Unit of Chemistry Teacher Education
Department of Chemistry
University of Helsinki

# HOLISTIC AND INQUIRY-BASED EDUCATION FOR SUSTAINABLE DEVELOPMENT IN CHEMISTRY

**Marianne Juntunen**

ACADEMIC DISSERTATION

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**Supervisor**
Professor Maija Aksela
The Unit of Chemistry Teacher Education
Department of Chemistry
Faculty of Science
University of Helsinki

**Reviewers**
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University of Jyväskylä

Adjunct professor, Senior lecturer Ilkka Ratinen
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Faculty of Education
University of Jyväskylä

**Opponent**
Professor Ilka Parchmann
Leibniz Institute for Science and Mathematics Education
Kiel University, Germany

**Custos**
Professor Mikko Oivanen
Department of Chemistry
Faculty of Science
University of Helsinki

# ABSTRACT

Chemistry plays an important role in making the future more sustainable and solving the related global issues. Curricula, national and international educational strategies, research literature and chemical industry are all focusing on sustainable development. We need more environmentally literate chemists, chemistry teachers and students – future citizens, who are to solve the numerous environmental challenges that face the whole world.

The main aim of this design research study was to find out what are the features of holistic and inquiry-based education for sustainable development in chemistry. At the same time, the aim was to foster students' environmental literacy, argumentation skills and positive attitudes towards chemistry. Education for sustainable development in chemistry is related to socio-scientific issues, e.g., life-cycle thinking and green chemistry.

Theoretical problem-analysis of the study was used to investigate the approaches that are of key importance to the study presented in this dissertation: sustainable development, green chemistry, the life-cycles of different products, environmental literacy, socio-scientific education, and the pedagogical methods of inquiry-based learning and argumentation. The empirical design phase sought an answer to the main research question: What are the main features of holistic and inquiry-based education for sustainable development in chemistry? The main focus of the research was in teaching life-cycle analysis, which is one of the key elements in the Finnish national curriculum.

The design research project constituted of three phases, which were conducted during the years 2010–2014. The first empirical phase was conducted in four chemistry teachers' in-service training courses. During these courses, a total of 20 chemistry teachers created new inquiry-based methods for teaching life-cycle analysis in chemistry. This development process was based on theoretical problem analysis. The second empirical phase focused on creating a collaboratively-developed design solution based on the teachers' concepts and the effects of this solution. The participants in this second phase were 105 $9^{th}$ grade students, whose environmental literacy, argumentation skills and attitudes towards chemistry learning were evaluated. The third phase was theoretical. It consisted of comparing the gained empirical knowledge to theoretical literature in order to answer the main research question. The methods of data analysis included content analysis of texts, semi-structured interviews and quantitative surveys. The validity of the results of the conducted cyclic design research project is enhanced by theoretical literature analysis, methodological triangulation, researcher triangulation, the testing of the developed teaching concept in authentic environments and the systematic, visualised documentation of the design phases.

The design phases resulted in three types of knowledge: 1) new chemistry teaching concepts for sustainability education that use life-cycle thinking and inquiry-based learning methods, and a collaboratively-developed design solution (Article I), 2) knowledge about how inquiry-based learning of life-cycle analysis affects students' environmental literacy, argumentation skills and attitudes towards chemistry (Articles II and III) and 3) domain knowledge about holistic and inquiry-based education for sustainable development in chemistry (Article IV).

Holistic and inquiry-based education for sustainable development in chemistry includes interdisciplinary and socio-scientific issues. Socio-constructivist and contextual chemistry education is bound to societal actors and co-operational, real-life activities. Learning occurs in social interaction, through argumentation and self-reflection, for example. The students themselves may choose the focus of inquiry, and it may relate to raw materials, consumer products, food substances or water, for example. As the knowledge of chemistry is combined with possibilities for societal action, the importance of chemistry becomes apparent to the students. They gain competence to act towards building a more sustainable future. The improved scientific and ecological argumentation skills reflect their environmental literacy and competence in societal thinking.

The holistic and inquiry-based chemistry education presented in this dissertation supports versatile studying and citizenship skills in a new way. It motivates students to study chemistry and guides them to take sustainable development into account. Education for sustainable development is needed at all school levels. The approaches presented in this study may be applied on all levels of education. The results may be used to promote sustainable development in the planning of chemistry education and the education of chemistry teachers.

**Keywords**: chemistry education, sustainable development, green chemistry, teaching concepts, design research

# TIIVISTELMÄ

Kemia tieteenalana on suuressa roolissa kestävämmän tulevaisuuden tekijänä ja globaalien ongelmien ratkaisijana. Kestävää kehitystä ja kokonaisvaltaiseen eettiseen vastuullisuuteen kasvattamista painotetaan opetussuunnitelmien perusteissa, kansallisissa ja kansainvälisissä opetusalan strategioissa, kemian opetuksen tutkimuskirjallisuudessa ja kemianteollisuudessa. Tarvitaan lisää ympäristötietoisia kemistejä, kemian opettajia ja oppilaita – tulevia kansalaisia lukuisten koko maapalloa koskettavien ympäristöhaasteiden ennaltaehkäisemiseen ja ratkaisemiseen.

Tutkimuksen päätavoitteena oli selvittää, mitä on kokonaisvaltainen ja tutkimuksellinen kestävä kehitys kemian opetuksessa. Tavoitteena oli samalla vahvistaa oppilaiden ympäristötietoisuutta, argumentointitaitoja sekä positiivista kemiakuvaa. Kestävä kehitys kemian opetuksessa liittyy yhteiskuntaperustaisiin kemian aiheisiin, esimerkiksi elinkaariajatteluun ja vihreään kemiaan.

Kehittämistutkimuksen teoreettisessa ongelma-analyysissä tarkasteltiin tutkimuksen näkökulmasta keskeisiä lähestymistapoja: kestävää kehitystä ja kemiaa, vihreää kemiaa, elinkaarianalyysiä ja -ajattelua, ympäristötietoisuutta, yhteiskuntaperustaisuutta, sekä opetusmenetelminä tutkimuksellista opiskelua ja argumentaatiota. Empiirisessä kehittämisosassa etsittiin vastausta päätutkimuskysymykseen: Millaista on kestävää kehitystä edistävä kokonaisvaltainen ja tutkimuksellinen kemian opetus? Päätutkimuskohteena oli valtakunnallisten opetussuunnitelmien perusteiden keskeinen sisältö tuotteen elinkaari ja sen opettaminen.

Kehittämistutkimus koostuu kolmesta vaiheesta vuosina 2010–2014. Tutkimuksen ensimmäinen empiirinen vaihe toteutettiin neljän kemian aineenopettajien täydennyskoulutuksen yhteydessä. Niissä yhteensä 20 kemian opettajaa loi uudenlaisia tutkimuksellisia tuotteiden elinkaaren opetusmalleja. Opetusmallien kehittäminen pohjautui teoreettiseen ongelma-analyysiin. Tutkimuksen toisessa empiirisessä vaiheessa opetusmalleista yhteisöllisesti kehitetyn kehittämistuotoksen vaikuttavuustarkasteluun osallistui 105 peruskoulun yhdeksäsluokkalaista. Kehittämistuotoksen vaikuttavuutta tutkittiin oppilaiden ympäristötietoisuuteen, kemiakuvaan ja argumentaatiotaitoihin liittyen. Kolmas tutkimusvaihe oli teoreettinen. Siinä kerättyä empiiristä tutkimustietoa verrattiin teoreettiseen aineistoon, jotta voitiin vastata päätutkimuskysymykseen. Aineiston analysoinnissa käytettiin tekstien ja puolistrukturoitujen haastattelujen sisällönanalyysiä sekä kvantitatiivisia kyselyitä. Syklisen kehittämistutkimuksen tulosten luotettavuutta lisäävät laaja teoreettinen kirjallisuusanalyysi, metodologia- ja tutkijatriangulaatio, sekä kehitettyjen opetusmallien testaaminen autenttisessa ympäristössä ja tutkimuksen kulun systemaattinen visualisoitu dokumentointi.

Tutkimuksen kehittämisvaiheiden tuloksena saatiin: 1) kestävän kehityksen opetukseen uusia elinkaariaiheisia tutkimuksellisia kemian opetusmalleja ja niistä yhteisöllisesti kehitetty kehittämistuotos (Artikkeli I), 2) tietoa elinkaariaiheisen tutkimuksellisen kemian opetuksen vaikutuksista oppilaiden ympäristötietoisuuteen, kemiakuvaan ja argumentaatiotaitoihin (Artikkeli II ja III), ja 3) syvempää tietoa kehittämiskohteesta liittyen holistiseen ja tutkimukselliseen kestävän kehityksen opetukseen kemiassa (Artikkeli IV).

Holistinen ja tutkimuksellinen kestävän kehityksen kemian opetus sisältää poikkitieteellisiä ja yhteiskuntaperustaisia aiheita. Sosio-konstruktivistinen ja kontekstuaalinen kemian opetus liitetään yhteiskunnallisiin toimijoihin ja yhteistoiminnallisiin, aitoihin aktiviteetteihin. Oppiminen tapahtuu sosiaalisessa vuorovaikutuksessa, esimerkiksi argumentaation ja itsereflektion kautta. Tutkimustehtävien kohteet voivat olla oppilaiden itse valitsemia, ja voivat liittyä esimerkiksi raaka-aineisiin, kulutustavaroihin, ruoka-aineisiin tai veteen. Kun kemian tieto yhdistetään yhteiskunnallisiin toimintamahdollisuuksiin, kokee oppilas kemian merkityksellisempänä. Samalla hänen kompetenssinsa toimia kestävämmän tulevaisuuden rakentamiseksi kasvaa. Kompetenssi näkyy oppilaiden luonnontieteellisinä ja ekologisina argumentointitaitoina liittyen yhteiskunnalliseen ja ympäristötietoiseen pohdintaan.

Väitöstutkielmassa esitetty holistinen ja tutkimuksellinen kemian opetus sisältää uudenlaisia opiskelu- ja kansalaistaitoja monipuolisesti tukevia lähestymistapoja. Ne motivoivat oppilasta kemian opiskeluun sekä ohjaavat pohtimaan kestävää kehitystä. Kestävää kehitystä tukevaa kemian opetusta tarvitaan kaikilla kouluasteilla. Tässä väitöstutkimuksessa esitetyt lähestymistavat sopivat kaikenikäisille. Väitöstutkielman tuloksia voidaan käyttää kemian opetuksen suunnittelussa ja kemian opettajien koulutuksessa kestävän kehityksen aiheisiin liittyen.

**Avainsanat**: kemian opetus, kestävä kehitys, vihreä kemia, opetusmallit, kehittämistutkimus

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During the 15 years I have spent in three universities, I have learned that the world urgently needs scientifically literate, active and participating people. Improvements are needed on all possible levels and they can stem from every possible direction. Also, the development of science education needs a new kind of holistic understanding of sustainable development. Most of the people around me are profoundly sharing the same vision: we must try to change the world together and we must do it now. All levels of evolvement and involvement are equally important: life-long learning of individuals, informal and non-formal education, politics and policies, consumer actions, discussions between citizens, entrepreneurship, adaptation to changes and critical inspection of every aspect of life.

My thesis states that new education for sustainable development in chemistry is holistic, inquiry-based and socio-constructivist. This topic is both internationally and nationally interesting and current. Chemistry is related to numerous aspects of daily-life. In the field of education, chemistry should be approached in a more relevant and socially activating manner. The role of educators is to sow the seeds of sustainable progress. We, the teachers, are catalysts and sometimes only mere observers of what can and will happen through our students.

Finally, a statement from a 15-year-old girl expressing her attitudes after an inquiry-based project that investigated the life-cycle of a product: *"I understood how much even a small thing, such as a simple newspaper, affects everything. It is simple to manufacture but it still consumes a lot. So the importance of recycling is huge. I mean, you need to recycle, otherwise nothing makes sense."* That statement closely resembles the description of an ideal future by Salonen (2010, 36): "*Ecosystems formulate the basis of thinking… In material cycle there is an aim to know the life-cycle of a material from cradle to re-use. Waste and pollution issues*

*will be faced and solved. Polluting or waste producing processes is thought to be error planned. Energy is produced by using renewable resources.”*

In Espoo and Pelkosenniemi, May 2015

Marianne Juntunen

# LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following publications, which are referred to in the text by their roman numerals I-IV:

**I** Juntunen, M. & Aksela, M. (2013). Life-cycle analysis and inquiry-based learning in chemistry teaching. *Science Education International, 24*(2), 150–166.

**II** Juntunen, M. & Aksela, M. (2013). Life-Cycle thinking in inquiry-based sustainability education – effects on students' attitudes towards chemistry and environmental literacy. *CEPS Journal, 3*(2), 157–180.

**III** Juntunen, M. & Aksela, M. (2014). Improving students' argumentation skills through a product life-cycle analysis project in chemistry education. *Chemistry Education Research and Practice, 15*(4), 639–649.

**IV** Juntunen, M. & Aksela, M. (2014). Education for sustainable development in chemistry – Challenges, possibilities and pedagogical models in Finland and elsewhere. *Chemistry Education Research and Practice, 15*(4), 488–500.

# ABBREVIATIONS

ESD = education for sustainable development

IBL = inquiry-based learning

LCA = life-cycle analysis

The IBL-LCA concept = inquiry-based learning of life-cycle analysis of a product (= the designed consensus concept for holistic and inquiry-based ESD in chemistry)

SSI = socio-scientific issues

STSE = science, technology, society, environment

# CONTENTS

# 1. INTRODUCTION: RATIONALE AND PURPOSE

Sustainable development has become a central educational objective during the past decades. Despite a huge amount of scientific research and multiple action initiatives, the state of the Earth is more than worrying. The enormous global sustainability challenges facing individuals and societies are becoming increasingly complex.

