemical equilibrium, one of the core concepts covered in any upper secondary school chemistry curriculum (National curriculum, UK , 2004; Australian Curriculum, 2008; Education Bureau, Hong Kong, Science curriculum, 2012; IB chemistry curriculum, 2009).

Prior to the interviews the students had approximately two weeks of instruction on topics that included chemical equilibrium, Le-Chatelier's principle, enthalpy and catalysts. The Haber process was mentioned in the course of teaching chemical equilibrium in IB3 chemistry.

The full name for the process is the Haber-Bosch process. This process is used for the synthesis of ammonia (NH_3) gas, from its elements nitrogen (N_2) and hydrogen (H_2). Ammonia is an important component in the manufacture of inorganic fertilisers and explosives. In most chemistry textbooks very little, if anything at all, is said about the effects of this process on the course of history and on society (Glickstein, 2005). Two German scientists, Fritz Haber and Karl Bosch developed the process to produce ammonia efficiently and in 1913 Germany were able to produce ammonia on an industrial scale. Many historians and scientists think that Germany would have run out of nitrates by early 1916 if it were not for German discoveries and industrial technology and World War I would not have lasted till 1918 (Erisman *et. al*., 2008). Fritz Haber was awarded the Nobel Prize for Chemistry in 1918 for the synthesis of ammonia from its elements (Stoltzenberg, 2004). I have chosen to probe students' conceptions about complex system in the context of the Haber process, precisely for the reason that this process had and still has such an impact on society. This process is familiar to upper secondary school students and it allowed for exploration of conceptions on many different levels as a way of probing students' ways of conceptualizing complex-industrial systems.

Another reason for choosing the Haber process as a starting point for the interviews with the students lies in the expert knowledge of the researcher, who is herself a chemist with twelve years' experience of teaching chemistry to upper secondary school students.

Pilot study

A small pilot study was carried out prior to starting the study. This involved trialling the interview protocol with two students. The feedback given by the students was used to revise some of the interview questions (Appendix II). It appeared that the students were a bit uncomfortable with very open-ended questions and were seeking assurances for their answers. At which point, as the researcher, I had to assure the students that I was not looking for right or wrong answers and that this study is not about evaluating their answers. The interview was for them to share with me their understanding and thinking about the phenomenon being discussed.

Data collection – The interviews

The data was collected in the form of one-to-one semi-structured interviews, which allowed for in-depth dialogue, is flexible and able to respond to the direction in which the interviewee takes the interview (Bryman, 2008, p. 437; Cohen, 2011, p. 412). The emphasis is on how the interviewee frames and understands issues and events and views as important in explaining and understanding events, patterns and forms of behaviour (Bryman, 2008). I (the researcher/interviewer) had an interview protocol but used it only to guide the interview, to enable the interviewer to open up the discussion to as many aspects of the phenomenon as is feasible and relevant. Not all the questions were asked nor were the questions asked in the same manner or order. The main focus of the interview was to allow the interviewees to respond freely, describe as fully as possible their experiences relating to the phenomenon studied. I would seek elaboration, clarification on aspects that the interviewees brought up in the interview themselves and to see the phenomenon from the interviewee's perspective. It was also important to ensure that the participants attended to the *same* phenomenon during the interview process. Hence it was vital that the interviewees had a shared interview context. To achieve this I used an interview guide (see Appendix II) with some prepared entry point questions as well as using very similar wordings from interviewee to interviewee. Interviewees were also given a schematic diagram and chart of the Haber process to stimulate recall, when the interviewees were unable to remember what the Haber process is. For those who could describe the Haber process they also had the diagram and chart available to them.

Each student took between 30 minutes and 50 minutes to interview and on average each interview took 40 minutes. The interviews were audio recorded and later transcribed verbatim by the researcher herself.

The interviews took place in a quiet area away from other students and distractions and at the convenience of the students participating. It was also emphasized to the participants that taking part is voluntary and that they can pull out of the study at any time. Prior to conducting the interviews I held a meeting with the class and their teacher to explain the purpose of the study answer any questions that the students might have and work out convenient dates to carry out the interviews.

Data Analysis

The analysis process began with familiarisation of the text of the interview transcripts, which were transcribed verbatim. This was achieved by the iterative reading of individual transcripts and getting to know them as a whole as well as a collective. In the early stages of the analysis, reading of the transcripts was characterized by a search for themes or meanings or variation in them and for interesting threads that ran through the interviews. This stage of the analysis was approached with an open mind to possible meanings. It was also important to minimize ('bracketing', Ashworth & Lucas, 2000), as far as possible, any predetermined views and researcher subjectivity about the nature of the categories of description. However, my experience is not seen as a liability but instead may be an asset in bringing about a more meaningful and relevant outcome space (Akerlind, 2002; Collier-Reed, Ingerman and Berglund, 2009).

There were many different and interesting aspects found in the interview transcripts but as the analysis progressed, the focus shifted towards utterances that were interesting and pertinent to the phenomenon being studied. The term 'utterances' used here referred not merely to talk for the purpose of communication or 'accounting practices' (Säljö, 1997) but to talk that involves the act of intentionality that has an expressive perspective, focusing on the individuals' use of socially and culturally constructed language in their thinking. The aim of the study was to understand how upper secondary school students conceptualize, perceive or experience a chemical process in particular and industrial systems in general so excerpts of the interviews were selected and marked. The transformation of the empirical data from a set of whole length interviews into a set of focused units of interview excerpts took place and became the relevant units *(pool of meaning,* Marton & Booth, 1997, p.133*)* for comparing and contrasting the empirical data. At this stage of the analysis, the interview excerpts were inspected on two fronts, firstly in the context of all the other excerpts that talked about similar and related ideas and secondly, in the context of the individual interviews. Interview excerpts with similar criteria were combined while others were split. Consequently, meaningful variation and differences emerged between the subsets of interview excerpts and tentative categories of description became apparent. Once the criteria for each subset and the meanings stabilised, the collective meaning of the subset was abstracted and formed the first draft of a category of description. These categories of description were then described in terms of their qualitative differences as well as their distinguishing features. Following the first draft of the categories, further revision and refinement of the categories were carried out to arrive at the final set of categories of description. The whole process of revision and refinement took place over a period of a month with discussion and dialogue between me and my supervisor. I also gained useful and informative feedback from other phenomenographers at a 'Variation theory and phenomenography' seminar where I presented my tentative categories of description of the study for discussion.

In order to facilitate a more detailed analysis of the empirical data, I used the analytical framework relating to the referential and structural aspects on the first level and then on the second level relating the structural aspects to their internal and external horizons. In accordance with the phenomenographic research approach, this analytical tool allowed me to examine the context, the meaning in which the phenomenon is experienced or conceptualized as well as examine the 'parts' that constituted the experience. I was always mindful of the limits of using this framework to analyse learning which is seen to be extremely complex, relational, dynamic and contextual in nature (Harris, 2011, Mansour, 2009). In phenomenography, learning is always about learning *something*, reconstituting the already constituted world (Marton & Booth, 1997, p. 139) and in this study, using this framework allowed for more powerful ways of describing how upper secondary school students constitute an understanding of a complex chemical-industrial system, like the Haber process. However it must be recognised that both the referential and structural aspects of a way of experiencing a phenomenon are closely related and connected hence are only used as analytical tools to further understand the categories of description.

The referential aspect refers to the meaning of what is experienced, the phenomenon and its global aspect (Marton & Booth, 1997, p. 87, 91, Marton & Pong 2005). In this study it refers to what does a chemical-industrial system mean to the students as individuals and as a collective in society.

The structural aspect or organization of awareness (Marton & Booth, 1997, p. 87, p. 100) is twofold, firstly it is the way in which the whole is discerned from its context and secondly how the parts are discerned and related to each other and also to the whole. The structural aspect can be further described with respect to its internal and external horizon. The internal horizon refers to the parts constituting the process or system and their relationships, in this study they are the entities and their relationships in the reaction process or system, which is the focus and *figural in awareness* (Bruce *et al.*, 2004). The external horizon extends from the boundary of the experience through all other contexts in which the phenomenon may have been experienced. In this study it refers to all that surrounds the process and system, in all its different contexts and extends to the outer limits of understanding a phenomenon or its perceptual boundary. In summary the structural aspect denotes the specific combination of features that have been discerned and focused on and the referential aspect the global meaning of the object conceptualized (Marton & Pong, 2005).

The outcome space was reached which showed four qualitatively different ways of experiencing a chemical-industrial system and the logical relationships between them.

Research rigour, validity and reliability

In qualitative research the terms validity and reliability have come to have slightly different meaning than is used in quantitative positivist research. It has been suggested that validity and reliability in qualitative research refers to the rigour and quality of the research carried out (Bryman, 2008, p. 376). LeCompte and Goetz (1982) also wrote about reliability and validity in qualitative research namely internal and external validity as well as internal and external reliability. The ideas of whether there is a good match between observations and theory, degree to which findings can be generalized across social settings, degree to which a study can be replicated and whether there is inter-observer consistency were discussed by LeCompte and Goetz (1982). Guba and Lincoln (1994, p.114) suggested another alternative criteria for evaluating qualitative research namely trustworthiness (comprising of credibility, dependability and transferability) and authenticity (concerning the wider impact of the research). They argued that instead of focusing on validity and reliability of results as an appropriate measure of rigour, a different set of criteria should be used to judge the rigour and value of qualitative research.

According to Lincoln and Guba (1996) trustworthiness can be considered with respect to credibility, corresponding to internal validity, whether there is a good match between the researcher's observations and the theoretical ideas being developed. It can be considered along the lines of dependability, corresponding to reliability, and the notion of inter-observer consistency and transferability which corresponds to external validity that is to what degree are the findings generalized across social settings or to the notion of applicability.

Phenomenography is a qualitative, interpretive research approach and in this study trustworthiness is used as a criterion for assessing the value of the research as well as the rigour of the research process. In an article by Collier-Reed, Ingerman and Berglund (2009) they discussed how trustworthiness is important for establishing rigour in phenomenographic research and discussed it with respect to credibility, dependability and transferability.

Credibility

In this phenomenographic study the notion of credibility is considered along three constructs of content-related credibility, credibility of method and communicative credibility (Collier-Reed *et al.*, 2009).

Content-related credibility

This refers to the researcher's grasp or insight into the topic related to the phenomenon under study as well as the researcher's openness during the whole research study to the different ways of understanding as described by the participants themselves. Hence during the analysis process it is important that the researcher is able to 'bracket' or set aside her own assumptions about the phenomenon and allow the categories of description to be constituted from the empirical data and is a reflection of the participants' point of view and not that of the researcher (that is from a second order perspective).

Credibility of method

This relates to the correlation between the research design and the research question, whether there is a match between the aims of the study and its design and execution. Consequently, it is important to select a relevant sample population and ensure that the participants have a shared interview context so as to allow the interviewees opportunities for describing the same phenomenon. To aid in ensuring a shared interview context, a phenomenographic interview guide was followed (see also Appendix II).

Communicative credibility

This refers to the presentation of findings of a study to the research community in an open and transparent way to allow for scrutiny and critique of the study by others. In this respect I have presented the tentative categories of description on two occasions for discussion and feedback from other phenomenographers. This also allowed for intersubjective agreement and for others to recognise and judge for themselves the credibility and legitimacy of my interpretation of the data (Collier-Reed *et al.*, 2009).