In terms of sustainable development, there is a need to improve the state of chemistry education. Chemistry is a school subject and a field of technology which significantly contributes to the direction of development. As a science, chemistry can help people to better understand sustainability issues and create more scientifically literate consumers, parents, voters, and decision-makers. Scientifically literate people can push chemistry itself further to develop more sustainable practices. Besides scientifically literate citizens, the world also still needs more environmentally literate chemists who are driven by sustainable values. After all, it is the chemists who design the principles of the life-cycles of products and materials. Thus, holistic chemistry skills urgently need to evolve towards sustainability on all levels of society. As Zoller (2012) describes:

”*Chemistry and science literacy for sustainability means developing the capability of evaluative system thinking in the context of science, technology, environment, and society, which in turn requires the development of students' higher-order cognitive skills, system critical thinking, question-asking, decision-making, and problem solving*.”

Presently, one of the main obstacles to this aim and one of the challenges in chemistry education is that students and teachers rarely associate chemistry with sustainability or ethical issues. The application of sustainability issues in chemistry lessons appears to be rather rare in many countries. Chemistry teachers seem to be lacking in both the knowledge about education for sustainable development (ESD) and the relevant pedagogical skills.

In order to support more sustainable citizenship, chemistry educators must attain cross-disciplinary 21$^{st}$ century skills. These include such skills as environmental literacy, life-cycle thinking, competence to take action on socio-scientific issues (SSI), argumentation skills and active citizenship. Novel teaching methods involve cross-curricular and inquiry-based social and societal collaboration. A holistic understanding of complex systems is also a new and necessary part of basic education. Besides supporting more sustainable citizenship, more meaningful studying contents and methods are of key importance in increasing the students' interest in understanding and studying chemistry. Education for sustainable development is a means to make the subject of chemistry more interesting to students.

The main purpose of this thesis is to improve the state of education for sustainable development in chemistry through holistic approaches, i.e., cross-curricular, socio-constructivist and student-centred pedagogies and context-based SSI. The goal is to promote a certain understanding and certain values and skills in chemistry education, which relate to coping and solving acute environmental issues.

This dissertation represents literature on sustainable development in chemistry technology and education. It empirically describes ESD concepts created by chemistry teachers. Students' life-cycle thinking, active participation and argumentation skills, as well as their attitudes towards studying chemistry, are also empirically studied. Finally, the focus is placed on the theoretical dimensions of holistic and inquiry-based ESD in chemistry.

# 2. DESIGN RESEARCH

This thesis documents a cyclic design research project (Edelson, 2002). It includes three empirical case studies and a theoretical study. It seeks domain knowledge about holistic, inquiry-based and context-based socio-constructivist pedagogies of ESD in chemistry.

## 2.1. Research problem and main research questions

The aim of this study was to investigate and describe a sustainability problem in chemistry education. This problem is the disconnection between socio-scientific systems and institutions and the daily lives of people (Louhimaa, 2002). The theoretical framework reveals the problem: there is a need to more frequently include sustainability aspects in chemistry education as it is traditionally uncommon to associate chemistry with ethics and morals (Kärnä et al., 2012; Lymbouridou, 2011; Vilches & Gil-Pérez, 2013).

The guiding theories behind this design research project were socio-constructivism (Lave & Wenger, 1991), context-based learning (Gilbert, 2006) and collaborative development of pedagogical methods (Pernaa, 2011). These theories were chosen based on previous theoretical analysis (Juntunen, 2011). The main concepts of this design research were sustainable development (Brundtland Commission, 1987) and education for sustainable development (Burmeister, Rauch & Eilks, 2012). Regarding sustainable development, green chemistry (Anastas & Kirchhoff, 2002) and life-cycle analysis (Blackburn and Payne, 2004) were the main focus. Regarding education for sustainable development, the concept of sustainability and socio-scientific issues (Sadler, 2011) were focused on. Pedagogical choices may promote environmental literacy (Roth, 1992), life-cycle thinking (Nair, 1998), inquiry-based learning (Colburn, 2000) and socio-scientific argumentation skills (Albe, 2008).

The interactions of the main concepts of the research problems are illustrated in Figure 1. Due to the limitations of the resources in this study, environmental knowledge is not studied.

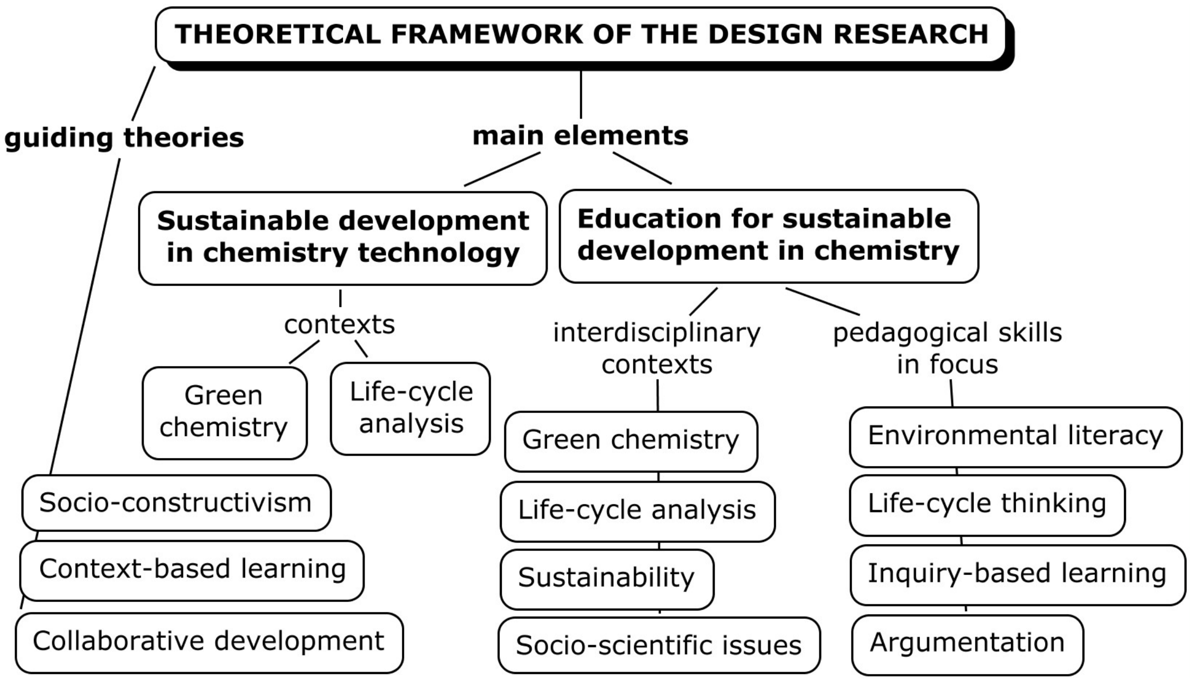


**Figure 1.** The interactions of the main concepts of the dissertation. The guiding theories were socio-constructivism, context-based learning and collaborative development of pedagogical methods. The main elements of sustainable development in chemistry were limited to interdisciplinary green chemistry and life-cycle analysis. In addition to these, education for sustainable development also focused on the concept of sustainability and socio-scientific issues. The core pedagogical skills analysed in this thesis were environmental literacy, life-cycle thinking, inquiry-based learning and socio-scientific argumentation skills.

In order to address the needs discussed in the rationale (see Section 1.), this design research project aims to answer the main research problem with four sub-questions **RQ1–4**:

**What are the main features of holistic and inquiry-based education for sustainable development in chemistry?**

**RQ1. Design solution:** What kind of teaching concepts related to product life-cycle analysis do chemistry teachers develop in their own practice? (see Section 4.1. and **Article I**)

**RQ2. Knowledge about design solution:** How does an inquiry-based, product life-cycle analysis project in chemistry education affect students' attitudes towards chemistry and environmental literacy? (see Section 4.2. **Article I**)

**RQ3. Knowledge about design solution:** How do students use scientific, ecological, socio-economical and ethical argumentation in the life-cycle analysis of products? (see Section 4.2. and **Article III**)

**RQ4. Domain knowledge:** How to teach education for sustainable development in chemistry? (see Section 4.3. and **Article IV**)

**RQ1** aimed to apply ESD in chemistry education in a novel way. The context used was product LCA (see Section 3.1.2. and 3.2.4.) and inquiry-based learning (IBL) (see Section 3.2.5.). The focus of the study was on teaching concepts collaboratively-developed with chemistry teachers (Pernaa, 2011) on the basis of which a design solution could be formulated. The intervention and research methods used are explained in Section 4.1.

**RQ2** aimed to investigate the perspectives of students who studied chemistry with the design solution, which was a product LCA concept designed by the teachers. The focus was on assessing the students' environmental literacy (see Section 3.2.2.) and interest in studying chemistry using the study concept designed by the teachers in order to further improve its quality. The intervention and research methods used are explained in Section 4.2.

**RQ3** aimed to investigate the students' level of argumentation (see Section 3.2.6.) as they studied using the design solution in order to further improve the quality of the design solution. The focus was on the students' scientific, ecological, socio-economical and ethical expressions. The intervention and research methods used are explained in Section 4.2.

**RQ4** aimed to formulate a theoretical summary of the analysis of the problem. The focus was on seeking domain knowledge on context-based and socio-constructivist pedagogies for ESD in chemistry and comparing the knowledge to the empirical results of **RQ1–3**. This is explained in Section 4.3.

## 2.2. Design research

The research questions were approached by using a design research method (Edelson, 2002). It comprises of theoretical problem analysis and three phases in the empirical design phase, which utilised the case study approach. The case study method was selected because it is suitable for making a deeper analysis of a certain group in a framed context. The goal was to understand the context, not to statistically generalise anything. (Cohen, Manion & Morrison, 2007) The ESD context described in this study is the quality of learning in an inquiry-based project about the life-cycle analysis of a product.

Design research is a cyclic method, which combines theoretical and empirical phases. Theoretical problem-analysis is steering the research. Throughout the research project, formative assessment of the developed concept was conducted as empirical results were compared to theoretical problem-analysis and the aims of the study. (Edelson, 2002) To understand the effects of theoretical and empirical variables on a phenomenon, this dissertation utilized a case study method (Cohen et al., 2007; Collins, Joseph & Bielaczyc, 2004). The dissertation involves three case studies, **Articles I–III**, which served as a basis to the conclusions of **Article IV**.

The definition of design research is vague. Wang and Hannafin (2004) have defined design research as a method which aims to improve educational settings through systematic, flexible and iterative theoretical analysis, planning, design and implementation aimed to create rules and theories for real-life situations. A definition by Collins (1992) states: *"Design research* *creates context-based but flexible solutions on a research phenomenon in social interaction"*. The contextual reflection may focus on an individual or a culture (Cantell & Koskinen, 2004; Pernaa, 2013; Sandovall & Bell, 2004). More detailed description of the definitions, the benefits and challenges and the implementation and history of the method are described in Juntunen (2013).

A cyclic design research project typically combines qualitative and quantitative study methods (Sandovall & Bell, 2004). It produces knowledge about (Edelson, 2002):

i) how to continue the design (design process),
ii) what kind of needs and goals there are for the design (problem analysis), and
iii) what kind of results are generated in the context of the design (design solutions)?

## 2.3. Description of the design process – developing holistic and inquiry-based ESD in chemistry

The research was oriented towards understanding, improving and utilising the design context and the theory. As is typical for a design research project, this process of design was interventional, iterative and it occurred in a real world setting.

The interventional and cyclic design process contributed to the selection of the design methodologies and to the development of new design frameworks (see Section 5.3.) (Edelson, 2002; Van den Akker et al., 2006). A holistic view was cast on the opportunities and challenges of the research problem. That is why this dissertation took a methodological triangulation approach, utilising mixed methods to overcome the broad and complex problem setting. The mixed methods research setting is typical for social sciences. It enabled analysing the main research question at the levels of an individual, a group and a society. (Cohen et al., 2007)

The design framework iteratively evolved during the cyclic design process (see Section 4.). (Edelson, 2002). The cyclic design process has similarities with participatory action research (Eilks & Ralle, 2002), as in both of them the key objective is to change the practices in schools. In design research, the form of the report is more detailed. The advantage of design research is that the researcher is more involved in the schools' practices together with the teachers (Cohen et al., 2007). When the teachers needed support, the researcher attended the lessons or offered them virtual online guidance.

The main elements of this design research project are illustrated in Figure 2. The development process was based on theoretical problem analysis and on the three empirical case studies: one focusing on the teachers' concepts and two studies focusing on the students' perspectives.

The theoretical problem analysis started with an analysis of the needs stemming from relevant literature, schoolbooks and curricula (Juntunen, 2011). The theoretical problem analysis focused on the following contexts of chemistry education: green chemistry, SSI, ESD and LCA. The pedagogical methods in focus were socio-constructivism, IBL and argumentation.

Together the contexts and pedagogies aimed to promote the cross-curricular skills of environmental literacy, societal co-operation, action competence and systems thinking.

During the case study involving the teachers, four in-service training courses were organised, because the inclusion of life-cycle thinking into chemistry education using IBL seemed to be a new approach for teachers. A team of researchers developed the first framework for the in-service training course. The framework continuously evolved as experience was gained on the needs of the teachers. The teachers preferred in-service training courses lasting no more than 1–2 days. Their commitments caused minor challenges as there were teachers who were too busy to hand in their mental concepts about the inquiry-based teaching of LCA. However, the course was still functional with regard to its key elements: discussion, collaborative tasks and theme lectures. During the design process, it was observed that the chemistry teachers recognised similar challenges as educational research publications have done: the most common approaches to chemistry education in schools are still lacking student-centred learning methods and socio-scientific sustainability themes. The IBL methods were chosen as an approach to product life-cycle issues, as they have been recognised to support students' interest in studying science (see, e.g., Colburn, 2000; Minner, Levy & Century, 2010).