Dependability

In a phenomenographic study, ensuring dependability means to allow for consistency of data interpretation and hence for consistency in the research findings. It is of vital importance that care is taken during the interview process, during the transcription of data and most importantly during the constitution of the categories of description.

Interview process

It is critically important for the interviewer/researcher to be conscious of allowing and ensuring that the interviewees are expressing how *they* perceive, conceptualize or understand the phenomenon under investigation (Collier-Reed *et al.*, 2009). The interviewer/researcher must guard against prompting or indeed leading the interviewee during the interview process (Kvale, 1996, p.157). In a phenomenographic interview only entry point questions or conversation openers are predetermined as discussed previously and throughout the interview process questioning strategies were developed based on what was brought into focus by the interviewees themselves.

Transcription of data

All interview data was audio recorded and transcribed verbatim by the researcher herself. In contrast, studies which focused on linguistic elements and used discourse analysis, where it was necessary to record every tonal inflection or pause in speech, in phenomenographic analysis what is important is what is said in the interview. Hence, the interviews were transcribed as accurately as possible.

Analysis of data

Intersubjective agreement of categories of description in a phenomenographic study forms the basis of assuring dependability of results (Åkerlind, 2005). In phenomenography the idea that categories of description can be recognised by others and used by them is recognition that a high degree of intersubjective agreement or confirmation has been reached (Marton, 1986, p. 35; Säljö, 1988; Sandberg, 1997). It can be argued that by analysing essential aspects of the research study namely the context and structure, it is possible for similarities and differences to be discerned and hence for the results to be of relevance possibly across different social settings (Collier-Reed *et al.*, 2009).

Transferability

The findings of a phenomenographic study, the categories of description and the outcome space, that have emerged from empirical data may be rigorously developed and be trustworthy. In the eyes of others however, they may be viewed from their perspective as a set of idealised and not necessarily ‘real’ set of descriptions. At this point then the direct application to a broader social setting or context may become limited and the argument supporting the original study is diluted. However, it does not mean that the findings are not applicable or potentially useful. The strength of the study's findings lies in others who will need to take the results forward in application. This could mean in some cases that the research must be repeated in a new context or be reformulated or reconstituted (Collier-Reed, *et al.*, 2009). Nevertheless, the findings can contribute to a growing body of knowledge and understanding and the constitution of outcomes gained from a phenomenographic study.

Ethical considerations

This study adhered to the ethical code of the Swedish research council, "Ethical principles for research" (Vetenskapsrådet, 2002). This is summarised as four requirements; (i) information requirement; (ii) consent requirement; (iii) confidentiality requirement and (iv) utility requirement (Appendix 1).

The researcher held a meeting with the participants and their teacher prior to carrying out the study to present the purpose of the research study and to answer any questions that the participants may have. It was made clear to the participants taking part in the study that it was entirely voluntary and that they could leave the study at any time. The participants were also assured of their anonymity. All data pertaining to the identities of the participants have been treated confidentially as per the ethical code of the Swedish research council (http://www.codex.vr.se/en/index.shtml).

5. Results

The outcome space (Marton & Booth, 1997, p. 125) was reached and is depicted as four qualitatively different ways of experiencing a chemical-industrial complex system and the logical relationships between them. This is summarised in Table 1 below.

Table 1– Summary of analysis of categories of description in relation to the referential and structural aspects.

Categories	**Referential aspect** (the meaning of the phenomenon, its global aspect)	**Structural aspect** (the organization of awareness, the parts that are delimited from and related to each other)	
		Internal horizon (that which is in focus and figural in awareness)	**External horizon** (extends from the immediate boundary of the experience through all other contexts in which related occurrences have been experienced)
A: **Talks about a process**	Making a product.	Discrete entities like energy and matter in general terms for example like heat, temperature, pressure, air nitrogen, hydrogen and catalyst.	Chemical processes.
B: **Describes a process**	Producing a product.	Discrete entities but in more specific terms like atoms, molecules, iron catalysts, activation energy.	Chemical processes.
C: **Describes a process in relation to the whole system**	Process embedded in a system, enabling a system. A closed system.	Entities or components within the process as interconnected and not as discrete entities.	Chemical processes as part of industry or industrial complexes and in part connected to society and the environment.
D: **Describes the system in relation to society and the environment**	A system, with all its interconnected parts and interacting with other systems. An open system.	Components of processes intertwined with aspects external to the process, like waste produced by the process and waste management and consequences to environment and humans.	Chemical processes, industrial complexes interconnected with society and the environment.

Each category is described in detail below, showing the relationships within categories as well as between categories and illustrated with excerpts from the interviews. The excerpts represented the main feature of each category since no one excerpt can fully characterize the whole category.

Categories of description
A: Talks about a process
B: Describes a process
C: Describes a process in relation to the whole system
D: Describes the system in relation to society and environment

Category A: Talks about a process
In the interviews, students talked about energy and/or matter in terms of their use and function in the Haber process. Energy and/or matter in this category were not seen to be connected to other parts of the system. They were viewed as discrete entities in a process and their roles related directly to the chemical reaction itself.
In this least complex category, students were able to state the conditions needed for the reaction, in terms of temperature and pressure. In some instances, students were explicit in giving exact temperatures and pressures (quantified amounts) required by the reaction to produce best yields of the product. In others the answers were vague and referred to just heat and pressure in general terms. They did not attempt to talk about heat or pressure in qualitative terms as shown in the excerpts below.

> *Q. If I show you this chart (graph showing % yield of ammonia against pressure and temperature) can you interpret what you are seeing there? What do you think that the graph is showing you?*
> *A. Well, it's the amount of ammonia being produced, at pressure, at equilibrium, where at equilibrium the most ammonia is produced most at 200˚C and least at 600˚C.*

> *Q. So if you think it is using air, and air is all around us, why do you think it is not just reacting and ammonia is dropping down on us?*
> *B. (Laughter), yeah....*
> *Q. If I were to wave the catalyst around in the air, do you think ammonia will form?*
> *B. No, heat and energy is needed.*

Students talked about energy and/or matter in terms of discrete entities like nitrogen, hydrogen, air, catalysts, 200˚C and 600 atmospheres relating to the structural aspects of the process making up the internal horizon. The relationship between them is that they were used in the reaction implying that the entities interacted to form ammonia.

> *Q. Ok, that's a good start. Can you tell me apart from its purpose, can you tell me about the Haber process, itself? What you understand about the Haber process?*
> *C. Well, I understand that they use of course nitrogen and hydrogen under certain temperature and under certain pressure in connection with a catalyst, iron to create ammonia.*
> *Q. So what can you say about its conditions? What would you say would be the best conditions to use? And what would you say would be the conditions that industry would use?*

C. OK, judging from this graph I'll say you'll get the highest yield if you use quite a low temperature and this scale goes from 200˚C to 600˚C so the lowest temperature here is 200˚C and then the highest pressure.
Q. OK and that will give you the maximum yield there.
C. Yeah. So a low temperature and a high pressure will give you the highest yield.
Q. So it would be kind of like 600 atmospheres?
C. Yeah, around 600 atmospheres and 200˚C.

The external horizon of the structural aspect is about chemical processes only.
The referential aspect is the making a product and in category A, it is the making of ammonia.

Category B: Describes a process

This category of description is more advanced and higher up the hierarchy than the previous category A, in that students were able to describe energy and/or matter as constituting parts of a whole system. They were not relating to energy and/or matter in vague or general terms and were making tentative links to other parts of the industrial system like economy and rate of production.

In this category, energy and/or matter were described in more qualitative terms. Students were able to describe energy as having specific characteristics like "*sufficient speed", "amount of collisions"* which was linked to *"the rate of reaction"* and the possibility of the reaction being *"not economically viable."* An example of this way of describing energy is shown in the excerpt below.

Q. So what do you think are the considerations by the industry, why do they choose to operate at those temperatures and pressures?
D. Yeah, so in order to get the reaction going you'll have to have sufficient err... firstly you have to have enough speed in the collisions, collision theory, yeah, you'll have to have sufficient speed in the collisions and also the amount of collisions too. So the amount increases as speed increases, and as speed increases, the temperature increases. So the lower the temperature the fewer the err… the smaller the collisions will be. Which means that the rate of reaction will be much slower and that's from what I've heard is not economically viable to have a too slow a reaction.

Students were able to talk about a specific form of energy, *"activation energy"* which was needed if a reaction was to proceed. In their answers it was implied that this energy had to be provided and they used terms like *"put in"* and "*you need to ...*" as shown in the interview excerpts below.

Q. Now what would you say would be the key conditions needed? Can I take some nitrogen and hydrogen from the air and wave it around and ammonia is made?
E. No, there needs to be some…ahh… you need some activation energy and you need to make them react because they don't react just like that.
Q. Exactly, so… cause in the air you have the two gases but you don't see it raining down ammonia?
E. So you need to put in the work and some energy to make a mix.

Q. Yes, that's another important consideration. If I were to say to you that you can find nitrogen and hydrogen quite naturally in the air, why doesn't it react?
F. Because it doesn't have enough energy to react. Not like this process (Haber process) where we are forcing it to react to make a product, whereas in nature they don't particularly want to react.
Q. So this forcing of the reactants to react you would require this (pointing to the catalyst in the chamber in the diagram shown), so how does the catalyst come into play?
F. OK, I remember the important part is that the catalyst speeds up the reaction. Ermm…but how it works…
Q. It's to do with the energy you mentioned before.
F. Isn't the ions always… aren't the catalysts always ions or…is that not …
Q. It doesn't matter what form the catalyst is, it has a function and that function is related to energy. Have you heard of the activation energy?
F. Oh yes, yeah. It brings the activation energy curve lower in the presence of a catalyst and it reduces the energy needed for the reaction to take place.

Students also described energy as being related specifically to chemical bonds being formed and broken. They described explicitly that energy is "*use to break*" bonds and by the formation of bonds *"we gain energy, which releases energy."* This way of expressing energy points to the students' prior knowledge of enthalpy and ideas relating to exothermic and endothermic reactions. In terms of matter, students talked about "*combining*" nitrogen and hydrogen.

Q. So in terms of the energy used, what happens to the energy?
C. Well, bonds break and bonds form, right, so when bonds break we need to use energy to break them up and when bonds form we gain energy, which releases energy. I guess we can say that…..yeah, combining nitrogen and hydrogen could release energy. Yeah, so then you will have to look at if it releases more than what it takes to form nitrogen or hydrogen.

They were able to articulate energy interaction at the sub microscopic level relating it to the chemical reaction of forming ammonia in the Haber process. Students talked about "*molecules collide*" and "*molecules or atoms are moving*" which alluded to their prior knowledge on kinetic/particle theory, which was then related to the idea of molecules reacting and increase in temperature.

Q. Do you see using a higher temperature linking in with the actual energy part of the reaction?
C. Yeah, I would…I guess if you look at a container with err…higher volume. So lower the volume you get a higher pressure, right. And since the molecules or atoms are moving err…you raise the temperature…
Q. So if you imagine, a gas and you increase pressure you are causing it to come closer, because you are forcing it together.
C.Yeah.
Q. So your volume gets smaller.
C. Yeah. Of course. Then wouldn't the energy cause the temperature to go higher.
Q. Yes.
C. Yeah, so that's what I was trying to say.

For some students their ideas were not entirely correct, in their reasoning, for example in the excerpt below, when the student talked about *"more molecules on the reactants' side than on the products' side ….. as low a pressure as possible... to produce as much ammonia…"* in fact a high pressure is needed to produce more ammonia in this equilibrium reaction. Nevertheless the student was able to deploy what she had experienced before in lessons in her reasoning about the reaction at a sub-microscopic level.

> *Q. Yes, that's precisely what it is. And you've mentioned pressure, so it's not just one factor controlling the equilibrium, it's something else as well. So what can you say about pressure?*
>
> *G. Hmmm….pressure should be low, I remember because there are more molecules on the reactants' side than on the products' side. Because you want err… as low a pressure as possible to produce as much ammonia as possible.*
>
> *Q. …Can you think of reasons why industry would choose to run the process at these conditions rather than to go for the maximum yield conditions?*
>
> *G. I think it has to do with, a little bit, with time. I mean the warmer it is the faster the reaction goes, since the molecules collide more often. So I'm thinking it probably has something to do with time…*

In category B students were also able to describe the idea of energy flow within the process. They talked about using *"a natural coolant"* in this case using water to take heat out of the gas, thereby *"cooling it"* and making the water warm, *"the coolant goes out is warm."* In their discussions there were signs that point to the idea of energy flowing from hot regions to cooler regions.

> *Q. You look at kind of the distribution, err… what else did you mentioned, we've got three things so far?*
>
> *B. ….But I can also guess that the coolant ….for the plant to be effective and the costs be as low as possible to produce ammonia, you may be need a natural coolant, for example water. The coolant that goes out is warm of course, which can be used for houses for heating and that can be effective. And so that might, you can maybe say that since it is effective there, you can invest in like errr….companies that supply electricity basically. They could pay you since you give them energy and so maybe then you reduce the costs.*

In the excerpt below, matter was seen to be transformed from a gaseous state to a liquid state by the removal of heat. The idea of energy flowing from a region of higher temperature to a region of lower temperature was again articulated in this excerpt where the student talked about *"the coolant goes through the gaseous ammonia…condensing it and the warm coolant is brought out."*

> *Q. …So what would you say would be the core ideas that you would explain to someone who has not heard of the Haber process before?*
>
> *H. Well, I will explain perhaps how hydrogen and nitrogen are combined, in the presence of a catalyst at a certain temperature and pressure and how it goes through err… the coolant goes through the gaseous ammonia, cooling it and therefore making it turn into liquid, condensing it and the warm coolant is brought out and new coolant brought in. Then the leftover hydrogen and nitrogen that did not react is brought back into the … and react.*

Q. OK. How do you see the idea of matter and energy within this system? What do you understand about what's happening in there in terms of energy and matter?
H. Well, it would be, well you need constant energy to take the heat out of the coolant after it's gone through the gas.

Q. …And if you were to explain this to somebody who doesn't know anything about chemistry what would you say to them? So have a few minutes to look at this (referring to diagram).
I. So, I'm gonna say it's like these two gases hydrogen and nitrogen they react together with a catalyst, so when they react together with a catalyst they form liquid ammonia and condensation happens and there is a change in temperature…

The internal horizon of the structural aspect of category B was very much related to discrete entities at the sub microscopic level and how they specifically interacted with each other. This differed from category A where the entities were talked about in more general and non-specific terms but nevertheless, they were still talked about as discrete entities which was similar to category A. The external horizon was seen to be about chemical processes. The referential aspect was very much about producing a product and making a profit.

Category C: Describes a process in relation to the whole system

In this category students were able to link energy and/or matter in a chemical process with other aspects of a system, like the rate of production and are beginning to experience the phenomenon as a whole. They were beginning to conceptualize the process more as part of a system and less as discrete entities that are unrelated. Students described how heat and temperature affects how fast a reaction was carried out, as shown in the following interview excerpt.

Q. I mean how do you relate the temperature with the time factor? What do you mean by that?
G. Well, I mean time is money, that's important. So you want to get as much done as possible within a specific time. And if the temperature is good enough then the reaction can proceed as fast as possible, I mean that is also a factor. I mean one part says that you need a low temperature so that the reaction can get a great yield but that if the temperature is too low then the reaction is too slow.

This idea of rate was further linked to other considerations within the system like costs, profits and the purpose of carrying out the process. This can be seen as a more advanced way of describing the Haber process as opposed to the previous two categories where students talked about use, function and the mechanics of the reaction.

Q. What would you think would be happening if we didn't have the catalyst?
A. I think the catalyst is very important for the reaction because it enhances the reaction and makes it take much less energy and that could also be very financially…it's important for the finance because we need …we use less energy to create more, so if we remove the catalyst it will be more expensive to create ammonia. But again that depends how much it cost to make the catalyst.

Q. Now, if I were to say to you that in industry they tend to use the conditions in the shaded area here (pointing to graph). Can you think of reasons why this is happening?
F. …Something to do with when you use this temperature the process is much slower and it takes so much longer to produce it even though you're getting more, so in a sense you do get more with this because you are producing it more quicker even though not so much is being turned into ammonia and it then gets re-put into the process again, so it's much quicker.
Q. So there's a time factor you've alluded to in making the choice of what conditions to use, what other factors do you think is in play?
F. That could probably be due to err…you might not want one that is super quick but barely producing any and making you pay lots of money but not use up all your products. So I guess it's an economic issue as well, I guess they want to create the peak amount in the quickest time to make them the most money.

Students also described energy and/or matter in relation to a cycle within a process. This cyclical flow was linked to the idea of efficiency. Again this can be seen as a more powerful way of experiencing the phenomenon or a more advanced way of conceptualizing a process embedded in a system.

Q. So how do you see this process, do you think it is an efficient process or not?
H. I think it has the potential to be an efficient process.
Q. What makes you say that?
H. Because ermm….like the leftover reactants are brought back to react again, maybe some of them will never react so they are constantly brought back which will definitely increase the chance of reacting when brought back and reduces the leftover reactants.

Q. So grow crops and your crops will provide food. So why is food important?
J. Do you want me to relate this to getting food? Cause you start here…H_2 and N_2 and you get NH_3, ammonia. Then you make fertilizers and the fertilizers fertilise the ground and you grow harvest, you grow crops then you make that into food and then you feed the humans and any animals maybe. And then you process that …they defecate and then err….it happens again and if you do to animals …you'll get the fertilizers once again. So can increase fertilizers.
Q. You can say that. And you can see this process as being quite like a cycle…kind of?
J. Yeah.

In this category C, students related to the behavioural aspects (how it progressed and what impact it has) of a process and its purpose. Students were able to talk about the Haber process in the wider context of industrial processes and making connections with use of energy and/or matter and the economy.

The structural aspect of category C referred to the components making up a systemic process, the internal horizon. In this study, it was energy and/or matter flowing and transforming as well as having effects on other parts of the system like the rate of production, efficiency, profitability and linking these ideas partly with the economy. The external horizon was seen to be industry and the economy.

The referential aspect is a process embedded in a system, it seemed to be more than just producing a product or seen to be a means to an end.

Category D: Describes a system in relation to society and the environment

In this most advanced category students were able to relate energy and/or matter not just to processes (internally) but also to the system (externally) and in particular to society and the environment. They were beginning to show signs of talking about systems (experiencing or seeing the whole constituted of entities or components, society and environment) rather than processes. Students described the waste produced by industrial plants which may be in the form of energy and/or matter, and related it to how it can be further dealt with. They were able to describe the consequences of the waste produced which impacted on the environment and society. The involvement of humans features largely in this category of description. Students talked about responsibilities and decision making by individuals as well as governing bodies and how these were interlinked within the system, such that humans can be seen as both interacting as well as influencing the system. Students were able to show signs towards complex systems thinking when they talked about one system like an industrial complex interacting with another system like the environment, how the actions of one part can have repercussions on other parts of the system.

In the interview excerpt below, the student talked about the positive and negative impact of the Haber process and the production of fertilisers (matter) on the environment and society.

> *Q. The product fertilizers, do you know what it is further used for, for what purpose?*
> *K. For growing plants, in the greenhouse. So you can have vegetables in whatever season you want.*
> *Q. So you use the greenhouse and supplementing ...*
> *K. Not necessary greenhouse , you could do it in your home as well. So the main purpose is to grow stuff.*
> *Q. Ok, so in this growing of stuff, it's for us humans, how do you see this impacting on society besides just feeding us?*
> *K. I think it is quite negative for the environment. Because, you know those fertilizers, it's err…if we can't use it properly, for example it flows into the oceans and waters. The micro-animals they can get the nutrients from the fertilizers and they err…it will cause huge damage to the environment, like they can grow insanely, will kill the fish by covering the surface of the water. It can also cause like poison stuff, if it goes round into the human food and err… I think the environmental problem is one of the main issues of fertilizers.*
> *Q. So that's pretty negative. Can you see anything positive things about the purpose of making fertilizers?*
> *K. Crops I think is one of the major positive things, like I think it's a great innovation and now we have more and more people who need to eat food and the problem is that we cannot produce food effectively without the fertilizers. So we need the food to grow faster and so we need to borrow the function of the fertilizer to make it grow faster and then it'll achieve the amount of food that we want*

Students described matter (chemical waste) as flowing into another system (water supply) and impacting not only on the environment but also human beings.

Q….Can you summarise your thoughts and ideas about by-products and waste, where do you think it goes and what happens to it and things like that?

H. Well, generally a lot of waste from one process can be used as a reactant or a catalyst for another process which could reduce amount of waste. But waste that can't be used for any other reaction, generally they may be hidden or…err…

Q. What do you mean by hidden?

H. Well err… buried deep underground or err…thrown up into the atmosphere or in the water or…

Q. ….What do you think are some of the consequences of some of these practices?

H. I err… it depends on what the waste products are of course, but there could be certain reactions in the atmosphere with these waste products that could produce things that are not necessarily wanted. For example the mercury with some parts of it released into the water then gets into the fish population which if the concentration is high enough it could be harmful to us and fish and our entire eco-system.

Q. Yeah. So you can see that there are kind of repercussions from say one act of getting rid of something.

H. Yeah, it escalates.

Q. Would you further elaborate on that or would you concentrate on the reaction itself?

H. I would probably concentrate on the reaction itself, and maybe mention some of the rippling effects it might have on society due to the by-products of the process.

Q. Well, for this specific process (Haber process) do you know what some of these rippling effects can be?

H. Well, there has been some talk that the fertilizer that is produced from ammonia, runs off into the water and err… which err… for example there's in the east of Sweden, it promotes algae growth and lots and lots of algae growth there, so it blocks off the sunlight and pretty much kills off the animals living there, which might not be very good.

Q. When you mentioned chemicals and safety and you mentioned about the environment can you elaborate more on what you mean by safety of the environment?

L. Well, I mean you don't want any chemical to be release into the ground cause that could affect the plants, like the plants and water as well, and it could have big consequences for the whole environment and the destroy the source of water.

Q. And that could impact on a lot of people.

L. Exactly… and that might ruin the….. If people are growing crops and that might make people sick from if the waters ruin. Then that will make a lot of people sick and the ground not fertile and they can't grow their crops. So that might cause a lot of problems.

Students also described matter in terms of transforming waste from industrial processes into less harmful and/or other useful products, thereby conserving natural resources. Students also talked about the creative use of waste, all with the idea of lessening the impact on the environment and/or society.

Q. ….How do you see industries in general impacting on society, you know, can we go on and on just building lots of industries? How do you see that system playing a part in society? Do you see this as a positive thing or a negative thing? Is it a good thing or not?