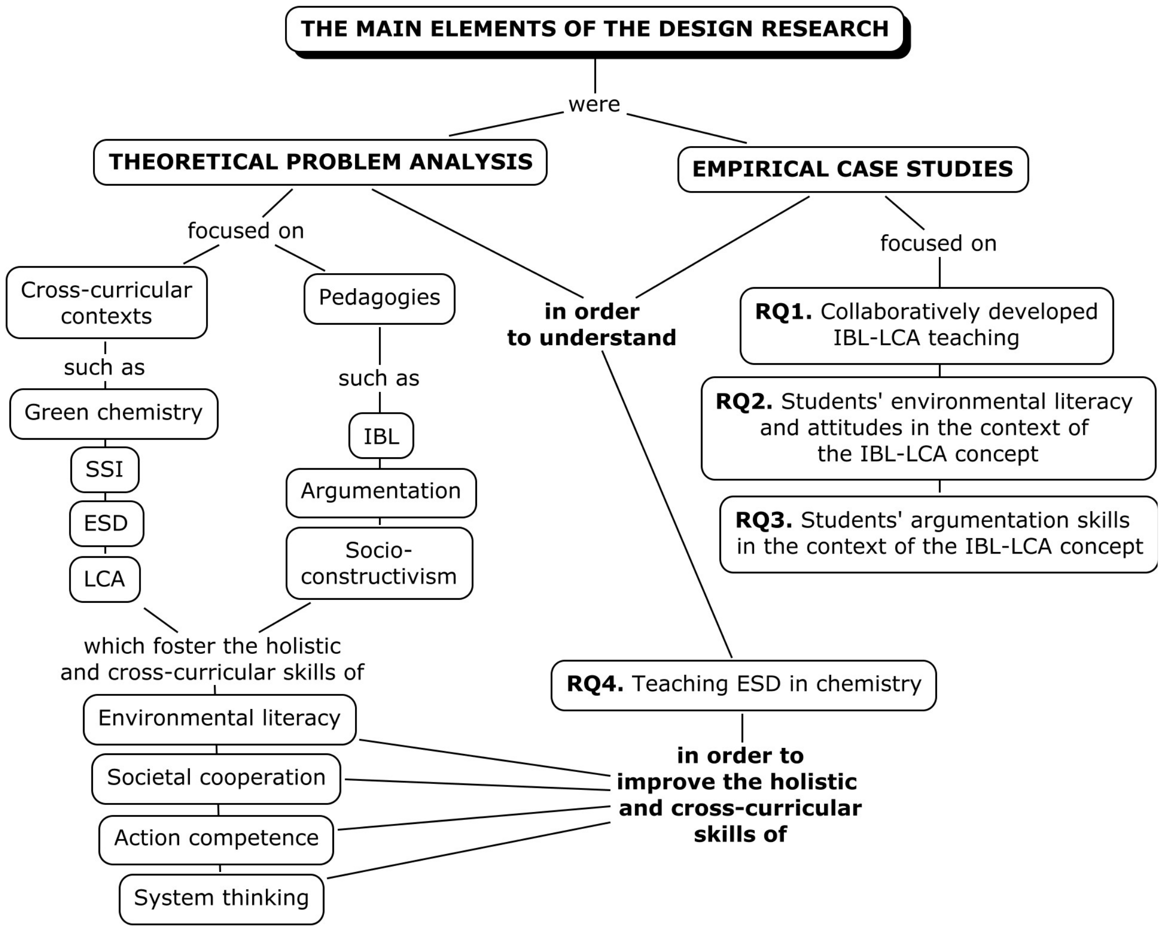


**Figure 2.** The main elements of this design research project (Edelson, 2002)

In order to answer **RQ1**, the chemistry teachers who took part in the in-service training courses developed novel inquiry-based concepts for teaching LCA for their own needs. The designed teaching concepts were tested in a real-world setting in schools by the teachers themselves and further developed in later in-service training courses by other chemistry teachers towards a design solution – the IBL-LCA concept (see **Article I**).

The next focus of the research in **RQ2** and **RQ3** was to analyse the outcomes of the design solution (the IBL-LCA concept) and its effects on students. The problem analysis is presented via two case studies (see **Articles II** and **III**): the first one focused on environmental literacy and attitudes towards the IBL-LCA concept, and the second one focused on the students' argumentation skills in product LCA. A detailed review of the possibilities to measure environmental literacy is presented in Juntunen (2013).

The participants of these three empirical case studies were interested teachers and randomly selected students. When testing the concepts in junior high schools, a minor challenge was to find talkative students for the study discussions in **RQ2** and **RQ3**. Some of the students stated that discussing chemistry-related issues is too difficult for them. This partly affected the selection of the participants.

The iterative understanding gained from the empirical design process influenced how **RQ4** was answered. Comparing the theoretical literature to the empirical knowledge resulted in the discovery of the key concepts of the design context and in the generation of theoretical domain knowledge about holistic and inquiry-based ESD in chemistry (see **Article IV**).

# 3. THEORETICAL FRAMEWORK

This chapter introduces the theoretical background of the dissertation, covering the main rationales and aspects of ESD in chemistry. Firstly, a review of the current state of sustainability in chemistry is presented by providing an overview of green chemistry and life-cycle analysis (LCA) (see Section 3.1.). Secondly, ESD in chemistry is discussed in terms of its main concepts (see Section 3.2.).

## 3.1. Sustainable development in chemistry

There are over 300 different definitions or visual representations of the concept of sustainable development (Johnston et al., 2007; Mann, 2011). The most well known written definition is from the Brundtland commission (1987): *"...development that meets the needs of the present generation without compromising the ability to meet their own needs"*. Sustainability science is a modern field of research, which aims to bridge the natural and social sciences in seeking solutions to the conflicts between them (Jerneck et al., 2011). These enormous challenges are related to the environmental boundaries of the planet Earth and to health issues, the economy and peace between peoples (Barnosky et al., 2012; Rockström et al., 2009). If the ongoing crisis could be turned into an opportunity in the philosophies of science and among chemists, their role in the 21st century could be renewed and they could begin to strive for their original, sustainable, life-preserving virtues (Bray, 2010; Tundo et al., 2000).

Sustainable development is usually considered to consist of ecological, economical and socio-cultural aspects. From the ecological point of view, the greatest challenges result from the western life-style. We consume the resources, change the biotopes and climate and, therefore, induce the loss of biodiversity at an accelerating speed (Governmental…1998; Jerneck et al., 2011; WWF, 2012). In economics, the challenge is to separate economical growth from the use of natural resources and pollution. The ecological debt resulting from the use of available natural capital is increasing. (Costanza et al., 1997; Davidsdottir, 2010; Governmental…1998; WWF, 2012). The third dimension of sustainable development involves socio-cultural challenges, including poverty, human rights problems and issues relating to education, nutrition and health care (Governmental…1998; Jerneck et al., 2011). Behind these problems one often finds unfair, unequal and oppressing contracts. It is a holistic challenge for local and global initiatives to combine these aspects into well-functioning real practices (Salonen, 2010, 36).

The ecological, economical and socio-cultural aspects often exclude one another. So far it is unclear whether we can reach economical growth, environmental health and social justice all at the same time either in the present time or in the future. As long as economical growth is tied to unsustainable use of natural resources and socially unfair contracts, sustainable development cannot be authentically realised. (Bray, 2010; Dryzek, 1997, 132−136; Kahn, 2008; Rohweder, 2008a; Särkkä, 2011, 85) Dryzek (1997) has stated that the discourse on sustainable development is powered by human-centeredness, development belief and belief in combining contradictory aspects. The discourse resembles the discussion about ecological modernisation, which emphasises specialists' power and consequently transfers the problems from societal discussion into the business sphere (Kahn, 2008; Laine & Jokinen, 2001, 64; Särkkä, 2011, 85; Åhlberg, 2005).

Concern for the state of the planet is also expressed by the large research communities (see, e.g., Stern, 2006; UNDP, 2007; UNEP, 2007; World Bank, 2009; Worldwatch Institute, 2012; WWF, 2012). The values of sustainability are universal: freedom, responsibility, ecological diversity, the dependence of people on each other, democracy, nonviolence and peace (Salonen, 2010, 60).

It is obvious that the ethical and practical principles of sustainability have not yet transferred from research into the human society (Wolff, 2004a). People with systems thinking skills are urgently needed (Hogan, 2002; Zoller, 2012). Systems thinkers can habitually look at things within the context of the environments that affect them, consider multiple cause and effect relationships, anticipate the long-term consequences and possible side effects of presentactions, and understand the nature of change (Hogan, 2002). This dissertation designs novel chemistry education to answer the call.

Section 3.1. defines the concepts of green chemistry and LCA from a historical perspective within chemistry. The organisational use and practical applications of these concepts are reviewed in my licentiate thesis (see Juntunen, 2013).

### 3.1.1. Green chemistry

Over the past centuries chemistry has played a major role in improving our welfare. Meanwhile, some of the designed molecules have polluted the environment either in some stage of their regular life-cycle or as a result of accidents. For instance, the creation of chemical weapons, thalidomide, CFCs and hormonal disruptors has negatively affected the people's attitudes towards chemistry. Many accidents (e.g., the Bhobal pesticide leak) are all too familiar examples of chemistry gone wrong. (Hartings & Fahy, 2011)

In response to growing concern, the concept of green chemistry was introduced in the 1980s (Centi & Perathoner, 2009). As the concept of green chemistry could easily be associated with the political ”green movement”, the concept of sustainable chemistry was introduced in the 1990s.

IUPAC (2013) defines green chemistry as “*the invention, design, and application of chemical products and processes to reduce or to eliminate the use and generation of hazardous substances*”. OECD (1999) defined sustainable chemistry as ” *the design, manufacture and use of efficient, effective, safe and more environmentally benign chemical products and processes*”. Sustainable chemistry has a more holistic definition than green chemistry. It includes similar goals as green chemistry, but it also seeks a balance between economical growth and development on the one hand and environmental protection and societal sustainability (health and quality of life) on the other. (Böschen, Lenoir & Scheringer, 2003; Centi & Perathoner, 2009; IUPAC, 2013; OECD, 1999) According to IUPAC (2013), in practical terms, green chemistry and sustainable chemistry include similar goals and contents. The European Cooperation Group in the field of Scientific and Technical Research has given the following definition (IUPAC, 2013): ”*Sustainable/green chemistry is design of products* *for sustainable applications, and their production by molecular transformations that are energy efficient, minimise or preferably eliminate the formation of waste and the use of toxic and/or hazardous solvents and reagents and utilize renewable raw materials where possible*.” Thus, this dissertation considers these concepts to be synonymous and uses the term ’green chemistry’ throughout the thesis.

Green chemistry is a strategy to design less risky chemical products and processes, where hazardous substances are absent or formed only in tiny amounts. The smaller risk means reducing or eliminating the hazards (Poliakoff et al., 2002; Singh, Szafran & Pike, 1999). Chemistry can be used to prevent environmental pollution already in the design phase of a molecule or chemical reaction. Chemists can manipulate the molecular characteristics of a substance so that it poses a reduced hazard or no hazard at all. Considering the safety of a substance in the very beginning, in the molecular design phase, affects the whole life-cycle of the substance. This is also most often the economically efficient to design a molecule or reaction. (Anastas & Lankey, 2000; Böschen et al., 2003)

The development of environmentally benign products and processes may be guided by the 12 principles of green chemistry, which, after their publication, markedly affected the implementation of green chemistry within the chemical industry (Anastas & Warner, 1998; Centi & Perathoner, 2009). The principles are:

i) prevention,
ii) atom economy,
iii) less hazardous chemical syntheses,
iv) designing safer chemicals,
v) safer solvents and auxiliaries,
vi) design for energy efficiency,
vii) use of renewable feedstocks,
viii) reduce derivatives,
ix) catalysis,
x) design for degradation,
xi) real-time analysis for pollution prevention, and
xii) inherently safer chemistry for accident prevention.

Elsewhere, Tundo *et al.* (2000) have listed the principles as:

i) use of alternative feedstocks,
ii) use of innocuous reagents,
iii) employing natural processes,
iv) use of alternative solvents,
v) design of safer chemicals,
vi) developing alternative reaction conditions, and
vi) minimising energy consumption.

More wide-spread awareness about green chemistry practices and continuous development is vital to the realisation of green chemistry science and scaling it up to its full potential (Hjeresen, Schutt & Boese, 2000). To facilitate international co-operation, the Green

Chemistry Institute was founded in 1997 by representatives from industries, universities, organisations and government agencies. The Institute aims to promote green chemistry research, education and outreach with major initiatives, which have been published around the globe. (Hjeresen et al., 2000) Since its inception, green chemistry has grown into a significant internationally engaged focus area within chemistry (Anastas & Kirchhoff, 2002). Also, according to the chemical industry (see Honkanen, 2013; Nikander, 2010), there basically is no other choice than to adopt the more holistic view – sustainable development, environmental questions, life-cycle thinking (see Section 3.2.4.) and social responsibility are the core evaluative practices and objectives in developing the field of chemistry technology today.