G. How do I see it? I think we are a growing population and there is a need for employment to survive but at the same time if we build too many industries that will kind of affect…. I mean the resources we have may be used up or yeah….the damage may be too great for us and for the environment. I don't know, it's like if you do one thing, then something else bad might happen. And if you do another thing, then something bad might still happen.

Q. So how do you see society trying to manage this? Like you said, it goes one way when something goes wrong, so you know something has to counteract it. How do you see, or what are the ways in which society can help this along? How can we manage this?

G. Ahh….ummm…. that's a good question (laughter). I think the alternative is pretty much to find ways to conserve our resources and to use them more wisely because….or find a way of developing or recycling better because there's so much that's getting thrown away and there's so much that we think that it's OK, then oh wow then suddenly we're stuck somewhere. I guess, while considering the environmental factors, that the fact that the population is growing and more employment is needed, we need to consider that we need to find a way to produce it in another way.

Q. …Do you know what happens to the waste that cannot be recycled?

K. There are some ways I know, one of it is to burn it, it is very common. The second way is that they bury it. And the third way is that they will put them into the oceans.

Q. Can you see what are some of the consequences of that will be?

K. Absolutely. For example if you bury it, many countries cannot do it properly, which can give huge amount of problems and for example you cannot use those chemicals and some of them cannot be dissolved. So some of them are really reactive, like some batteries that go into waters which can be dangerous for the human beings. So if we can recycle those stuff we can significantly reduce the risks.

Q. So there is a big risk factor here isn't it? If we can't manage our waste in a proper way then future generations can suffer.

K. Yeah, but they can be creative, I mean, they can err…like in some places where they've buried already, they build golf clubs on top of it. So we don't have to use valuable stuff to fill in the field we can use trash.

Students talked about human involvement in terms of companies, industries and governments making decisions, taking responsibilities and ensuring compliance to regulations and standards set down to safeguard society. They also related human involvement at different levels in the system such as the workers or the labour force in an industrial plant to the board of directors for the companies and industries and finally to government officials who enforce the laws and policies of a country.

Q. So apart from, investment in technology, the environment, profit making and motivation, what else do you think there is to consider?

K. Government policies.

Q. What about government policies? They are important, I agree, so what about them?

K. Well, for example there are some limitations. Like for example in Sweden, they have some policies against pollution. If I were the boss, I wouldn't pick Sweden as a country to manufacture stuff.

Q. Because of the strict government policies? Why do you think Sweden has such strict government policies? What do these policies do?

K. Yeah, the strict government policies. I think because Sweden is a developed country, they have such good system to err…like the law, to supervise the country. And then base on this I think it is kind of like everyone like has to follow the law. So if you do something only for profit you have to pay extra tax. It may reduce the level of profit and you may break the law also and may even be put in jail.

Q. So the is law is protecting who do you think?

K. I think it is protecting both…err….mainly …I would say everyone. The people and the producers as well, because in the long term for the economic growth you need to have a good ecosystem, as a thing to support your industries. And you may be destroying the industries, say like in the chemical field or the weapon field, in the long run is not good for the country.

Q. …. So where do you see the responsibility lie or how do you see this as fitting into this whole system?

L Yeah, I think the responsibility is the factory owner or the industry. I think they have the responsibility to make sure that they are not destroying the land and the people if they are exposed to dangerous chemicals daily, yeah, I think it's the responsibility of the factory to make sure of that.

Q. So is it just the responsibility of the factory? Can you think of any others who might be responsible?

L. I think it's like not just the factory because they produce for some other countries like for example, like clothes factories they are most often like rich countries like Sweden and all the companies have factories in like poorer countries. I think it is also their responsibility to make sure that the factories keep a good standard for the workers and the environment.

Q. Yeah, like you said, we in Sweden may not have the type of factories that mass produce things, but the labour force is cheaper somewhere else, so it's not just for that country to enforce the things but also for the country that is actually wanting to produce these things to enforce it.

L. Yeah, because I think we always want the lowest price for everything so if it is .... like it costs money to take care of things like waste products and ensuring that they like keep a good safety standard and then that might bring the price up for us then we might go err… then they might not sell as much like even if the factory took measures to help the environment and their workers but they might not be able to sell their products because it is too expensive. Yeah, so I think it's like we have to be willing to pay more to ensure that the products are produced under like fair conditions.

Q. Yeah, and we talked a little about how the economy worked in society. Maybe we can talk about the environmental effects that you've just mentioned. How do you see industries and their environmental effects impacting on society?
H. Well, if there is for example lot of emissions from factories that are supposed to be regulated such as for example, my dad works for a company that uses mercury for electrolysis and this is rather err… considered bad by the Swedish government. I guess, it's not so much an environmental effect than it is a social effect that the company gets less, or that industrial process gets less not credibility, but perhaps prestige, because of the negative connotations affiliated with it.
Q. Does that particular industry do anything to limit the impact?
H. Well, they are trying to move away from using mercury altogether but err… yeah, they apparently have the least mercury emissions in Europe among the type of companies and yet it's still too much according to the Swedish government and Swedish laws.
Q. OK. Let's say you are dealing with an industrial process that does have negative environmental impact, who do you see the responsibility lie in trying to limit this? Is it with the government or is it with the company, what do you think?
H. I think it should be with the company but sometimes that's not enough, that's why the state intervenes.
Q. And what kind of intervention do you see the state doing?
H. Well, they set quotas or like this is the most you can emit and if you do more than this you have to pay a big fine.

In category D, the highest in the hierarchy of ways of conceptualizing a system, the structural aspect is what is discerned and focused on and in this respect it refers to the elements, components within the processes as well as aspects outside the processes and also constituting the whole system. In this category students were able to talk about the waste produced within the processes and related this with waste management, impact on humans and the environment and consequences to society, which are aspects outside of the industrial processes themselves. The students talked about these parts in relation to the whole and the whole in relation to its parts and the external horizon is perceived to be society and the environment. This way of understanding is inextricably linked with the referential aspect, its global perspective of the phenomenon and in this study it referred to the holistic experience of an open system.

Summary of Results

The four qualitatively different ways of conceptualizing complex systems are listed below:

Category A - Talks about a process
Category B - Describes a process
Category C - Describes a process in relation to the whole system
Category D - Describes the system in relation to society and the environment

In categories A and B, discrete entities relating to the Haber process were talked about in general terms in the former category and described in more specific terms in the latter category. In both categories the systems aspect was overlooked and linear reasoning was evident at the process level. The categories are hierarchical and logically inclusive and exemplified in the following interview excerpt.

Q. Let's come back to the Haber process, how you see energy and matter being transformed or not?

M. Well, you have to put in heat and keep it at high pressure, and you have to move these in and ship these out and you've got a cooling pipe and take the ammonia out. The catalyst is not used up but you still got to buy it once.

Q. What else can you say about the energy?

M. Well, the energy is used to heat this and the energy is used to keep it at high pressure and that takes energy, to suck all the air out and keep it at high pressure and you need heaters to keep it heated at high temperatures. And it costs money to do that. So you have to balance efficiency with the cost of it.

In categories C and D, the discrete entities, the 'parts', receded into the background and what was foregrounded was the system, the 'whole'. Category C was talked about in terms of a closed system, components in the system were seen to interact and influence each other but operating within an industrial system. This way of conceptualizing can be seen in the following interview excerpt.

Q. So you've said fertilizers and food production as one way of impacting on society what else?

C. The effects of the products on society, the impact on the working market, how it employ the population in society. I guess.

Q. So employment.

C. Yes. Employment and can give option for trade. If we can make a profit of trading these goods. So you can look at this establishment of this industrial complex and provide a comparative advantage, that's what you say in economics and increase our capacity of producing this product to the extent to which we can make trade of it. And produce it more efficiently than other countries and entities on the market.

Conceptions in category D were perceived as an open system, where components not only interacted and influenced each other within the system, they also interacted and influenced elements outside the system like humans and society and pollution and the environment. Students were able to integrate the different 'parts ' of the system into a 'whole' and make connections to other systems outside of the chemical-industrial system, which the Haber process is part of. This can be seen in the excerpt below.

Q. So coming back to the chemical industry, how do you see these different parts working to benefit or not benefit society?

L. I think they all interact. So you have the government they affect international relationships, I guess. Like to help the standards of living and population for other countries and all that. I think that individual industries and the government can influence the laws and standards....like working standards which then affects the standards of living. Here the industries and also the government can ensure that safety is held at a certain standard and the environment as well.

An important jump in complexity of the categories of descriptions is between category B and category C. This is where students make the leap from conceptualizing at a process level to conceptualizing at a systemic level pointing to signs of them having a kind of systems perspective.

6. Discussion

The aim of this study is to investigate a segment of understanding that has not been previously studied. It is an explorative study on upper secondary school students' systems thinking in the context of the Haber process. In the literature there is not a clear understanding of what a well-developed systems thinking could look like. But there are numerous studies characterising what system thinking features should look like from a normative stance (Boersma, Waarlo & Klaassen, 2011; Booth Sweeney & Sterman, 2007). In this discussion firstly, I want to highlight what systems thinking looks like as constituted by upper secondary school students. Secondly I want to reveal what kind of reasoning or conceptualizing that is possible in this advanced group of students that could point towards a systems perspective. Finally I want to discuss what would it take for upper secondary school students to make the leap towards having a systems perspective.

What do upper secondary school students understand of complex systems in terms of their constituent parts in the context of learning about the Haber process?

My finding as depicted in an outcome space is both a reflection of the empirical data collected and my interpretation of it. Upper secondary school students were seen to have four qualitatively different ways of conceptualizing complex systems. Student participants in this study can be seen as having more than one way of conceptualizing complex systems. Their ways of understanding of such systems can change and vary within the range of contexts in which the phenomenon was discussed. These ways of experiencing complex systems can be seen as dynamic and relational.

In the first two categories A and B, students experience complex systems predominantly at a *process* level. Their understanding of complex system is simplistic and involved linear thinking (i.e. cause and effect; input and output). Students focused on discrete entities and were concerned with how each of these factors affected the chemical reaction, as shown in the interview excerpt below.

> *Q. Ok, that's a good start. Can you tell me apart from its purpose, can you tell me about the Haber process, itself? What you understand about the Haber process?*
> *C. Well, I understand that they use of course nitrogen and hydrogen under certain temperature and under certain pressure in connection with a catalyst, iron to create ammonia.*

These first two categories A and B of ways of conceptualizing complex systems could be deemed as unproductive ways of understanding complex systems and the system aspect has been overlooked by the students. There is clearly a lack of system perspective in these two categories.

The next two categories C and D show more advanced ways of conceptualizing complex systems and points towards the possibility of students having a systems perspective and the possibility of learning systems thinking skills. In category C, students begin to describe the Haber process as being part of a bigger system, but the focus was still within the system, viewing it very much as a *closed* system. The interaction of energy and matter was targeted towards the efficient production of an end product in order to achieve profitability within an industrial system.

Q. So there's a time factor you've alluded to in making the choice of what conditions to use, what other factors do you think is in play here for the manufacture of ammonia?
F. That could probably be due err...you might not want one that is super quick but barely producing any and making you pay lots of money but not use up all your products. So I guess it's an economic issue as well, I guess they want to create the peak amount in he quickest time to make them the most money.

In category D, students can be seen to experience energy and matter as being exchanged with the environment and society. They can be seen as understanding complex systems as *open* systems. This way of conceptualizing complex systems is pointing towards students having the capacity for acquiring a systems perspective.