Green chemistry combines so-called ”pure chemistry” with ethics. The premise of green chemistry is a fundamental shift: a benign process or product presents no risk at any stage of their life-cycle. This is an inevitable step forward in contrast to regulation initiatives, which are introduced only to restrict the amount or improve the quality of pollution. Environmentally literate chemists can design sustainable products and production processes. By these means, chemistry can contribute to the quality of different biotopes, the health and wellbeing of species and achieve sustainable development. (Tundo et al., 2000)

### 3.1.2. Life-cycle analysis of a product

Life-cycle analysis (LCA) is a technical method for evaluating the environmental burden of a product, process or activity by quantifying the net-flows of different chemicals, materials and energy (see, e.g., Blackburn and Payne, 2004; Vervaeke, 2012). The assessment of resource use, emissions and the related health impacts creates possibilities for environmental improvements on a product's life-cycle (Anastas & Lankey, 2000). From a chemistry perspective, LCA is a uniting approach: it combines the systems thinking approach of circular economics (Ellen MacArthur Foundation, 2012; Hogan, 2002), green or sustainable chemistry (Anastas & Lankey, 2000; Böschen et al., 2003; Poliakoff et al., 2002) and engineering (Eissen, 2012) – all of which relate to the aspects of science ethics and moral awareness (Burmeister & Eilks, 2012; Vilches & Gil-Pérez, 2013; Zeidler et al., 2005).

Early LCA on cumulative energy requirements was conducted in the 1960s and early 1970s for certain industrial products such as steel, pulp and paper, and for the petroleum refining process (Bousted & Hancock, 1979). After the oil crisis of the 1970s faded, these energy analyses were conducted less frequently. But during the 1990s, evidence of different environmental crises began to emerge. Based on several meetings of researchers in 1991, the Society of Environmental Toxicology and Chemistry (SETAC) published a framework for life-cycle assessment (Nair, 1998; US Congress Office… 1992). This framework is illustrated in Figure 3. Since then, LCA has evolved to be more holistic as the importance of environmental pollution prevention has gained public attention. The demand for more information about chemicals that are present in people's communities has increased. In the chemical industry, quantitative LCA supplements the set of environmental management tools already in existence together with the 12 qualitative principles of green chemistry (see Section 3.1.1. and Anastas & Warner, 1998).

Today, moving towards a more circular economy is essential in delivering on the worldwide resource efficiency agendas for smart, sustainable and inclusive growth. Circular economy is a generic term for an industrial ecology, which is by design or intention restorative and in which materials flows are of two types. The flows are either biological nutrients, which are designed to re-enter the biosphere safely, or technical nutrients, which are designed to circulate at high quality without entering the biosphere. Circular economics draws from a number of more specific approaches including cradle to cradle, biomimicry, industrial ecology, 'waste is food' and 'blue economy'. (Ellen MacArthur Foundation, 2012) The data and analysis following an LCA study can be used to identify 'hot spots' and focus efforts when building the circular economy and when looking at resource efficiency at large.

Understanding the circular economics and the life-cycle of a product requires chemistry knowledge (Anastas & Lankey, 2000; Blackburn & Payne, 2004). As illustrated in Figure 3., LCA includes designing, extracting and processing raw-materials, as well as manufacturing, packaging, transportation, distribution, use/re-use/maintenance, recycling and final disposal (Johanson, 2010). The inputs constitute of energy, raw-materials and products. The outputs include waste management – solid, liquid or gasified substances released into the air, water or ground. The outputs may also be immaterial pollution, such as noise or odour problems. Unrecyclable products can be considered to be output waste as well. Knowledge of green design (Hendrickson & McMichael, 1992), green chemistry (see Section 3.1.) and engineering sciences (Nair, 1998) is required in different stages of a product's life-cycle.

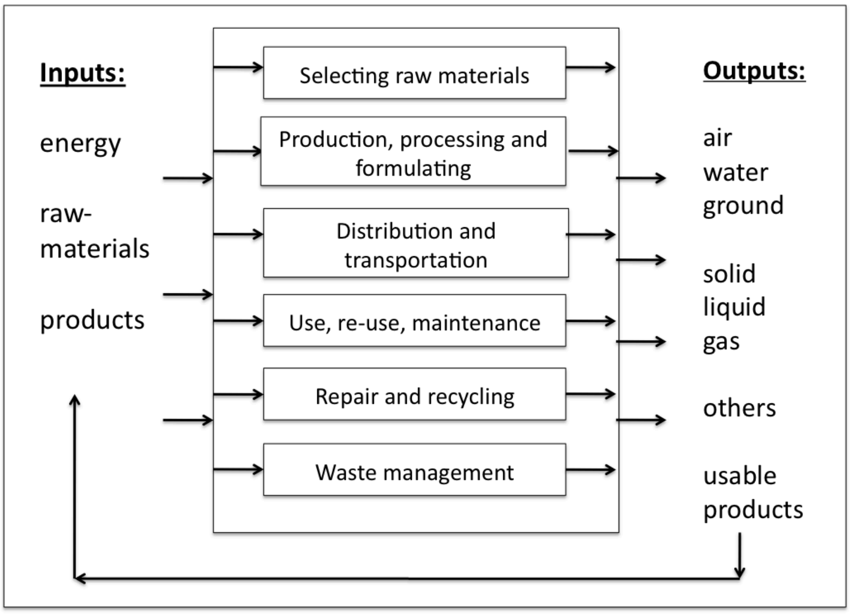


**Figure 3.** Product life-cycle inventory (Fava et al., 1991; US Congress Office… 1992). The inputs constitute of energy, raw-materials and products. The outputs include the multifaceted waste management.

LCA is an increasingly popular method of evaluating the significance and quality of the environmental impact of those inputs and outputs by quantifying the net-flows of different chemicals, materials and energy (see, e.g., Antikainen et al., 2013; Askham, 2011; Blackburn

& Payne, 2004). It is not yet mandatory, but LCA is used as the basis for ecolabels and carbon footprints, for instance. Also, the standardised Environmental Product Declarations, created in accordance with standards developed by the International Organization for Standardization (ISO), are a way of quantifying the emissions by using information gathered via LCA. When a company conducts an assessment of resource use and emissions and their health impacts, it creates possibilities for improving the ecological and economical efficiency and socio-cultural acceptability of their product, process or activity (Askham, 2011; Anastas & Lankey, 2000; Anastas & Warner, 1998; Böschen et al., 2003; Karpudewan, Ismail & Mohamed, 2011). LCA enables novel directions in the fields of R&D, investment decisions, communication and marketing (Askham, 2011).

LCA is carried out in phases: definition of the goal and scope, inventory analysis, impact assessment and interpretation (Askham, 2011). These phases are illustrated in Figure 4. In practice, LCA is a complicated field of expertise. LCA can be conducted using one of the over one hundred modelling programs available. These programs save and analyse data of inputs and outputs in different stages of the production chain. This type of information can be found in several databases. (Blackburn & Payne, 2004; Koskela et al., 2010)

| | |
|---|---|
| Goal and scope definition | Interpretation ↓ |
| Inventory analysis | |
| Impact assessment | |

**Figure 4.** The four phases of LCA include definition of the goal and scope, inventory analysis, impact assessment and interpretation (Askham, 2011)

The methods of LCA are in continuous and rapid development. This development is needed to recognise key indicators, monitor changes and create simpler reporting practices. Some of the easier approaches, including energy assessment, carbon footprint and ecological footprint, can already be included in LCA. But some others, such as water footprint and Material Input Per Service Unit (MIPS), still lack certain allocation and limitation practices suitable for proceeding from early assessment to complete LCA. (Mattila & Antikainen, 2010) As the phases of LCA involve similar system definitions and balances, the procedure can be considered as a material or substance flow analysis. When scaling up LCA studies, the substance flow studies covering a single material are targeted. (Brunner & Ma, 2009)

System boundaries limit which unit processes should be included in any given study and in what level of detail (Antikainen, 2010). The challenge is to find up-to-date, standardised data and meet the ambitious goals. LCA is normally conducted on an average process – not on a worst-case scenario (Blackburn & Payne, 2004). Uncertainties or errors with the variable, scenario or model cause common validity problems (Finnveden et al., 2009). Other system boundaries in LCA include the selection of impact categories, category indicators and characterisation models. These categories can include different environmental impacts, such as global warming potential, ozone depletion potential and acidification potential, as well as potential toxic effects on humans and the environment. (Askham, 2011; Koskela et al., 2010)

## 3.2. Education for sustainable development in chemistry

Education for sustainable development (ESD) is critical in promoting more sustainable practices. The nature of ESD is highly multidimensional and cross-curricular. ESD research encompasses numerous different concepts and methods. In educational situations these concepts and methods interact and align with the dimensions of personal knowledge, effect, morals and skills. (Nichols, 2010) This dissertation summarises and analyses this complexity in relation to chemistry education research. Especially **Article IV** in this thesis reviews the state and practices of ESD in chemistry in more detail.

The roots of environmental education begin in the 1960s (Wolff, 2004a). Several theoretical models framing the methodology of this dissertation (see Section 2.1.) about environmental education have been published (e.g. Hesselink et al., 2000; Järvikoski, 2001; McKeown & Hopkins, 2003; Palmer, 1998; Paloniemi & Koskinen, 2005; Tani et al., 2007; Willamo, 2005; Åhlberg, 2005). Internationally, the most referred to and famous model of environmental education is Palmer's (1998) tree model. It is based on an assumption that different kinds of environmental experiences support social participation skills and can increase a student's concern and willingness to act. In order to develop knowledge, concepts, skills and attitudes, an education *about*, *in* and *for* the environment is needed. When Palmer's tree model (1998) is applied to ESD in chemistry this means the following:

i) knowledge *about* green chemistry and sustainable development,
ii) experiences and knowledge *in* a place outside a classroom, and
iii) value-based discussions about acting *for* sustainable development, which also involve chemistry

In Finnish research, ESD is mostly considered as a continuum of environmental education (see Saloranta & Uitto, 2010; Wolff, 2004a). The concept of education for sustainable development contains all institutionalised pedagogical actions related to environmental themes. Additionally, in this dissertation, the term 'education for sustainable development' is used interchangeably with 'environmental education'. The different theoretical models and the deeper analysis of the dimensions of the terms is presented in Juntunen (2013) and elsewhere (see Hesselink, van Kempen & Wals, 2000; McKeown & Hopkins, 2003).

The wide definition of ESD can be seen either as an opportunity or as a risk. At its best, the different sustainability themes can support one another and help the students to broadly capture the big picture (Laininen, Manninen & Tenhunen, 2006, 33). ESD incorporates educational elements related to citizenship, the future, peace, human rights, equality, health, sustainable consumption, systems thinking, critical thinking, participation, networking, fellowship and protection of natural resources (Tani, 2008; Tilbury & Cooke, 2005; Zoller, 2012). Elsewhere ESD is seen to fall under the concept of globalisation education, which constitutes of sustainable development, human rights, multiculturalism and peace (Melén-Paaso & Kaivola, 2009). What is common to all of these themes is that they can all be incorporated into every school subject and that they are all based on ethics and values. ESD aims to empower citizens, consumers and educators to act on the levels of a person, community, ecosystem or the whole world. Ecocentric habits, practices and skills that extend to all levels of daily life allow people to actively participate for a more sustainable world with high motivation. (Dwyer, 1993; Grace, 2006; Heimlich & Ardoin, 2008; Littledyke, 2008; Paloniemi & Koskinen, 2005, 29; Sadler, Barab & Scott, 2007) Traditionally, ESD has aimed to affect attitudes and behaviour with the help of knowledge (Hungerford & Volk, 1990). The complex relationship between these concepts and how they may be measured is reviewed in Juntunen (2013).

On the other hand, the wide definition and cross-curricular nature of ESD can be a risk. In real life situations, the possibilities of an individual to contribute to the development of society are often very limited. The neutrality and generality of the aims is promoting a spirit of consensus among educators and politicians. The term 'sustainable development' is simplified rather than problematised in public discussions. The multidimensional goals and dimensions of the sustainability concepts are not fully defined either. There is the concern of compromising too much and fading the societal contradictions and power relationships. Self-criticism of the goals and utilised teaching methods should be allowed even if the general goal is lofty and multidimensional. (Louhimaa, 2005, 219−226; Särkkä, 2011; Wolff, 2006)

The numerous disastrous future scenarios and reports of the present state of the world (see, e.g., Worldwatch Institute, 2012; WWF, 2012) and critical educational research (Hungerford & Volk, 1990) tell their crude language how, in the large scale, despite the multiple initiatives of the past decades, ESD has mainly been either inefficient or inadequate. The role of school or chemistry lessons is not to solve political problems, but as sustainability issues increasingly touch the lives of everyone, it is crucial to expose educational goals to the value discussion. As several scholars have argued, science education for citizenship and scientific literacy ought to include content-transcending goals or topics such as ethics and attitudinal education (Allchin, 1999; Böschen et al., 2003: Dondi, 2011; Feierabend, Jokmin & Eilks, 2011; Fensham, 2004; Holbrook, 2010; Holbrook & Rannikmae, 2007; Reis & Galvao, 2004; Zeidler et al., 2005; Wolff, 2004b). Scientific literacy has been defined to include knowledge of not only scientific concepts, models and processes, but also of societal humanistic contexts (Driver et al., 1996; Sjöström & Talanquer, 2014). The deeper critical discourse on ideological roles and the pedagogical methods of learning theories is reviewed in Juntunen (2013).

In Finnish curricula, environmental education was first mentioned in 1985 as a uniting theme for all school subjects. New educational strategies (Melén-Paaso, 2006; Ministry of Education, 2009) and curricula (Finnish National Board of Education, 2015; 2014; 2003) emphasise implementing sustainability issues into practice. They encourage schools and students to actively participate in society and co-operate with organisations outside of school. The content of these educational strategies and curricula is reviewed in my licentiate thesis (see Juntunen, 2013).