Q. When you mentioned chemicals and safety and you mentioned about the environment can you elaborate more on what you mean by safety of the environment?
L. Well, I mean you don't want any chemical to be release into the ground cause that could affect the plants, like the plants and water as well, and it could have big consequences for the whole environment and the destroy the source of water.

What does it mean to understand complex systems in the light of the Haber process?

In phenomenography, the referential and structural aspects of a phenomenon are known to be closely intertwined (Marton & Booth, 1997, p. 87, 91). In this study that which is focused on by the students (i.e. the structural aspect) is closely related to what it means to understand (i.e. the referential aspect) the Haber process in particular but also as constituted in a complex system.

In categories A and B students perceived the Haber process as a means to an end that is the making and production of ammonia. The meaning is confined to simple chemical processes. Students in these two categories do not integrate the knowledge they have about the Haber process to a larger complex-industrial system. Instead they find meaning in the discrete elements of the chemical process to facilitate the reaction, as illustrated by the interview excerpt below.

Q. So what can you tell me about the Haber process? What do you understand about it?
D. Basically it is an industrial process to make ammonia. And you take hydrogen and nitrogen and react it to form ammonia. And I studied how to make the optimal yield and so on.
Q So what are some of the important considerations for doing that?
D That'll be to find the optimal temperature and pressure and err...to sort of make a compromise between the rate of reaction and the actual yield.

A dramatic shift in the referential aspect occurs between categories B and C, where the meaning shifts from making and producing a product (processes) to a more systemic perspective. In category C the meaning with respect to the 'parts' is no longer in focus but what is becoming more important is the 'whole', the processes as embedded in a closed system. Finally in category D, the referential aspect takes on a global meaning, where a chemical-industrial system can be seen to interact with other systems like the environment and society, in an open system.

What does it take for students to connect seemingly disparate elements as encountered in the Haber process to industrial systems, to pollution, to the economy and to the wider context of the environment and society?

One of the core ideas of complex systems thinking is the ability to represent and assess dynamic complexity, which involves understanding how behaviours of a system is a result of interactions of its agents over time (Booth Sweeney & Sterman, 2000). These interactions can give rise to non-linear dynamics and emergent behaviours that would otherwise not have arisen if the agents were independent of each other (Goldstone, 2006; Sabelli, 2006).

In this study it can be concluded that some students have more productive ways of making connections to other parts of the system than others and thus pointing towards having some kind of systems perspective. So what is the critical aspect that differentiates these two main groups of students' conceptions (i.e. categories A and B compared with categories C and D)?

Both groups of advanced students knew a lot about the Haber process and the principle ideas relating to chemical reactions, this is a reflection of how they have been taught in class. They have not been explicitly taught systems thinking skills but for one group of students they were capable of making interdisciplinary links between the Haber process, in chemistry with pollution and eutrophication, in biology with supply and demand in economics. As a point of departure, this qualitative study is not geared towards evaluating or differentiating the type of knowledge content that students have about the Haber process. Rather it is a study intent on revealing what productive ways do students understand the Haber process and thereby opening up for future research how to use such knowledge to guide students towards learning systems thinking skills.

Students, in general, have a knowledge landscape where they know something in one discipline and something else in another discipline. When they have to make sense of something the tendency is to start piecing things together usually by trial and error or in a haphazard way or trying to interpret it in the light of existing ideas and beliefs (Mulford & Robinson, 2002; National Research Council, 2000). This way of going about learning is quite hit-and-miss and can result in misconceptions or holding alternate conceptions which are inconsistent with the consensus of the scientific community (Mulford & Robinson, 2002).

It can be seen that for one group of students, in categories C and D, their ways of conceptualizing complex system is via *associative linking* or *associative relevance.* They do not conceptualize complex system in a systematic or analytical way, as an 'expert' with a systems perspective would. But they are capable of making links across different contexts for example when describing that fertilizers are needed *'for growing plants'* they make connections with *'feeding the people'* and by associative relevance to feeding the world, '*we have about 7 billion people on earth, and we don't see it stopping any time soon. So what's going to happen....'* and '*we have more and more people who need to eat food and the problem is that we cannot produce food effectively without the fertilizers'.* As advanced students they were able to reason and raise both positive and negative points of the impact of the Haber process on the environment and society. Another example of this interdisciplinary nature of connectedness is in seeing that fertilizers can be used to '*grow plants...to help feed* *the poor...find a cheaper way to make fertilizers so people in Africa can grow crops more efficiently and create a fertilizer that can withstand harsher environments could also help'.*

Another example of an integrated view of components in a system, interacting and influencing other systems as a network can be seen when student described that *'fertilizers if not used properly...flow into the oceans and waters...the micro-animals...grow insanely...covering the surface of the water...kill the fish'.* Students when talking about a chemical process were able to link ideas in biology to negative effects in the environment. They made associative links between a chemical-industrial system with the hydrosphere and the environmental system.

Consequently, knowing the pathways in which advanced students make connections can open up new perspectives for students when they negotiate the different knowledge domains, support their sense making and aid in the integration of ideas from across different contexts and disciplines. In addition knowing how students make links can help teachers to design teaching sequences that can be guide students' thinking of complex systems from an associative relevance mode of reasoning towards an 'expert' systems perspective.

Implication for learning and teaching – some reflections

The outcomes of this study have identified students' potential for systems thinking and in particular the qualitatively different ways in which upper secondary school students conceptualize complex systems. The next stage would be to use the insights gained to work with teachers, collaboratively, to help design lessons that would encourage the development of system thinking skills in different settings and across different learning contexts. It has been postulated that systems thinking does not develop 'naturally' as does say language, but must be developed through formal education (Booth Sweeney & Sterman, 2007; Jacobson & Wilensky, 2006). On this basis then, systems thinking need to be introduced into the school curriculum. Further work could be done with teachers to look at subject content materials to identify existing topics that may act as building blocks for learning systems concepts (e.g. dynamic feedback cycles, non-linearity and multi-causality) and to ensure they are not counter-productive in developing systems thinking.

7. Conclusions

Contributions of the study

This study has revealed that advanced students have a fairly good grasp of the Haber process from the perspective of knowing in detail the reaction conditions and requirements for an efficient chemical process. This raises the question ‘Does having a good understanding of chemistry also imply having good systems thinking skills?’ For a particular group of students, with conceptions in categories A and B, their conceptual framework appeared to be confined to the chemical knowledge domain and the systems aspect is overlooked. The other group of students, with conceptions in categories C and D, were able to make tentative connections to different domains of knowledge such as biology, economics and the environment. Consequently, the latter way of conceptualizing complex systems could point to the potential for learning systems thinking skills.

In this study it was found that students used a particular strategy that involved ‘associative linking’ or ‘relevance’ as a pathway for constructing or conceptualizing complex systems. This mid-way approach to understanding complex systems could offer students a productive framework for reasoning and thinking about complex systems without requiring students to make too great a leap towards an ‘expert’ systemic approach. This approach needs to be developed further and teachers need to be made aware of these pathways. Teachers can utilize this approach in their teaching as well as support students to gain a robust understanding of complex systems. This is because students’ new knowledge and perspective of complex systems can be fragile and have a tendency to revert to non-complex systems ways of thinking (Jacobson & Wilensky, 2006).

Implications for future research

The implications of this study are firstly, to use the insights gained to enable identification of the interdisciplinary nature of complex systems. In addition science and technology education can benefit by developing opportunities for students to make links between seemingly disparate elements of the curriculum and provide a conceptual framework of coherence and knowledge progression. Secondly, the mapping of variation in ways of conceptualizing complex systems will form an important part of developing a system perspective. Lastly, the findings of *how* students conceptualize about complex systems can be used in collaboration with teachers to design lessons to teach complex systems such as ecology and homeostasis in biology, chemical equilibrium in chemistry and technological systems in ways that will support students in acquiring a systems perspective and achieve a robust understanding of complex systems.

8. Summary of Article

The article is basically a concise version of what has been discussed in the previous 'kappa' section. It is an article that presents a phenomenographic study of students' conceptions on complex system and their systems thinking skills. This article is a working progress and more refinement is needed before it is ready for submitting to a journal for publication. I have included an abstract of the article below.

Abstract
The question "How do students in an upper secondary school conceptualize complex systems?" was asked. A phenomenographic study was carried out to identify the ways in which this is experienced by the students. The analysis arrived at an outcome space which revealed four qualitatively distinct categories of description of the ways of conceptualizing complex systems and the logical and hierarchical relationships between them. The first two categories could be seen as least complex, delimited and simplified ways and the latter two as more advanced or powerful ways of experiencing complex systems. The findings point towards traits necessary for a systems perspective. Some reflections for learning and teaching are also included.

Key Words
Haber process, complex systems, phenomenography, upper secondary school students

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Part II

1. The article

Ways of conceptualizing complex systems – A phenomenographic study of upper secondary school students' systems thinking in the context of the Haber process.

Abstract

The question "How do students in an upper secondary school conceptualize complex systems?" was asked. A phenomenographic study was carried out to identify the ways in which this is experienced by the students. The analysis arrived at an outcome space which revealed four qualitatively distinct categories of description of the ways of conceptualizing complex systems and the logical and hierarchical relationships between them. The first two categories could be seen as least complex, delimited and simplified ways and the latter two as more advanced or powerful ways of experiencing complex systems. The findings point towards traits necessary for a system perspective. Some reflections for learning and teaching are also included.

Key Words

Haber process, complex systems, phenomenography, upper secondary school students

Introduction

This is an empirical exploratory study into what perceptions do upper secondary school students hold about complex systems. For education it is of particular importance to know what students' intuitive concepts or pre-concepts of complex systems are, as they have implications for learning and teaching of other complex systems (Jacobson & Wilensky, 2006; Hmelo-Silver & Azevedo, 2006, de Vries & Tamir, 1997) as well as for developing science and technology curricula (Ingerman & Collier-Reed, 2011; Svensson & Ingerman, 2010). There is a plethora of research studies investigating pupils' attitudes towards technology (PATT reports, de Vries, 1986, 2005) and on students' concepts of technology (Davis, Ginns & McRobbie, 2002) but there is a scarcity of studies on *how* students conceptualize about complex systems and in particular upper secondary school students. It is the intention of this study to shed light on the ways in which upper secondary school students understand, conceptualize or perceive of complex systems and to discover if these advanced students show potential traits towards system thinking.

The findings from numerous studies on students conceptualizing technology are varied and different but they also have much in common. They afforded four views of conceptualizing technology namely as artefacts, as knowledge, as processes and as human practice (de Vries, 2005; DiGironimo, 2011). In another study by Svensson & Ingerman (2010), they showed that pupils discerned systems in everyday objects in five increasingly complex ways namely as using objects, the function of objects, objects as part of a process, objects as components in one system and objects as embedded in systems. The study by Davis *et al*, 2002 was on elementary school children, the one conducted by DiGironimo (2011) involved middle school-aged students in grades 6, 7 and 8 and Svensson and Ingerman's study (2010) interviewed young people who were 10 and 15 years old. There have been very few studies conducted on upper secondary school students, which is of particular interest as they represent the more advanced students and would add to the deeper understanding of how students (*from elementary level through pre-college level*) experience technology and technological systems in particular. It can be argued that a deeper understanding of systems concepts has the potential to promote higher order learning skills such as interdisciplinary thinking and modelling (Barak & Williams, 2007).