Even though in many countries sustainability issues are absent from curricula (Vilches and Gil-Pérez, 2013), in Finland the themes of sustainable development are nothing new in the chemistry curriculum. According to the curriculum, Finnish pupils face issues related to, for instance, water purification, acid rain, ozone depletion, recycling, chemical safety and product life-cycles in their regular chemistry lessons. The Finnish curriculum also includes themes related to foodstuffs, materials and resources, the carbon cycle and life-cycle analysis. In relation to ESD, these themes could be bound to value analysis of different kinds of choices, e.g., recycled and renewable resources versus non-renewable resources in the production of raw materials and products (Finnish National Board of Education, 2015; 2014; 2003). However, 21st century chemistry education can extend further towards ESD by

i) adopting the green chemistry principles as part of science laboratory work,
ii) adding sustainability strategies as content in chemistry education,
iii) using controversial socio-scientific issues as examples, and
iv) developing the whole school institution towards sustainability (Burmeister et al., 2012; Taskinen, 2008).

Combining these elements might provide a practical, feasible strategy for learning holistically *about* and *for* sustainable development in all areas of chemistry education (Burmeister et al., 2012). This must be realised with the same scientific accuracy and on the same intellectual level as the teaching of any other chemistry topic. Jegstad & Sinnes (2015) have identified five different categories of ESD in chemistry: chemical content knowledge, chemistry in context, chemistry's distinctiveness and methodological character, ESD competences and lived ESD. These ESD categories represent different aspects of a complex whole and partly overlap. All of them must be considered in order to achieve a holistic perspective of ESD.

The holistic dimensions of sustainable development (socio-cultural, ecological and economical) seem to be present in different amounts in chemistry lessons. **Article IV** describes in detail how the phases of ESD in (basic) chemistry occur in relation to the socio-cultural, science-ecological and future-economical dimensions. Students' feelings, either those of empowerment or disempowerment, are consequences of these phases (Figure 5.). The three-phase ESD model is formulated by comparing the educational research on student empowerment in environmental education (Paloniemi and Koskinen, 2005) to the examples of teaching SSI controversies in chemistry lessons. In terms of opportunities for action, Paloniemi and Koskinen (2005) highlight the importance of involvement when promoting motivation, societal empowerment, creation of personal experiences, co-operative work and capability for action. Phases similar to those presented in Figure 5. can be seen in the conceptual framework for socio-critical, problem-oriented science teaching presented by Marks and Eilks (2009). The problem analysis and laboratory working stages of their framework could be included here in Phases 1 and 2. To conclude an SSI learning session, Marks and Eilks (2009) suggest using discussions and meta-reflection. Also, the categorisation of STSE perspectives proposed by Pedretti and Nazir (2011) includes similar elements to those presented in Figure 5. Their application and design-oriented education is similar to the chemistry context of the model presented here. Additionally, Pedretti and Nazir (2011) have recognised the historically-oriented and value-centred socio-eco justice categories.

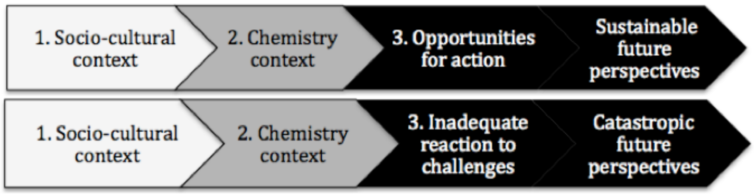


**Figure 5.** Three-phase presentation of teaching a socio-scientific issue to empower rather than disempower students in ESD in chemistry. Phase 1 includes the socio-cultural causes and background of an issue. Phase 2 presents the main chemistry aspects of the issue in relation to ecology. Phase 3 includes co-operative and value-driven discussions about the opportunities for action and sustainable or unsustainable future perspectives, possibly involving all three dimensions of sustainable development.

Presently, the challenge is that chemistry is rarely associated with sustainability issues by the students (Tirri et al., 2012). This is due to the fact that teachers seldom consider ethics as part of chemistry and rarely teach environmental issues and action possibilities (Kuusisto et al., 2012; Kärnä, Hakonen & Kuusela, 2012; Lymbouridou, 2011). The application of sustainability issues in chemistry lessons is rare in many countries as chemistry teachers lack knowledge and pedagogical skills related to novel ESD approaches (Burmeister, Schmidt-Jacob & Eilks, 2013; Kärnä et al., 2012). More sustainable citizenship requires, for instance, chemistry education that enables the students to productively interact in groups around intellectual tasks (Hogan, 2002). The relevant teaching methods often involve cross-curricular inquiry (Colburn, 2000) and peer collaboration (Keys & Bryan, 2001).

This dissertation tries to answer the challenge by reviewing ESD in chemistry and designing a novel teaching approach. Holistic ESD in chemistry can involve ethical considerations, green chemistry and simplified LCA. This Section (3.2.) defines the educational background of green chemistry, sustainable development and environmental literacy. Socio-scientific issues, life-cycle thinking, inquiry based teaching and the argumentation approach as methods of ESD pedagogy for cross-curricular, context-based, socio-constructivist chemistry teaching are also framed in this Section. Perspectives on the challenges and opportunities posed by these concepts on the teacher and student levels are reviewed in Juntunen (2013) and summarised in Section 4.4. Based on these notions, a novel approach for chemistry education was developed during this dissertation.

### 3.2.1. Green chemistry in education

The topic of green chemistry can be incorporated into all levels of chemistry education. All existing chemistry courses can adopt greener practices and new scientific, ecological, economical and socio-cultural concepts. (Anastas & Kirchhoff, 2002; Andraos & Dicks, 2012; Karpudewan et al., 2011; Karpudewan, Ismail & Roth, 2012; Liu, Lin & Tsai, 2010; Mandler et al., 2012)

Teaching concepts related to green chemistry seem to be more common in higher chemistry education (Karpudewan et al., 2011; Poliakoff et al., 2002; Singh et al., 1999). They are also present in chemistry teacher education (Kaivola, 2007). One example of green chemistry in action is the suggestion that in balanced equations, the term ‘yield’ should be replaced with the term ’atom economy’ (Anastas & Kirchhoff, 2002). However, as of yet there are only few green chemistry lesson plans available for the basic school level (see Aksela & Boström, 2012).

Green chemistry brings ethics into ”pure chemistry”. Ethics are a system of moral principles that deal with the rightness and wrongness of certain actions and the goodness and badness of the motives and end results of such actions. If green chemistry is to be incorporated into lessons at all school levels, should not the questions of ”why is this right to do?” and ”why not?” be asked more often? (Vilches & Gil-Pérez, 2013). Considering that the principles of green chemistry (see Section 3.1.1.) are a part of basic learning and understanding of a certain technology. The issues involved are often socio-scientific (see Section 3.2.3.) and discuss whether a certain chemistry procedure should be abandoned, changed or accepted as it is (Hartings & Fahy, 2011; Tundo et al., 2000). In practice the topics may include, for instance, water or carbon cycles (Mandler et al., 2012), waste to product ratios (Eissen, 2012), selection of chemicals or catalysts (Poliakoff et al., 2002) or micro-scale experimentation (Singh et al., 1999).

However, educators must be careful not to ”green wash” neither the common practices nor the chemical industry. It should be kept in mind that the concepts of ”green” and ”sustainable” are criticised for promising endless material and economical growth, even though there is no evidence to suggest it is possible for all people (Eskelinen, 2011). Educators and chemists must be aware of the complexity of evaluating the total impact of developed technologies. The total impact includes variables related to the three dimensions of sustainable development, environmental health and the well-being of creatures. True green chemistry is therefore a lofty goal, which can only be realised by devoted people who are competent in implementing it in all fields of chemistry fields – including chemistry education.

### 3.2.2. Environmental literacy

Besides scientifically literate people, the world clearly and urgently needs more environmentally literate consumers, parents, voters, and decision-makers who are driven by their sustainable values. In ESD, the educational challenge in terms of environmental literacy is multifaceted.

Educators are especially interested in how knowledge will lead a person to an action. A persons’ behaviour is affected by multiple psychosocial elements (Bamberg & Möser, 2007; Hines, Hungerford & Tomera 1987/86; Hungerford & Volk, 1990; Kaiser, Wölfing & Fuhrer, 1999). Sociologists and sustainability educators have tried to understand and simplify the concept of environmental literacy (Courtenay-Hall & Rogers, 2002; Hollweg et al., 2011). The concept has been criticised for being problematic and vague by nature, as both parts of the concept, ’environment’ and ’literacy’, are difficult to define even on their own (Järvikoski, 2001). However, environmental literacy is extensively studied and used for describing the aspects of a person’s ethical responsibility.

Environmental literacy is defined to consist of ecological knowledge and understanding, strategic behaviour, active participation, cognitive analysing skills and affective personal characteristics (such as values, attitudes, sensitivity and control skills). An environmentally literate person is engaged to preserve the dynamic equilibrium between humans and nature. (Marcinkowski, 1991; Roth, 1992) Environmental literacy is cross-curricular and closely resembles the broad definitions of scientific literacy (Holbrook & Rannikmae, 2009; Simmons, 1989) and ecoliteracy (Nichols, 2010).

Multiple models have been published to illustrate environmental literacy (e.g. Heimlich & Ardoin, 2008; Kaiser et al., 1999) and to measure it (Dunlap et al., 2000; Hollweg et al., 2011; Johnstone & Reid, 1981; Kaiser et al., 1999; Leeming, Dwyer & Bracken, 1995; Schultz, Zelezny & Dalrympe, 2000; Stern, 2000; Uitto & Saloranta, 2010a; Uitto et al., 2011). The opportunities and boundaries of these and other models are reviewed in Juntunen (2013).

A teacher will most probably promote environmental literacy in a classroom if she/he is aware of the societal power relationships and able to view the environment as personally or socially meaningful. Also, moral responsibility, environmental sensitivity, ability to critically evaluate one's own culture and capability and willingness to act for the environment affect the amount and quality of a teacher's ESD choices. (Hsu & Roth, 1998; Käpylä & Wahlström, 2000)

Similarly, the more the students have personal experiences from school or from their daily life, the more easily they contribute positively to environmental protection (Palmer, 1998; Saloranta & Uitto, 2010; Uitto et al., 2011). Thus, the teaching methods which promote the students' active role and value-related questions are especially needed in chemistry education. For instance, in chemistry the questions can focus on different levels (applied from Wilmes & Howarth, 2009):

i) Personal level: Which is the better choice: tap water or bottled water?
ii) Societal level: "What is the best way to produce energy for a certain need?"
iii) Global level: "Why do different countries use different amounts of natural resources?"

One answer is to promote inquiry-based teaching methods (see Section 3.2.5. and Rocard et al., 2007; Tirri et al., 2012; Wilmes & Howarth, 2009) and cross-curricular approaches that have been rarely utilised so far (Kärnä et al., 2012). Application of socio-scientific issues (see Section 3.2.3.) in various learning environments is also needed to raise the level of environmental literacy (Saloranta & Uitto, 2010). Well-designed education materials promote the learning of content knowledge and the acquiring of meaningful real-life experiences (Lester et al., 2006).

### 3.2.3. Socio-scientific issues

STSE (science, technology, society, environment) approaches were introduced into science education in the early 1970s. This teaching stems from moral, political and environmental aspects related to the science, technology, society and environment people face in their daily lives. (Pedretti & Nazir, 2011; Zeidler et al., 2005) Socio-scientific issues (SSI) are a pedagogical strategy that has recently gained attention as a part of educational STSE research (Sadler, 2011). The technological view is stronger in traditional STSE than in socio-scientific education (Pedretti & Nazir, 2011).

The importance of including SSI into chemistry education is emphasised in chemistry education research (see, e.g., Marks & Eilks, 2009) and in Finnish educational research studies (Kärnä et al., 2012; Saloranta & Uitto, 2010; Uitto & Saloranta, 2010a; Uitto et al., 2011). The research supports the goals on the student level: students learn scientific content knowledge in a social context (Bulte et al., 2006; Dori, Tal & Tsaushu, 2003; Klosterman & Sadler, 2010; Yager, Lim & Yager, 2006). When the contexts of chemistry are more relevant, they improve the students' attitudes towards science (Albe, 2008; Mandler et al., 2012; Sadler, 2004; Taskinen, 2008; Yager et al., 2006; Van Aalsvoort, 2004). Controversial SSI topics stimulate the students' moral and ethical thinking skills. The students learn communication skills so that they may use science in social and creative contexts, and when participating in initiatives. (Belland, Glazewski & Richardson, 2011; Sadler, 2004; Ratcliffe, 1997; Zeidler et al., 2005) The socio-scientific approach also helps the students to understand the nature of science in society and in their daily lives (Hofstein, Eilks & Bybee, 2011; Holbrook & Rannikmae, 2007; Kolstø, 2000, 2001; Oulton et al., 2004; Reis & Galvao, 2004; Sadler et al., 2007; Zeidler et al., 2005).

There is a wide range of socio-scientific issues that are easy to integrate into Finnish school chemistry. These issues are related to acute local, national or global sustainability problems, the 12 green chemistry principles, product life-cycle analysis, energy production alternatives, raw materials and future education. The 12 principles of green chemistry include the responsibilities of preventing the production of waste, using safe substances and conserving materials and energy (Anastas & Warner, 1998). Finnish teachers are already sometimes integrating these topics into their chemistry lessons (Aksela & Boström, 2012). Matters such as conserving or wasting resources, long-term needs, the quality of products, better choices in daily life and issues related to health are easy to discuss during any regular Finnish chemistry class. All of the topics that relate to socio-scientific issues or sustainable development found in the Finnish National Curriculum for Chemistry can be connected to aspects of the students' daily lives (e.g., housing, food, energy or product life-cycle issues) (Finnish National Board of Education, 2015; 2014; 2003).