Technological systems and systems approach

According to de Vries (2005, p.25) there are two ways of conceptualizing technological systems, firstly the way a set of parts work together and are connected is the 'physical nature' aspect and secondly the 'functional nature' aspect of the system as conceptualized by their input, process and output. Ropohl (1999) characterized inputs, states, and outputs as matter, energy, or information which can occur in time and space. This systems approach also incorporates the concept of feedback which is seen to be an important element in the systems concept (de Vries, 2005, p.26). According to Senge (1990), systems thinking is concerned *with seeing the ''whole'', understanding the inter-relationships between system elements and identified patterns of change*. The core of system thinking in technological contexts is the concept of the change with time of physical or social variables like temperature, volume or number of products (Barak & Williams, 2007), in other words, variables related to matter, energy or information (Ginns, Norton & McRobbie, 2005; Svensson & Ingerman 2010).

In a study by Svensson, Zetterqvist and Ingerman (2012), they described technological systems as sociotechnical systems, defined in terms of an ascribed function of what technological objects are expected to achieve (goal-directed) as well as components that may have either technical or human agency or rules. In their analysis of previous research and philosophical descriptions of technological systems, a synthesized framework of technological systems with four interconnected parts was derived namely the structure of the system, the function of the system, how the system interacts with humans and society and lastly how the system interacts with other technological systems and nature, which together points to a larger whole.

Booth Sweeney and Sterman (2007) in their study on 'Thinking about systems' defined system thinking and system thinking skills as abilities to *(i) recognize recurrent patterns of behaviour in different domains, (ii) distinguish types of system structures and (iii) make relevant policy recommendations.* They found that significant number of participants, regardless of age, exhibit limited understanding of complex natural and social systems.

Consequently, it is the aim of this study to elucidate how knowledge about complex systems or understandings of such systems is constituted by learners, particularly upper secondary school students. It is not the aim of the study to determine whether students conceptualize technological or complex system in the 'right' way or according to the 'expert's view' but rather to reveal the qualitatively different ways of conceptualizing complex systems. Hence the question 'How do upper secondary school students conceptualize complex systems' was asked, in the context of the Haber process.

What are some tentative characteristics of complex systems perspectives?

As alluded to in the introduction, another aim of this study is to identify any potential traits that upper secondary school students show towards complex systems perspective or systems concepts or possible hindrances to students developing such a perspective. Jacobson and

Wilensky (2006) argued for the importance of learning complex systems ideas particularly at the pre-college and college level and discussed some of the challenges involved in learning these principles. They and others (Eliam, 2012; Hmelo-Silver & Azevedo, 2006; Jacobson, 2001, Sabelli, 2006) have identified some of the core concepts of complex systems perspective as randomness, feedback loops, self-organization from decentralized interactions, emergence or emergent properties, non-linearity, multiple agents, multiple causality, energy and matter as multilevel phenomena and dynamic equilibrium and directionality to name a few. It has been acknowledged that learning complex systems is hard (Hmelo-Silver & Azevedo, 2006; Jacobson & Wilensky, 2006). In particular, some core systemic ideas have been shown to be counterintuitive to students' prior knowledge and beliefs, like the ''butterfly effect,'' randomness, decentralized interactions, self-organization, and nonlinearity (Grotzer, 2005; Hmelo-Silver & Pfeffer, 2004; Jacobson & Wilensky, 2006). As Jacobson and Wilensky (2006) pointed out it is important for students particularly pre-college and college students to learn these conceptual perspectives as citizens of the modern world, they need to deal with challenging social and global problems in the 21st century. One of the central tenets of complex system theorizing is that macroscopic behaviour of elements cannot be deduced from the elements considered independently but rather that the interactions and the interconnected components give rise to non-linear dynamics and emergent behaviours that would otherwise not have arisen if the elements were independent (Goldstone, 2006; Sabelli, 2006). So it is increasingly important for students to develop these new perspectives as it opens up new intellectual horizons and new explanatory frameworks that are becoming of central importance in the 21st century (Jacobson & Wilensky, 2006).

Using phenomenography to investigate ways of experiencing complex systems

Phenomenography is an empirical research approach which aims to investigate the qualitatively different ways in which people understand, conceptualize, experience, see or perceive a particular phenomenon or an aspect of the world around them (Marton & Booth , 1997; Marton & Pong, 2005). A fundamental assumption in phenomenography is that there are a finite number of qualitatively distinct ways of experiencing a particular phenomenon (Marton & Booth, 1997, p.32). The focus of this approach is on the collective human experience of the phenomenon, at a particular time, for the population represented by the sample group (Åkerlind, 2005). These different ways of understanding or conceptualizing make up the categories of description, which are further analysed with respect to the referential, that is the global meaning of the object conceptualized and the structural aspects, that is the specific combination of features discerned and focused upon (Marton & Pong, 2005). An outcome space is constituted which represents the range of possible ways of experiencing the phenomenon in question and their logical and usually hierarchical relationships between these different ways of experiencing (Marton & Booth, 1997, p.125).

The phenomenographic approach was chosen precisely on the basis that it can reveal the breadth of variation in the ways in which upper secondary school students conceptualize complex systems in the context of the Haber process. It was also chosen because phenomenography focused on the collective rather than individual experience and it is the intention of this study to identify these qualitatively different ways that upper secondary school students understand complex systems. Another intention of this study is to reveal whether these ways of understanding complex systems are naïve or do they point towards characteristics of a system perspective.

Research design and methodology

This empirical study used semi-structured interviews to generate data. The interview questions were piloted and revised before the in-depth interviews were conducted. The one-to one interviews lasted between 30 and 50 minutes and on average, each interview lasted approximately 40 minutes. The participants were all between the ages of 18 and 19 years old. A total of sixteen interviewees took part, 11 boys and 5 girls. The sample group were all from the same chemistry class, taught by the same teacher but none were taught complex systems explicitly. The topics that were covered in class before the interview included chemical equilibrium, Le-Chatelier's principle, enthalpy and catalysts; the Haber process was mentioned in the course of teaching chemical equilibrium. The Haber process was used as a conversation opener, when students were unsure or unable to recall the process, a schematic diagram of the Haber process was shown to the interviewees. As the interview progressed, the students responded freely and this allowed for opportunistic questioning and respondent elaboration. All the interviews were audio recorded and transcribed verbatim by the researcher herself.

Data analysis

The analysis took place over four phases firstly, all the interviews were transcribed verbatim and iterative reading of individual transcripts allowed for familiarisation of the text as a whole as well as a collective (in the context of all the individual transcripts). Second phase involved identifying and selecting the conceptions or understandings in terms of their meanings, with respect to complex systems and/or processes. This was done by marking out key utterances or interesting quotations that were relevant to the phenomenon studied. In this way full length individual interviews were transformed into focused key interview excerpts related to the object of conceptualization. The third phase is developing the first draft of the categories of description, which is an interpretative process. The 'pool of meaning' (Marton & Booth, 1997, p. 133) contained all the material that had been selected from the second phase and can be viewed from two perspectives, from the individual interviews ('parts') and the other in the context of all the other interview excerpts ('whole'). In the key utterances or interview excerpts, sometimes the meaning is explicit but other times an interpretation is made in relation to the context from which the excerpt is taken. As a result of this interpretative process, interview excerpts are brought together on the basis of their similarities into groups and criterion attributes were identified. These salient features identified were compared with and contrasted against other groups and eventually narrowed to form tentative categories of description. The tentative categories were further analysed using the analytical tools of structural and referential aspects (Marton & Booth, 1997, p.87) and the structural aspect was further described with respect to its internal and external horizons (Marton & Booth, 1997, p.91, 100; Svensson, Zetterqvist & Ingerman, 2012). Throughout this whole process, the researcher sought evidence from the empirical data i.e. within the transcripts and the pool of meaning to substantiate the draft categories of description, focusing on the similarities as well as what differentiates the categories. Discussions with other phenomenographers at a seminar on 'Variation theory and phenomenography' helped in reformulating, justifying and refining each aspect of the categories of description as well as discussions with her supervisor in negotiating the meaning of excerpts of data. All through this phase of the analysis iterative reading of the transcripts took place, each time from a slightly different perspective as the researcher became more familiar with the data. The attention was no longer on individual transcripts but on the collective level. The final phase of the analysis is arriving at an outcome space, which denotes the qualitatively different ways of conceptualizing complex systems, the categories of description and the logical relationships between them.

Results

The outcome space is summarised in Table 1 and resulted in four categories of description. Each category is described in detail below, showing the relationships within categories as well as between categories and illustrated with excerpts from the interviews. The excerpts represent the main feature of each category since no one excerpt can fully characterize the whole category.

Table 1– summary of analysis of categories of description in relation to the referential and structural aspects.

Categories	**Referential aspect** (the meaning of the phenomenon, its global aspect)	**Structural aspect** (the organization of awareness, the parts that are delimited from and related to each other)	
		Internal horizon (that which is in focus and figural in awareness)	**External horizon** (outer limits or perceptual boundary)
A: **Talks about a process**	Making a product.	Discrete entities like energy and matter in general terms for example like heat, temperature, pressure, air nitrogen, hydrogen and catalyst.	Chemical processes.
B: **Describes a process**	Producing a product.	Discrete entities but in more specific terms like atoms, molecules, iron catalysts, activation energy.	Chemical processes.
C: **Describes a process in relation to the whole system**	Process embedded in a system, enabling a system. A closed system.	Entities or components within the process as interconnected and not as discrete entities.	Chemical processes as part of industry or industrial complexes and in part connected to society and the environment.
D: **Describes the system in relation to society and the environment**	A system, with all its interconnected parts and interacting with other systems. An open system.	Components of processes intertwined with aspects external to the process, like waste produced by the process and waste management and consequences to environment and humans.	Chemical processes, industrial complexes interconnected with society and the environment.

Category A: Talking about a process

In the interviews, students talked about energy and/or matter in terms of their use and function in the Haber process. Energy and/or matter in this category were not seen to be connected to other parts of the system. They were viewed as discrete entities in a process and their roles related directly to the chemical reaction itself.

In this least complex category, students were able to state the conditions needed for the reaction, in terms of temperature and pressure. In some instances, students were explicit in giving exact temperatures and pressures (quantified amounts) required by the reaction to produce best yields of the product. In others the answers were vague and referred to just heat and pressure in general terms. They did not attempt to talk about heat or pressure in qualitative terms as shown in the excerpt below.

Q. So if you think it is using air, and air is all around us, why do you think it is not just reacting and ammonia is dropping down on us?
B. (Laughter), yeah…
Q. If I were to wave the catalyst around in the air, do you think ammonia will form?
B. No, heat and energy is needed.

Students talked about energy and/or matter in terms of discrete entities like nitrogen, hydrogen, air, catalysts, 200˚C and 600 atmospheres relating to the structural aspects of the process making up the internal horizon. The relationship between them is that they were used in the reaction implying that the entities interacted to form ammonia.

Q. Ok, that's a good start. Can you tell me apart from its purpose, can you tell me about the Haber process, itself? What you understand about the Haber process?
C. Well, I understand that they use of course nitrogen and hydrogen under certain temperature and under certain pressure in connection with a catalyst, iron to create ammonia.