However, at the practical level, including socio-scientific issues in chemistry is more than just a lecture about the relevant issues (Sadler, 2004). The educational practices of socio-scientific chemistry education are complex, controversial, topical and relevant to the daily lives of students (Sadler et al., 2007). The dimensions of the issues are not self-evident to the students. The issues need to be explained from different points of view and with regard to the students' level of understanding and their perception of the relevance of the issues (Holbrook & Rannikmae, 2009). The central focus is to connect the importance of personal actions and questioning to the issues (Newhouse, 1990; Wilmes & Howarth, 2009; Zeidler et al., 2005). Different argumentative perspectives and ethical dimensions are typical, and the issues may evolve as new knowledge is generated. A solution does not have to be found, even if a certain issue has been studied or discussed in a chemistry lesson. (Oulton, Dillon & Grace, 2004) Research into socio-scientific education highlights the benefits of group discussions as a practical means of supporting the students' socio-scientific decision-making and argumentation skills (Albe, 2008; Sadler, 2011; Tanner, 2009; Wilmes & Howarth, 2009; Zoller, 2012).

The variability of the interactions between humans and nature within the context of SSI in ESD is illustrated in Table 1. Environmental problems and their solutions are involved in a constant societal battle for definitions, i.e., the severity of the problems and the viability of the solutions are defined in different ways depending on political views. There are many different environmental discourses taking place in societies, and they often challenge one another. (Särkkä, 2011, 82)

**Table 1.** Humane and inhumane dimensions of ESD in chemistry (after Salonen, 2010, 9)

| | | |
|---|---|---|
| **Ecosystems** | Soil | Chemistry of the wellbeing of the soil, different kinds of agricultural lands and their quality, acidification and pollution, diversity of ecosystems |
| | Water | Quality and amount of water, change and pollution in water ecosystems |
| | Air | Quality of indoor and outdoor air, measuring air, operations of the global atmosphere |
| | Species and genomes | Diversity of genomes |
| | Using resources | Production, treatment and recycling of waste, energy and materials, mining, sustainable use of natural resources |
| **Humans** | Population and health | Physical and psychological health, fertility, growth of population |
| | Wealth | Fulfilment of basic needs (food, water, shelter), economics, revenue, trade, goods, infrastructure, welfare, time |
| | Culture and literacy | Education, research, literacy, beliefs, feelings, thoughts |
| | Community | Rights, freedoms, governance, institutions, legislation |
| | Equality | Equal distribution of benefits and disadvantages between individuals and different communities |

A few educational approaches have been published for implementing basic chemistry aspects of SSI into ESD. These SSI approaches have involved student argumentation tasks from social, scientific, economical and ethical points of view and on such topics as product life-cycle analysis (see **Article III**), diet issues in relation to potato chips (Marks, Bertram & Eilks, 2008), artificial musk fragrances in shower gels and their later behaviour in the environment (Marks & Eilks, 2010), debate about bio versus conventional plastics and related consumer tests (Burmeister & Eilks, 2012) and the energy consumption alternatives and challenges posed by hydrogen cars (Eilks et al., 2003). Water quality experiments, for example, may be broadened into value-based evaluations of the consumption and use of water in the making of products (Bulte et al., 2006). The issue of climate change has also been studied in order to gauge its potential for focusing students' argumentation and evaluation skills (Feierabend & Eilks, 2011). All of these ESD approaches involving SSI have been reported to support student interest in studying chemistry. The approaches seem to support the knowledge-based activist role of the student in chemistry (Lester et al., 2006; Vilches & Gil-Pérez, 2013).

The literature review indicates it is possible to involve all three dimensions of sustainable development in chemistry education by utilising higher-order thinking skills (Anderson & Krathwohl, 2001) in value-driven tasks. Economical aspects seem to be more rarely discussed in chemistry lessons than the other two dimensions of sustainable development. In addition to socio-cultural and ecological scientific views, the economical aspects are also present in at least such student-centred and co-operative approaches as the consumer test method (Burmeister & Eilks, 2012), interest groups' brochures used for discussions (Eilks, 2002), decision-making (Eilks et al., 2003), role-playing debate (see **Article III**), role-playing of a TV talk show (Marks et al., 2008) and the journalistic news production method (Marks & Eilks, 2010).

The chemistry involved in diverse socio-scientific issues is particularly overwhelming. This is illustrated in Table 2 by using environmental sustainability issues as examples. Themes that are very different from each other are all connected in detecting, analysing, solving and preventing environmental problems (Anastas & Lankey, 2000; Mark & Eilks, 2010). Chemical threats are connected to the health of living creatures, to the types of pollution and the risks in the hydro-, geo-, atmo- and biospheres (Lichtfouse et al., 2005). The issues in question can be studied from the perspectives of the three dimensions of sustainable development, e.g., via ethical questions and from a socio-cultural perspective on the level of adequate wellbeing for humans, economical sustainability and the right of every living creature to a healthy environment when preserving biodiversity (Bray, 2010; Salonen, 2010; Tundo et al., 2000; Vilches & Gil-Pérez, 2013).

**Table 2.** A summary of the effects of chemical substances on health and creatures, types of pollution and types of risks in ecosystems (Lichtfouse et al., 2005)

| | |
|---|---|
| **Effects on hydro-, geo-, atmo- and biospheres** | Additives in plastics (PBA, phthalates), algae, asbestos, cleaning agents, colours, dioxins, fuel leaks, furans, halogenated hydrocarbons (PCB, CFC…), heavy metals, medicines, methane, inorganic gases ($CO_x$, $SO_x$, $NO_x$, $N_2O$, HFC, PFC, $SF_6$), organic gases (HFC, PFC…), organically bound metals, PAH, pesticides, photochemically active hydrocarbons, radioactive substances, sewage, small particles in the air (VOC, PM, NMVOC), smells, tastes, toxics |
| **Types of pollution** | Fallout (burning processes), natural wash (in acidic conditions, e.g., dilution of aluminium and heavy metals), point stress (industries, cities), scattered stress (fields, livestock) |
| **Effects on ecosystems** | Accumulation of bioaccumulative substances in the food chain and trash (plastics), changes in pH, diversity loss (living creatures are sensitive to changes in pH because of pesticides or $SO_x$, $NO_x$, $NH_3$, for example), eutrophication (N, P…), oxygen loss ($H_2S$), salting |
| **Health effects** | Acute or chronic, at the level of the individual, population or species |
| **Effects are related to** | Breeding, changes in behaviour or biodiversity, death, diseases, genomes, growth, harmless carrying of bioaccumulative substances, hormones, metabolism of organs, tumours |

Chemistry education related to SSI has endless possibilities in terms of the suitable lesson themes. The issues may relate to acute local, national or global sustainability problems, the 12 green chemistry principles, product life-cycle analysis, energy production alternatives and raw materials. Similarly to Burmeister *et al.* (2012), the importance of green chemistry practices and socio-scientific chemistry issues are highlighted. The integration of sustainable development into 'normal' courses and chemistry education strategies is also considered a very important developmental step, as is having schools profiling themselves by joining sustainability programs that include chemistry elements. This thesis expands on their view by summarising possible topics for chemistry education that relate to socio-scientific issues or sustainable development. These include the effects of chemical substances on health and on living creatures, different pollution types and the diverse risks to ecosystems. When teaching, many of these topics can be connected to the students' daily lives and bound to the themes found in the Finnish National Curriculum for Chemistry (Finnish National Board of Education, 2015; 2014; 2003). These topics also enable imagining possible future scenarios and discussing the ethical responsibility of science. This dissertation extends socio-scientific chemistry education to the context of LCA, which is novel approach in basic school chemistry education.

### 3.2.4. Life-cycle thinking skills

Learning about product LCA by conducting an open-ended, student-centred LCA project is a new educational approach created in this thesis. There are only few other papers published that refer to LCA in chemistry education and most of them intended for educational purposes have been applied at the undergraduate level (Allen & Baskhani, 1992; Nair, 1998; Vervaeke, 2012). This dissertation applies inquiry-based chemistry teaching of life-cycle analysis (LCA) and life-cycle thinking skills at the junior high school level.

In this dissertation, life-cycle thinking skills are defined as abilities that one is required to have in order to understand the life-cycle of a product, a process or activity and its environmental effect at each stage of the life-cycle, to a certain extent. Life-cycle thinking is recognising and evaluating the amount, quality and effects of the inputs and outputs of a product life-cycle and seeing the possibilities for improvement (see Figure 3., Section 3.1.2. and Fava et al., 1991). Exploring a system such as a product life-cycle creates possibilities for promoting the goals and competences of sustainable development in chemistry (see Section 3.1.).

Novel chemistry learning should be more closely connected to socio-scientific contents (Bulte et al., 2006). A product LCA is a socio-constructivist and daily life-related, context-based approach in chemistry (Cantell, 2004, 73; Gilbert, 2006). Life-cycle thinking can be brought into the teaching of any product or material chemistry. This is important, because students are the most sluggish with practical tasks related to raw materials (Kärnä et al., 2012). This situation may be aggravated by the fact that was revealed in the initial analysis of this dissertation: in current chemistry study books, life-cycle thinking is still either completely absent or only glanced over. If LCA was presented at all, the topic was most often placed at the end of the book. The representation of LCA was one-dimensional and no inquiry-based tasks were present. (Juntunen, 2011) For the chemical industry, it is crucial that chemistry education promotes the students' skills for cross-curricular co-operation and sustainability (Finnish Chemical Industry, 2011; Honkanen, 2013).

Studies about SSI seem to support the notion that SSI are beneficial to the multifaceted skills required for more sustainable citizenship (Tundo et al., 2000). Previous studies on ESD and SSI have provoked debate about the potential of SSI in promoting higher order cognitive skills, such as competencies in communication and evaluation (Zeidler et al., 2005; Feierabend & Eilks, 2011; Burmeister & Eilks, 2012; **Articles I** and **II**). In the 21$^{st}$ century, students require functional scientific literature and skills (Fensham, 2004; Zeidler et al., 2005) that include sustainability competencies (Tytler, 2012), socio-scientific reasoning skills (Sadler, 2004), active citizenship (Zeidler et al., 2005), systems thinking (Hogan, 2002) and environmental literacy (Yavez, Goldman & Peer, 2009). All of these are in line with the goals of scientific literacy for all (Holbrook, 2010) and they are all present in this project-based LCA teaching approach. It seems that product LCA can serve as an example of a new way to organise chemistry education in the 21$^{st}$ century.

In practice, studying life-cycle thinking can be a social investigation of the raw materials and features of a production chain. The ecological backpack (material input per service unit), ecological footprint, water footprint or carbon footprint can all be considered as a part of LCA (Bulte, 2006; Mattila & Antikainen, 2010). Water quality experiments can be broadened into discussions about the use of water (Bulte, 2006). The chemical solutions for recycling products or raw materials can be brainstormed together with students. Here, ethical questions can also be asked about the use of water in the making of different kinds of consumer products, for example. The life-cycle of plastics is also a suitable topic for secondary school chemistry (Bulte, 2006; Burmeister & Eilks, 2012; Johanson, 2010).

The dimensions of life-cycle thinking are in line with STSE education (Pedretti & Nazir, 2011; Zeidler et al., 2005):

i) *Societal* – Which product am I interested in? Where and under what conditions is the product manufactured? How much does it cost and why? How is the product price related to the product's sustainability? What do environmental certifications mean?
ii) *Technological* – How is a product manufactured? Where will it end up?
iii) *Science and chemistry* – What materials is the product made of? What resources are consumed? Which chemicals are used? What kind of pollution is created?
iv) *Environment* – How does the product affect the environment, economy and general wellbeing? What environmental problems are caused by its production?

The goal is to develop and rouse holistic thinking in students. At a simplified level, LCA may be applied to cross-curricular thinking in the context of consumer products (Wilmes & Howarth, 2009). It enables the students to analyse economical and energy and resource policy-related aspects as a part of global material flow. The discussion may concern materialistic consumer habits and their unsustainable connections to the oppression of nature and people. (Kahn, 2008; Särkkä, 2011, 95)

Understanding complex systems is part of 21$^{st}$ century scientific literacy. Science curricula (Finnish National Board of Education, 2015; 2014; 2003) constitute a framework, which highlights the importance of teaching about different systems and the skills needed to analyse them (Hogan, 2002). A LCA (see Section 3.1.2.) is an example of a system.

### 3.2.5. Inquiry-based teaching methods

Extensive research (Aksela, 2005; Gibson & Chase, 2002; Juuti et al., 2010; Kärnä et al., 2012) and the main educational strategies all emphasise the benefits of inquiry-based science education (Inter Academy Panel, 2010; Rocard et al., 2007; US National Research Council, 1996). Through inquiry, it is possible to promote students' motivation and interest in chemistry, and also to boost their active content knowledge and participation, self-confidence and higher order thinking skills (Anderson & Krathwohl, 2001; Kipnis & Hofstein, 2008; Minner et al., 2010; Nieswandt, 2007). Understanding of the nature of science, experimentation skills and problem-solving skills can also be fostered as the students mimic the work of real scientists (Adams et al., 2008; Krystyniak & Heikkinen, 2007; Mikkola, 2012; Minner et al., 2010; Näsäkkälä et al., 2001; Välisaari & Lundell, 2008).

However, inquiry-based teaching is still far less common than the traditional deductive teaching methods (Anderson, 2002; Kärnä et al., 2012; Rocard et al., 2007; Smithenry, 2010). Inquiry is not used if the teacher is unfamiliar with its definition, practices and methods, or if the teacher is afraid of chaos or believes only the most skilful students could perform the inquiry tasks (Colburn, 2000; Reis & Galvao, 2004). Teachers need support and guidance in applying inquiry-based methods to their pedagogies. The support can take the form of teaching materials, which may be designed by the teachers themselves. In-service training courses on inquiry practices are also a way to help teachers to reflect on their own ideas. (Herrington et al., 2010; Smithenry, 2010; Keys & Bryan, 2001) The main features of a student-centred pedagogical strategy of a teacher who wishes to teach inquiry and SSI-based ESD in chemistry are presented in **Article IV**.