Q. So what can you say about its conditions? What would you say would be the best conditions to use? And what would you say would be the conditions that industry would use?
C. OK, judging from this graph I'll say you'll get the highest yield if you use quite a low temperature and this scale goes from 200˚C to 600˚C so the lowest temperature here is 200˚C and then the highest pressure.
Q. OK and that will give you the maximum yield there.
C. Yeah. So a low temperature and a high pressure will give you the highest yield.
Q. So it would be kind of like 600 atmospheres?
C. Yeah, around 600 atmospheres and 200˚C.

The external horizon of the structural aspect seemed to be chemical process only.

The referential aspect seemed to be the making a product and in category A, it was the making of ammonia.

Category B: Describing a process

This category of description is more advanced and higher up the hierarchy than the previous category A, in that students were able to describe energy and/or matter as constituting parts of a whole system. They were not relating to energy and/or matter in vague or general terms and were making tentative links with other parts of the system like economy and rate of production.

In this category, energy and/or matter were described in more qualitative terms. Students were able to describe energy as having specific characteristics like "*sufficient speed*", "*amount of collisions*" which is linked to "*the rate of reaction*" and the possibility of the reaction being "*not economically viable.*" An example of this way of describing energy is shown in the excerpt below.

> *Q. …So what do you think are the considerations by the industry, why do they choos to operate at those temperatures and pressures?*
>
> *D. Yeah, so in order to get the reaction going you'll have to have sufficient err... firstly you have to have enough speed in the collisions, collision theory, yeah, you'll have to have sufficient speed in the collisions and also the amount of collisions too. So the amount increases as speed increases, and as speed increases, the temperature increases. So the lower the temperature the fewer the err… the smaller the collisions will be. Which means that the rate of reaction will be much slower and that's from what I've heard is not economically viable to have a too slow a reaction.*

Students were able to talk about a specific form of energy, "*activation energy*" which was needed if a reaction was to proceed. In their answers it was implied that this energy had to be provided and they used terms like "*put in*" *and* "*you need to* ..." Students also described energy as being related specifically to chemical bonds being formed and broken. They described explicitly that energy was "*use to break*" bonds and by the formation of bonds "*we gain energy, which releases energy.*" This way of expressing energy points to the students' prior knowledge of enthalpy and ideas relating to exothermic and endothermic reactions. In terms of matter, students talked about "*combining*" nitrogen and hydrogen. They were able to articulate energy interaction at the sub microscopic level relating it to the chemical reaction of forming ammonia in the Haber process. Students talked about "*molecules collide*" and "*molecules or atoms are moving*" which alluded to their prior knowledge on kinetic/particle theory, which was then related to the idea of molecules reacting and increase in temperature.

In category B students were also able to describe the idea of energy flow within the process. They talked about using "*a natural coolant*" in this case using water to take heat out of the gas, thereby "*cooling it*" and making the water warm, "*the coolant goes out is warm.*" In their discussions there were signs that point to the idea of energy flowing from hot regions to cooler regions.

In the excerpt below, matter was seen to be transformed from a gaseous state to a liquid state by the removal of heat. The idea of energy flowing from a region of higher temperature to a region of lower temperature is again articulated in this excerpt where the student talked about "*the coolant goes through the gaseous ammonia…condensing it and the warm coolant is brought out.*"

Q. …So what would you say would be the core ideas that you would explain to someone who has not heard of the Haber process before?

H. Well, I will explain perhaps how hydrogen and nitrogen are combined, in the presence of a catalyst at a certain temperature and pressure and how it goes through err… the coolant goes through the gaseous ammonia, cooling it and therefore making it turn into liquid, condensing it and the warm coolant is brought out and new coolant brought in. Then the leftover hydrogen and nitrogen that did not react is brought back into the and react.

Q. OK. How do you see the idea of matter and energy within this system? What do you understand about what's happening in there in terms of energy and matter?

H. Well, it would be, well you need constant energy to take the heat out of the coolant after it's gone through the gas.

The internal horizon of the structural aspect of category B was very much related to discrete entities at the sub microscopic level and how they specifically interacted with each other. This differed from category A where the entities were talked about in more general and non-specific terms but nevertheless, they were still talked about as discrete entities which was similar to category A. The external horizon seemed to be the chemical process with tentative links to the economy.

The referential aspect is very much about producing a product and making a profit.

Category C: Describes a process in relation to the whole system

In this category students were able to link energy and/or matter in a chemical process with other aspects of a system, like the rate of production and were beginning to experience the phenomenon as a whole. They were beginning to conceptualize the process more as part of a system and less as discrete entities that were unrelated. Students described how heat and temperature affected how fast a reaction was carried out, as shown in the following interview excerpt.

Q. I mean how do you relate the temperature with the time factor? What do you mean by that?

G. Well, I mean time is money, that's important. So you want to get as much done as possible within a specific time. And if the temperature is good enough then the reaction can proceed as fast as possible, I mean that is also a factor. I mean one part says that you need a low temperature so that the reaction can get a great yield but that if the temperature is too low then the reaction is too slow.

This idea of rate was further linked to other considerations within the system like costs, profits and the purpose of carrying out the process. This can be seen as a more advanced way of describing the Haber process as opposed to the previous two categories where students talked about use, function and the mechanics of the reaction.

Students also described energy and/or matter in relation to a cycle within a process. This cyclical flow was linked to the idea of efficiency. Again this can be seen as a more powerful way of experiencing the phenomenon or a more advanced way of conceptualizing a process embedded in a system. In category C there was a distinct shift in conception from the discrete and unconnected' parts' (seen in categories A and B) to seeing the elements more as integrated into the 'whole', taking on more of a system perspective.

In this category C, students related to the behavioural aspects (how it progressed and what impact it has) of a process and its purpose. Students were able to talk about the Haber process in the wider context of industrial processes and making connections with use of energy and/or matter and the economy.

The structural aspect of category C referred to the components making up a systemic process, what was discerned and focused upon, the internal horizon. In this study, it was energy and/or matter flowing and transforming as well as having effects on other parts of the system like the rate of production, efficiency, profitability and linking these ideas partly with the economy. The external horizon, the perceptual boundary seemed to be industry and the economy.

The referential aspect is a process embedded in a closed system, it seems to be more than just producing a product or seen to be a means to an end.

Category D: Describes a system in relation to society and the environment

In this most advanced category students were able to relate energy and/or matter not just to processes (internally) but also to the system (externally) and in particular to society and the environment. They are beginning to show signs of talking about systems (experiencing or seeing the whole constituted of entities or components, society and environment) rather than processes. Students described the waste produced by industrial plants which may be in the form of energy and/or matter, and related it to how it can be further dealt with. They were able to describe the consequences of the waste produced which impacted on the environment and society. The involvement of humans featured largely in this category of description. Students talked about responsibilities and decision making by individuals as well as governing bodies and how these were interlinked within the system, such that humans can be seen as both interacting as well as influencing the system. Students were able to show signs towards complex systems thinking when they talked about one system like an industrial complex interacting with another system like the environment, how the actions of one part can have repercussions on other parts of the system.

In the interview excerpt below, the student talked about the positive and negative impact of the Haber process and the production of fertilisers (matter) on the environment and society.

Q. The product fertilizers, do you know what it is further used for, for what purpose?
K. For growing plants, in the greenhouse. So you can have vegetables in whatever season you want.
Q. So you use the greenhouse and supplementing ...
K. Not necessary greenhouse , you could do it in your home as well. So the main purpose is to grow stuff.
Q. Ok, so in this growing of stuff, it's for us humans, how do you see this impacting on society besides just feeding us?
K. I think it is quite negative for the environment. Because, you know those fertilizers, it's err…if we can't use it properly, for example it flows into the oceans and waters. The micro-animals they can get the nutrients from the fertilizers and they err…it will cause huge damage to the environment, like they can grow insanely, will kill the fish by covering the surface of the water. It can also cause like poison stuff, if it goes round into the human food and err… I think the environmental problem is one of the main issues of fertilizers.

Q. So that's pretty negative. Can you see anything positive things about the purpose of making fertilizers?

K. Crops I think is one of the major positive things, like I think it's a great innovation and now we have more and more people who need to eat food and the problem is that we cannot produce food effectively without the fertilizers. So we need the food to grow faster and so we need to borrow the function of the fertilizer to make it grow faster and then it'll achieve the amount of food that we want.

Students described matter (chemical waste) as flowing into another system (water supply) and impacting not only on the environment but also human beings. Students also described matter in terms of transforming waste from industrial processes into less harmful and/or other useful products, thereby conserving natural resources. Students also talked about the creative use of waste, all with the idea of lessening the impact on the environment and/or society.

Students talked about human involvement in terms of companies, industries and governments making decisions, taking responsibilities and ensuring compliance to regulations and standards set down to safeguard society. They also related human involvement at different levels in the system like the workers or the labour force in an industrial plant to the board of directors for the companies and industries and finally to government officials who enforce the laws and policies of a country.

Q. Yeah, and we talked a little about how the economy worked in society. Maybe we can talk about the environmental effects that you've just mentioned. How do you see industries and their environmental effects impacting on society?

H. Well, if there is for example lot of emissions from factories that are supposed to be regulated such as for example, my dad works for a company that uses mercury for electrolysis and this is rather err… considered bad by the Swedish government. I guess, it's not so much an environmental effect than it is a social effect that the company gets less, or that industrial process gets less not credibility, but perhaps prestige, because of the negative connotations affiliated with it.

Q. Does that particular industry do anything to limit the impact?

H. Well, they are trying to move away from using mercury altogether but err… yeah, they apparently have the least mercury emissions in Europe among the type of companies and yet it's still too much according to the Swedish government and Swedish laws.

Q. OK. Let's say you are dealing with an industrial process that does have negative environmental impact, who do you see the responsibility lie in trying to limit this? Is it with the government or is it with the company, what do you think?

H. I think it should be with the company but sometimes that's not enough, that's why the state intervenes.

Q. And what kind of intervention do you see the state doing?

H. Well, they set quotas or like this is the most you can emit and if you do more than this you have to pay a big fine.

In category D, the highest in the hierarchy of ways of conceptualizing a system, the structural aspect is what is discerned and focused on and in this respect it referred to the elements, components within the processes as well as aspects outside the processes and also constituting the whole system. The students were able to talk about the waste produced within the processes and related this with waste management, impact on humans and the environment and consequences to society, which are aspects outside of the industrial processes themselves.

The students talked about these parts in relation to the whole and the whole in relation to its parts and the external horizon is perceived to be society and the environment. This way of understanding is inextricably linked with the referential aspect, its global perspective of the phenomenon and in this study it referred to the holistic experience of an open system.

Discussion and reflections

What are the qualitatively different ways in which upper secondary school students experience complex system?

Student participants in this study can be seen as having more than one way of conceptualizing as their way of understanding complex systems can change and vary within the range of contexts in which they were discussed.

Starting with category A and moving up the hierarchy to category D, the results show an increasing complexity towards a more advanced way of conceptualizing complex systems. Students talked about complex systems as processes, as a means to an end and from a structural aspect, focused on the elements (like energy and/or matter) within a process, as shown in categories A and B. This is quite a narrow way of experiencing complex systems. It could be argued that in categories A and B, students focused on (internal horizon) discrete processes whose function was to make or produce an end product, they do not relate complex systems in a holistic way and do not make connections with other parts of the system, there is a lack of system perspective.