Inquiry-based methods have evolved from cognitive (Piaget, 1977) and socio-constructivist (Vygotsky, 1978) learning theories. Inquiry is a student-centred approach, which has been used in Finnish science teaching since the 1960s (Aksela, 2005). The definition is vague. Abraham & Pavelich (1999, 2) provided the following definition: *"[...] every student can work at their suitable level and do even a small research. The students are let to define their own research questions and problems, plan their own experiments, analyses and explanations from the data."* Words such as authentic, project-based, active and resource-based research education are also used in defining inquiry-based teaching (Alberta Learning, 2004, 109).

In practice, inquiry-based teaching may include elements of inductive learning, problem-solving and hands-on experiments (Välisaari & Lundell, 2008). The focus is on encouraging the students to ask questions. Especially in open studies, the students' own questions and interests are the starting point. Learning stems from the students' own active role and willingness to look for answers to their own questions. Five typical features of practicing inquiry-based learning with students are (Aksela, 2005; Hodson, 2014; Kipnis & Hofstein, 2008; Minner et al., 2010):

i) designing, planning and asking questions,
ii) performing and collecting data,
iii) reflection to summarise results, and
iv) reporting and discussing conclusions.

This practice is not linear. The students may return and change their research questions based on the information they find (Alberta Learning, 2004, 9). They may complete a project, discuss the issues, make reports and presentations or hold a debate (Millar, 2004; Näsäkkälä et al., 2001; Palmer, 2009). A study may focus on the nearby environment (Mikkola, 2012), stalactites (Keys & Bryan, 2001) or food chemistry (Palmer, 2009), for instance.

Inquiry-based education can be applied at all school levels (Alberta Learning, 2004, 9). The difficulty level is connected to the openness of the task. At a basic level, the research questions and methods are given to students so that they can perform an investigation. At an intermediate level, the research questions are still given to students, but now they have to decide on the study methods they intend to use to achieve the results. At an even more difficult level, the students have to form the research questions as well. (Blanchard et al., 2010; Colburn, 2000) The different difficulty levels allow the teacher to choose a suitable level that best supports the students' learning. Inquiry-based science education is possible for all students and actually especially supports the studying of lower achievers (Rocard et al., 2007).

### 3.2.6. Argumentation as a teaching method

During the mid-1990s, argumentation appeared as an area of research in science education. Since then, researchers working on such themes as science education for citizenship and language in the science classroom have addressed argumentation in their work. (Erduran & Jiménez-Aleixandre, 2007)

In the context of the design solution presented in this thesis, arguments are defined to include claims, data and justifications, which could be supported by evidence and modal qualifiers and be challenged with rebuttals (Osborne, Erduran & Simon, 2004). Argumentation has been suggested to emerge from personal, ethical, societal and scientific dimensions (Kolstø, 2001). Socio-scientific reasoning can include aspects of recognising the complexity of the issue, examining multiple perspectives, accepting ongoing inquiry and exhibiting scepticism about potentially biased information (Sadler et al., 2007).

Teachers need support in teaching and evaluating argumentation. Teachers are lacking the pedagogical skills to organise argumentative discourse within the classroom (Driver et al., 2000). The multi-dimensionality of socio-scientific issues and argumentation causes struggling, and teachers are also lacking in both the theoretical knowledge and the suitable practical approaches to ESD (Burmeister et al., 2013).

Students on their behalf need more opportunities for practicing argumentation to develop their skills (Driver et al., 2000). Students feel that their own lack of knowledge contributes to their inability to participate in SSI discussions (Tytler et al., 2001; Sadler and Zeidler, 2004; Albe, 2008).

The need for systematic, school-tested, collaboratively-developed material in the teaching of argumentation has been addressed in previous studies (e.g., Albe, 2008; Pernaa, Aksela & Västinsalo, 2010; Simon, 2008). There is a need for new socio-scientific lesson plans that deal with hard-to-define real-world questions. When compared to more traditional, deductive chemistry education approaches, these complex problems train the students to better meet the real world and form arguments regarding socio-scientific issues (Holbrook & Rannikmae, 2007; Rockström et al., 2009; Jho et al., 2013). The students need ample opportunities to practice justifying claims related to SSI.

According to the theoretical framework of this thesis, the most fruitful interventions within ESD in chemistry are the socio-scientific ones. Tasks related to SSI encourage personal connections between students and the issues discussed, explicitly address the value of justifying claims and expose the importance of paying attention to opposing opinions (Garcia-Mila et al., 2013; Sadler, 2004; Sadler & Donnelly, 2006). A student-centred, inquiry-based product LCA project addresses the needs discussed above. It is collaboratively designed by chemistry teachers themselves (see **Article I**). The empirical phase of this study enabled the students to practice their competencies and argumentation skills with issues relating to the life-cycles of consumer products.

# 4. THE PHASES OF DESIGN RESEARCH

The research questions (see Section 2.1.) are answered in the three following empirical case studies (see Sections 4.1. and 4.2.) and one theoretical study (see Section 4.3.), which produced new understanding of the design context.

The design phases of this dissertation aimed to generate (Edelson, 2002):

i) A collaboratively developed, practical *design solution* for ESD in chemistry, which takes the form of an inquiry-based teaching concept related to product LCA (**RQ1, Article I**),
ii) *Information about the design solution's effects* on students' environmental literacy, interest in studying and argumentation skills (**RQ2–3, Articles II** and **III**), and
iii) *Domain knowledge* about ESD in chemistry (**RQ4, Article IV**).

The phases of the interventional design process were cyclic. This means that not only the problem analysis contributed to the selection of the design methodologies, but also the knowledge and results gained contributed to the problem setting. The cyclic design process is iterative, meaning that the every phase affects the phases after it. The three main phases can be recognised from the design process. These phases and their focus at different stages of the process are illustrated in Figure 6.

The initial problem analysis of literature, chemistry course books and curricula resulted in chemistry teachers designing a design solution "prototype" created during the first in-service training course (Juntunen, 2011). This prototype was further developed during Phases 1 and 2, which constituted of three empirical case studies (**RQ1–3, Articles I–III)**. Phase 1 focused on the teachers' concepts and resulted in the creation of the design solution – the IBL-LCA concept. Phase 2 focused on the effects of design solution in terms of students' perspectives about the concept and their environmental literacy. These results were analysed in Juntunen (2013). Phase 2 also further investigated the design solution effects on students' argumentation skills. Based on the empirical knowledge gained, Phase 3 included a theoretical problem analysis in order to create domain knowledge about the features of holistic ESD in chemistry (**RQ4, Article IV**). Finally, this dissertation answers to the main research question.

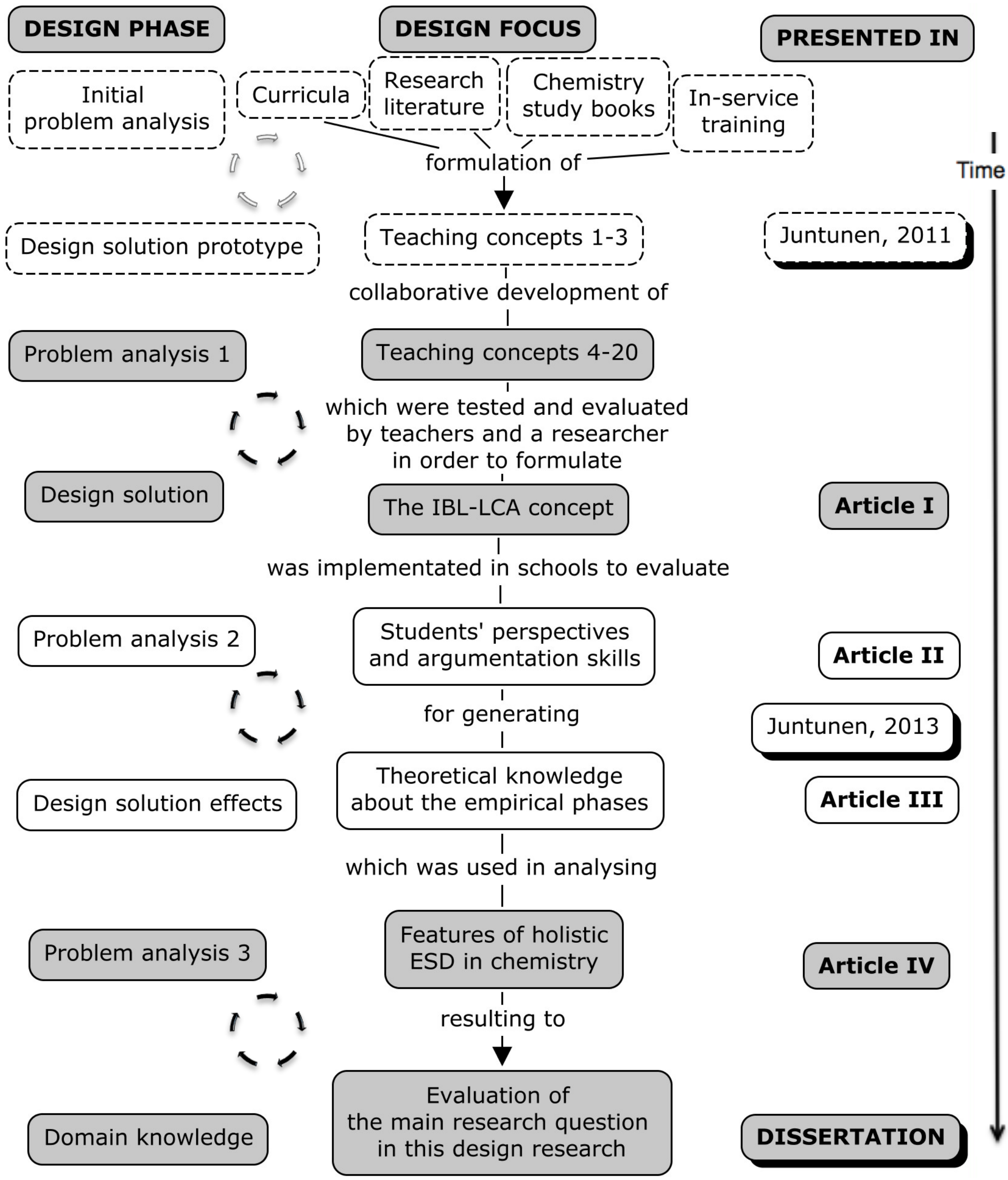


**Figure 6.** The initial design phase and the three main phases of the design research, the points of design focus and the references

The design process is explained in more detail in Juntunen (2013) and in Sections 2.3. and 7.4. of this thesis.

## 4.1. Design solution – Teaching life-cycle thinking

In order to answer **RQ1**, the teachers' pedagogical perspectives about teaching product LCA were studied.

The initial analysis of the pedagogical needs in LCA education was conducted in previous studies (see Juntunen, 2011; 2013). On the basis of these initial analyses and a literature review (see Section 3.), the study methods were selected for a case study involving chemistry teachers who participated in in-service training courses.

To support the work of teachers, four free of charge in-service training courses on ESD in chemistry were organised in Finland during the years 2010–2012. The participants were a random sample of 20 teachers from across Finland, teaching at levels from elementary school to high school. During the courses, which lasted a few days each, a total of 20 chemistry teachers collaboratively developed new inquiry-based LCA teaching for their own needs (Joyce & Weil, 1986; Juntunen, 2011).

The collaborative design setting used was based on literature. It was closely related to participatory action research described in Marks *et al.* (2008), as this setting also involved a group of teachers designing new teaching concepts together with researchers. Based on their experiences, Marks and Eilks (2009) have outlined a conceptual framework for a socio-critical and problem-oriented approach to chemistry teaching. The objectives of their framework include the multi-dimensional role of science knowledge in science literacy and the promotion of evaluation and communication skills. Their criteria for a socio-critical science approach are authenticity, relevance, open discussion and evaluation, as well as the incorporation of societal, chemical and technological dimensions. Relevance is defined by students' experiences of the present and future worth in personal, professional, social and societal choices (Hofstein et al., 2011; Holbrook & Rannikmae, 2009). In this study, the teachers were advised to take the following criteria into account when creating their new LCA chemistry teaching concepts. The concept should:

i) Use inquiry-based, student-centred approaches that emphasise the students' own ideas and questions (Colburn, 2000; Joyce & Weil, 1986),
ii) Develop skills for co-operative studying, critical thinking, problem solving, communication and evaluation (Colburn, 2000; Zoller, 2012), and
iii) Reveal the relevance of chemistry in environmental protection, sustainability, value-centred discussion and decision-making using LCA as an approach (Allchin, 1999; Pedretti & Nazir, 2011; Tundo et al., 2000).

The created teaching concepts were tested in schools by the teachers and collaboratively developed further by the teachers and one researcher. As illustrated in Figure 6., the teachers participating in the in-service training courses in 2011 developed the teaching concepts designed in 2010. Similarly, in 2012, the participating teachers developed the concepts from 2011. After the courses were completed, all of the created concepts (N=20) were subjected to two separate content analyses (Tuomi & Sarajärvi, 2006) by two separate researchers to improve the validity of the results. This type of analysis is called researcher-triangulation: two researchers independently conduct the same analysis of all of the data to validate the results.

Depending on their structure, the developed teaching concepts were classified according to Joyce and Weil (1986), who have described the differences between personal and social teaching concepts. Personal teaching concepts utilise individual learning processes that affect student achievement in basic areas, such as recalling information. Personal teaching concepts can be non-directive and person-centred. Social teaching concepts, on the other hand, may involve co-operative learning approaches, peer-teaching-peer and group investigations.