There was a distinct shift in the structural aspect both to the internal horizon as well as the external horizon from category B to category C. In category B, the internal horizon became more specific and less vague; nonetheless, the focus was still on discrete entities of energy and/or matter within a process. Whereas in category C, the internal horizon is constituted as elements that are interconnected with other parts of the process like the rate of production and also in part linked to other aspects of the system like the economy, it was not conceptualized as discrete entities. Finally in category D not only is energy and/or matter discerned as discrete entities that are interconnected within a process and within a system but also discerned as elements or components of a system relating to other systems. In this most complex category, the ‘parts’ have receded into the background and what is in the foreground is the ‘whole’. The way in which a complex system is understood can be described as reagents in a chemical process interacting to produce a product which is in turn a precursor for manufacturing many other products. The impact, consequences of these industrial processes and human involvement within a system is seen to have significant effect on other systems like society, the environment and mankind. The internal horizon of the structural aspect of the categories is inclusive but the same cannot be said of the referential aspect.

The referential aspect and the structural aspect of the categories of description are known to be closely intertwined (Marton and Booth, 1997, p. 87, 91). In this study, the referential aspect and the external horizon are related, in category A and B, the meaning (for individuals) of complex systems is confined to simple chemical processes with the purpose of forming products. The way a chemical-industrial system is conceptualized is contextually bound and limited to the function and intention of the chemical processes. It can be argued that was it really complex system that was experienced or rather was it a chemical process that was experienced. Nevertheless categories A and B described the less advanced ways of conceptualizing a complex system which could be discerned as chemical processes. A dramatic shift in the referential aspect occurs between categories B and C, where the meaning shifts from making and producing a product (processes) to a more systemic perspective. In category C the meaning with respect to the 'parts' is no longer in focus but what is becoming more important is the 'whole', the processes are embedded in the system. Finally in category D, the referential aspect takes on a global meaning, where a system can be seen to interact with other systems.

What are some characteristics that point to students' system thinking?

There have been many definitions of systems thinking and lists of system thinking skills (Booth Sweeney & Sterman, 2000, 2007; Jacobson & Wilensky, 2006; Richmond, 1993; Wilensky & Resnick, 1999). But one of the core ideas of systems thinking is the ability to represent and assess dynamic complexity, which involves understanding how behaviours of a system is a result of interactions of its agents over time (Booth Sweeney & Sterman, 2000). Another way of expressing the core tenet of complex system theorizing is that macroscopic behaviour of elements cannot be deduced from the elements considered independently but rather that the interactions and the interconnected components give rise to non-linear dynamics and emergent behaviours that would otherwise not have arisen if the elements were independent of each other (Goldstone, 2006; Sabelli, 2006).

In this study, signs pointing towards students' system thinking can be seen as exemplified in the following interview excerpt where the student is able to reason and make connections between scientific ideas not just in chemistry but in other subject areas like biology and technology.

> *Q. The product fertilizers, do you know what it is further used for, for what purpose?*
> *K. For growing plants, in the greenhouse. So you can have vegetables in whatever season you want.*
> *Q. So you use the greenhouse and supplementing ...*
> *K. Not necessary greenhouse, you could do it in your home as well. So the main purpose is to grow stuff.*
> *Q. Ok, so in this growing of stuff, it's for us humans, how do you see this impacting on society besides just feeding us?*
> *K. I think it is quite negative for the environment. Because, you know those fertilizers, it's err…if we can't use it properly, for example it flows into the oceans and waters. The micro-animals they can get the nutrients from the fertilizers and they err…it will cause huge damage to the environment, like they can grow insanely, will kill the fish by covering the surface of the water. It can also cause like poison stuff, if it goes round into the human food and err… I think the environmental problem is one of the main issues of fertilizers.*
> *Q. So that's pretty negative. Can you see anything positive things about the purpose of making fertilizers?*
> *K. Crops I think is one of the major positive things, like I think it's a great innovation and now we have more and more people who need to eat food and the problem is that we cannot produce food effectively without the fertilizers. So we need the food to grow faster and so we need to borrow the function of the fertilizer to make it grow faster and then it'll achieve the amount of food that we want*

The student is able to make connections between the nutrients, microorganisms and the negative environmental impact as well as societal benefits of feeding the people. The reasoning and the links made between scientific ideas like 'nutrients' and microorganisms (studied in biology) with the environment (eutrophication in geography) and society (in economics and history) point towards signs of system thinking. It also points to a more advance way of reasoning and making connections between abstract ideas which is presented in upper secondary school students.

Another sign pointing towards system thinking is the ability to relate inputs-outputs-processes (i.e. energy and/or matter) in cyclical way and not just in one-direction and be able to consider their interactions over time. This can be seen when the student talked about food production in the following interview excerpt.

> *Q So grow crops and your crops will provide food. So why is food important?*
>
> *J. Do you want me to relate this to getting food? Cause you start here…H_2 and N_2 and you get NH_3, ammonia. Then you make fertilizers and the fertilizers fertilise the ground and you grow harvest, you grow crops then you make that into food and then you feed the humans and any animals maybe. And then you process that …they defecate and then err….it happens again and if you do to animals …you'll get the fertilizers once again. So can increase fertilizers.*
>
> *Q. You can say that. And you can see this process as being quite like a cycle…kind of?*
>
> *J. Yeah*

Implications for learning and teaching – some reflections

The outcomes of this study have identified students' potential for systems thinking and in particular the qualitatively different ways in which upper secondary school students conceptualize complex systems. The next stage would be to use the insights gained to work with teachers, collaboratively, to help design lessons that would encourage the development of system thinking skills in different settings and across different learning contexts. It has been postulated that systems thinking does not develop 'naturally' as does say, language, but must be developed through formal education (Booth Sweeney & Sterman, 2007). On this basis then, systems thinking need to be introduced into the school curriculum. Further work could be done with teachers to look at subject content materials to identify existing topics that may act as building blocks for learning systems concepts (e.g. dynamic feedback cycles, non-linearity and multi-causality) and to ensure they are not counter-productive in developing systems thinking.

Conclusion

The aim of this article is to shed light on how upper secondary school students' conceptualize about complex systems. The findings from the phenomenographic study on students' systems thinking has shown that upper secondary school students indeed have different ways of experiencing complex systems and that some ways are more advanced ways of conceptualizing than others. The identification of the critical aspects and what differentiates one way of experiencing from another can contribute to the body of knowledge in this research field. The results can also contribute towards developing and designing science and technology curriculum for more productive student learning in the area of complex systems. For future research it would be worthwhile to use the findings to design a series of lessons around the teaching of the Haber process in collaboration with teachers and investigate whether students are able to 'learn' and 'acquire' a system perspective. Furthermore, it would be beneficial to study if these system thinking skills can be transferred to other subject knowledge domains.

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Appendix I:

PARTICIPANT CONSENT FORM

Project title: Master's Thesis – Students' Understandings of Technological Systems.

Researcher's name: Sue Lewis

Supervisor's name: Åke Ingerman

- The nature and purpose of the research project has been explained to me. I understand and agree to take part voluntarily.
- I understand the purpose of the research project and my involvement in it.
- I understand that I may withdraw from the research project at any stage and that this will not affect my status now or in the future.
- I understand that while information gained during the study may be published, I will not be identified and my personal results will remain confidential.
- I understand that I will be audiotaped during the interview.
- I understand that data will be stored as audio recordings and both hard and electronic copies of transcripts will also be kept. The researcher and her supervisor will have access to the data.

Signed ………………………………………………………(research participant)

Print name ………………………………………**Date** …………………………………

Contact details

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Supervisor: Åke Ingerman; +46 31 786 2637; ake.ingerman@gu.se

Appendix II:

Interview Protocol
Part 1: With teacher (background and informing context of data collection)
Questions:

1. Can you tell me a little bit about your background as a chemistry teacher?

2. Tell me about your teaching of chemical industrial processes?

3. Is there a textbook that you use directly, in the teaching of this topic?

4. With respect to what you've just mentioned about teaching the Haber process, can you tell me how **you** have understood this process? What do you see as the core principles/conceps or key ideas in this process?

5. Can you tell me about a particular lesson when you introduced your class to the Haber process or any other industrial process, most recently?

6. What was the intention of your lesson for the class (i.e. lesson objective)? How did you see the lesson went?

7. How do you know that the students have grasped the key concepts you were introducing to them?

8. What I want to know more specifically is, how do you assess your students' understandings?

9. What are the signs that you look for or pick up on to give you an indication that your students have understood the key ideas in the Haber process?

Interview protocol

Part 2: With individual students.

Questions:

Background questions:

1. Tell me a little bit about yourself; your name, age, how long have you been studying chemistry, what level of education are you at, what do you hope to do after you finish at this college?

Specific Level:

(A) Opening the phenomenon (Haber process) from different entry points:
- Can you tell me what you understand about the Haber process?
- What do you think the purpose of the process is?

- What do you think the Haber process is all about?
- Have a look at this picture (Haber process), tell me what you understand about the process?
- Have a look at graph/chart(optimum conditions), what does it tell you about the Haber process?
- Tell me about a chemical process you have come across recently?
- Tell me what you understand by the term chemical process?

(B) To establish a common understanding (researcher and interviewee)

- Can you tell me …..?
- Are you saying this…..?
- Can I confirm that you mean…..?
- Can you clarify what you mean by ……?

(C) Explorative questions and follow up questions on the specific level.

Exploring the internal horizon:

- If you were asked to explain the Haber process to someone else (who knows nothing about this process), how would you explain it? What would you say?
- What do you think are the important aspects of the Haber process?
- How do you view the Haber process? Is it just a chemical reaction? Or do you think it is connected to other things? If so, what other things is it connected to (exploring external horizons)?
- Is there anything else you would like to add (exploring external horizon)?

General Level:

(A) Opening the phenomenon (Industrial processes) from different entry points:

- We've discussed the Haber process as an example of a chemical process, what other industrial processes can you think of?
- What would you say would be the important considerations, if you were asked to plan to build an industrial plant to manufacture something?
- Would these considerations be different if you were making cars instead of chemicals?

(B) Exploratory questions:

- You mentioned earlier that you think that an industrial process is…..can you elaborate a bit more on what you mean?
- How do you think about energy and matter in these processes? (Transformational?)
- Can you draw a picture to show how the system works as a whole?
- Modify questions *Ask*:
    - *What would be the important considerations you would think about when planning to build an industrial plant?*
    - *What is there to know about these systems?*
    - *How would you manage the waste produced?*
    - *Where does it all go?*
    - *Do you think there are consequences to building lots of industrial plants?*
    - *What do you think are some of these consequences?*
    - *Can you further elaborate or explain what you mean?*

Complex Level:

(A) Opening the phenomenon (Complex technological systems):

- Why do you think that there are so many different types of industries? Can you give me some examples?
- What do you see is the role of the Haber process?
- [Show two pictures side by side of inorganic vs organic fertilisers] Can you reason out how you would choose one type of fertilizers over another?
- Do you think humans have a role in these processes/systems we've been talking about? If so, what do you think they are? (consumerism; consumption of end products; distribution; recycling)
- Do you think that these processes have a wider impact on society? If so what do you think they are? (economics; environmental)
- Can you draw a picture to show how these different aspects (humans, society and environment) may or may not be connected or as the case may be, to form a whole?

(B) Exploratory questions:

- Can you elaborate what you mean by……recycling; multi-causality; (from the picture drawn by the interviewee)?
- From your picture, you have shown …….(multiple arrows?, flow chart?) what do you mean by this?

Ending the interview

- Is there anything else you would like to say or add?
- Thanks for taking part in the interview.