The teaching concepts were also examined for their curricular dimensions, meaning their structure, pedagogy, broader framing purpose and the status and setting of their scientific knowledge (see Tytler, 2012). The final classification included the intended practices for inserting the LCA concepts into the chemistry curriculum, the topics discussed, the learning level, time consumption and the used methods.

### 4.2. Effects of the design solution – Students' perspectives on IBL-LCA

In order to answer **RQ2–3**, inquiry-based ESD in chemistry had to be assessed from the students' perspective. The design solution – a project based on the inquiry-based, student-centred, social teaching concept designed in **RQ1** by the teachers (see Colburn, 2000; Joyce & Weil, 1986) – functioned as the intervention. Knowledge about the effects of the design solution is important for possible further improvements and theoretical understanding of the design context. A detailed description of the design solution is presented in Results (see Section 5.1.) and illustrated in Figure 6.

In order to answer **RQ2**, the first case study involving students was conducted during the 2011–2012 school year in three schools in Southern Finland. The participants were 105 upper-secondary school students in the $9^{th}$ year (14–15-year-olds), 58 of which were girls and 47 were boys. Their chemistry teachers (N=3) tested the new approach to teaching life-cycle thinking. A researcher visited the three schools before and after the life-cycle project and collected and analysed all of the data used in this study. From the volunteers, 27 students were randomly chosen for interviews, which were documented on audio recordings. All of the other data collected was in written form in surveys. A summary of the research tools of the study is presented in Table 3. The tools of assessment were qualitative semi-structured interviews, open questionnaires (Eilks, 2005; Marks et al., 2008) and quantitative surveys (Marks et al., 2008; Yavez et al., 2009). A detailed description of the tools is presented in Juntunen (2013) and in **Articles I** and **II** of this dissertation.

**Table 3.** The research tools used in the case study of **Article II**

| | **Chemistry Attitudes** | **Environmental Literacy** |
|---|---|---|
| **Before the intervention (pre)** | Semi-structured interviews (Marks et al., 2008) | Survey (Yavez et al., 2009), semi-structured interviews (Marks et al., 2008) |
| **After the intervention (post)** | Open questionnaire (Eilks, 2005; Marks et al., 2008), survey (Yavez et al., 2009), semi-structured interviews (Marks et al., 2008) | Open questionnaire (Eilks, 2005; Marks et al., 2008), survey (Marks et al., 2008), semi-structured interviews (Marks et al., 2008) |

In order to answer **RQ3**, four different research tools were used in the second student case study to assess the students' level of argumentation skills during the year 2012–2013. The participants were eight ethnically homogenous 15-year-old students from a rural Finnish secondary school. This group of students was selected because the author of the research project was a chemistry teacher of the group. This type of a setting is suitable for educational intervention case studies (Cohen et al., 2007). This intervention was similar to the one conducted to answer **RQ2** and the students completed it in 6 weeks, which was also the time period between the first and last research tool presented in Table 4. The qualitative research tools were modified from Albe (2008), Baytelman and Constantinou (2014), Erduran (2013), Feierabend & Eilks (2011) and Mikkola, Luukka and Ahonen (2006). A detailed description of the tools is presented in **Article III** of this dissertation.

**Table 4.** The four qualitative research tools used in the case study of **Article III** (modified and inspired by the corresponding references)

| Research tools | References |
|---|---|
| Pre-argumentation argumentation task | Baytelman & Constantinou, 2014. |
| Post-argumentation argumentation task | Erduran, 2013; Mikkola, Luukka & Ahonen, 2006 |
| Role-playing debate | Albe, 2008; Feierabend & Eilks, 2011 |
| Final essay | Mikkola, Luukka & Ahonen, 2006 |

The variability of arguments (Grace, 2009; Liu, Lin & Tsai, 2010; Ratcliffe, 1997) was considered in terms four categories: socio-economic, ethical, ecological and scientific (Liu et al., 2010). This is in line with the most common models of sustainable development, which are usually considered to consist of economical, ecological and socio-cultural aspects, even if a definitive definition of the concept of sustainable development may be elusive, since there are over 300 different definitions or visual illustrations of it (Johnston et al., 2007; Mann, 2011; Burmeister et al., 2012). The analysis of the qualitative data was conducted by adapting the four categories reported in Liu *et al.* (2010) to fully describe the range of the participants' responses. The socio-economic category relates to costs or benefits to a person or a society (e.g., in the form of taxes or revenues). The ethical category relates to values or personal opinions about aesthetics or the future (e.g., what is right, what is wrong and what should be changed). The ecological category includes effects on the ecosystem and ecological human actions (e.g., recycling). The scientific category includes arguments concerning natural resources, technologies, energy, materials and pollution.

## 4.3. Generating domain knowledge about holistic and inquiry-based ESD in chemistry

In order to answer **RQ4**, the state of ESD in chemistry was evaluated throughout the design process by extensively reviewing existing research literature and using it to reflect on the empirical case studies presented in this thesis. This is illustrated in Figure 6. The reflection focused on, for example, the multiple challenges and future possibilities recognised on the levels of the teacher (Attachment 1) and the student (Attachment 2). This review framed the design process and affected the approaches selected for conducting the empirical research work.

Based on the review of the theoretical framework presented in this thesis and in previous studies (Juntunen, 2011, 2013), pedagogical frameworks found eligible for ESD in chemistry were analysed. In **Article IV**, the ESD-related lesson themes suitable for implementing SSI into basic school chemistry are discussed (Table 2. earlier in this thesis). Based on the review process, three new educational models were formulated in **Article IV** to help guide the work of teachers. The first model is presented in Figure 5. earlier in this thesis.

The second model is a student-centred pedagogical strategy for a teacher who wishes to teach SSI-based ESD in chemistry. The main features of the strategy are illustrated in Figure 7., which is explained in more detail in **Article IV**. The process begins with the setting of holistic, co-operative and student-centred goals and teaching methods for the chosen topic. These are set on the basis of what is being evaluated. The students are then introduced to the task and simply left to participate and create in the context of real-world issues. During the social activities, those students who need advice can be supported by both the teacher and their classmates. The teacher is also there to give ample personal feedback that is both formative and empowering, and to catalyse self-evaluative reflection among the students on the task in question.


**Figure 7.** The main features of a student-centred strategy for implementing SSI in ESD from a teacher's perspective (Applied from Dwyer et al., 1993; Jensen & Snack, 1994; Marks & Eilks, 2009). The goals of the task in question define the practices for action. The students socially participate and construct their knowledge in the context of real-world issues. Both the teacher and their classmates support them. The empowering formative feedback is given to catalyse self-evaluative reflection about the goals of the task.

The third educational model is presented in Figure 8. and explained in detail in **Article IV**. It summarises how a holistic approach to ESD in chemistry consists of several elements (see, e.g., Zoller, 2012; Vilches & Gil-Pérez, 2013): interdisciplinarity, topical socio-scientific issues involving discussion about solutions, hands-on societal co-operation with stakeholders from outside of the school, social interaction among students, socio-scientific argumentation practices and student-centred and inquiry-based learning methods. When combined, these elements can be used to create a context-based socio-constructivist approach to ESD.

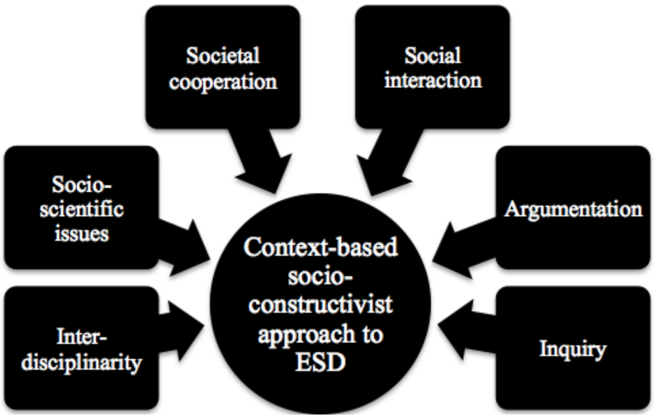


**Figure 8.** The elements of a context-based, socio-constructivist ESD pedagogy in chemistry

In comparison to previously published frameworks for SSI in ESD in chemistry, this design research project aimed to generate more holistic solutions. It was learned during the design process that while choosing a topic for ESD in chemistry, a teacher may develop a holistic approach by answering the following questions:

> i) Is the chosen issue authentic and relevant in the students' point of view? Is it socio-scientifically open-ended? Does it allow open debate? Does it deal with questions about science and technology? (Marks & Eilks, 2009)
> ii) Does the issue allow me to co-operate with other teachers or societies outside of school in an interdisciplinary way (Uitto & Saloranta, 2010a; Wilmes & Howarth, 2009)?
> iii) Am I applying social and student-centred approaches (Paloniemi & Koskinen, 2005, 29; Lester et al., 2006; Watson et al., 2013)?
> iv) Can I use argumentation or inquiry methods to support the students' appetite to study (Albe, 2008; Simon, 2008)?

When planning ESD in chemistry, one should consider available resources, the learning goals, the evaluation process and possible improvements to the teaching concept. Marks and Eilks (2009), for example, highlight the goals of promoting students' communication and self-evaluation skills in addition to the learning of factual science. Elsewhere, in order to achieve a holistic perspective of ESD, the elements of ESD in chemistry are considered through an elliptic model that incorporates the categories of chemical content knowledge, chemistry in context, chemistry's distinctiveness and methodological character, ESD competences and lived ESD (Jegstad & Sinnes, 2015).

# 5. EMPIRICAL RESULTS

The section summarises the results of the empirical (**Articles I–III**) and theoretical (**Article IV)** studies (see Section 4.).

## 5.1. Design solution – Teaching of life-cycle thinking

In **Article I**, the design solution was collaboratively developed from the initial inquiry-based LCA teaching concepts developed by 20 chemistry teachers, who participated in an in-service training course. These 20 initial teaching concepts were content analysed and classified in terms of their topic, learning level, time consumption, working method and the number of teachers using the concept (Tuomi & Sarajärvi, 2006). The concepts injected LCA into the chemistry curricula at all school levels. The approaches involved a certain theme, project work or a special course. Time consumption depended on the approach and varied from 1 hour to 30 hours. All these concepts could be implemented as structured, guided, or open inquiry, depending on the educational goals and the skill-level of the students (Colburn, 2000). The suitable working methods were either social or individual, or had elements of both (see Colburn, 2000; Joyce & Weil, 1986). The topics they discussed included the life-cycles of cotton, water, drinks, tobacco, plastic bottle, paper, food and an optional product.

The most common approach (N=16/20) was a social, inquiry-based investigation project of an optional product chosen on the basis of the interests of the students. This approach was collaboratively developed further towards a consensus concept, i.e., a design solution. This design solution became called *the IBL-LCA concept*. The structure of the IBL-LCA concept is presented in Figure 9.

The aim of the IBL-LCA concept is for students in small teams to investigate the life-cycle of a product. After a short and engaging introduction by the teacher, the students start their own project and work together with their peers to inquire into the life-cycle of their chosen product. The students choose the product for their team based on their own interests. During the project, the students are involved in setting their own research questions, searching for information, discussing their findings in teams, reviewing the work of other teams and presenting the results. The students collect data about raw materials, manufacturing processes and usage, as well as recycling and waste management. In cases where the team of students is particularly capable, their investigations may also include elements such as precise information or estimates of the product's lifespan, footprints, health effects and environmental impacts. The students are encouraged to make a presentation about their life-cycle studies in a format they consider best. After the project, the students have an opportunity to engage in debate about the pros and cons of the products. They can share their views regarding responsibility, the usefulness of the products and the individual's possibilities for action. Further on, it may become a cyclic process if the students continue their own investigations based on arisen ideas about consumer products or materials.

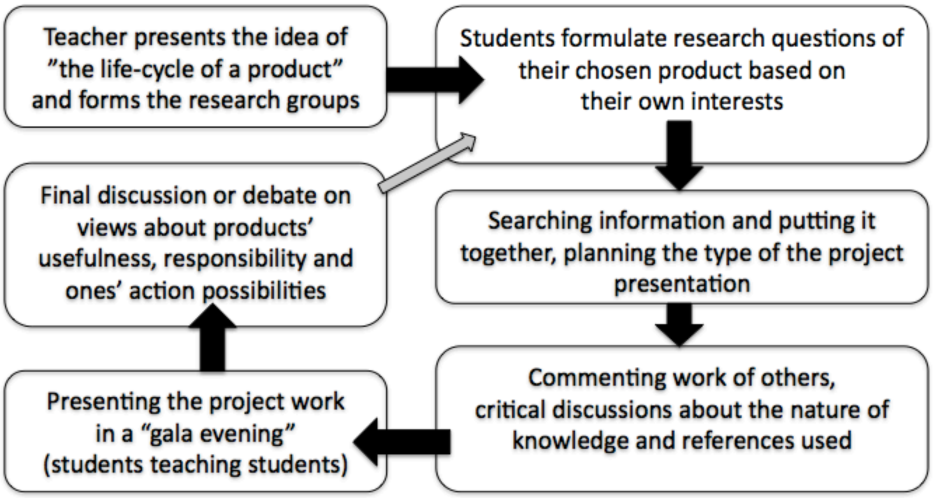


**Figure 9.** The structure of the IBL-LCA concept

Depending on the teacher, the group of students and the chosen product, the intervention lasts approximately 10–15 hours over a period of 2–3 weeks. The content of the work is up to the students themselves, which means they learn to take responsibility for their own learning. Throughout the project, the role of the teacher is that of a facilitator, supporting the students with ideas whenever they need help or encouragement. The teacher's formative assessment focuses more on the students' inquiry, their research process and the LCA related discussion than on their command of factual chemistry knowledge.

## 5.2. Effects of the design solution – Student perspectives

The qualitative results about the students' self-reported effects after the IBl-LCA project are illustrated in Figure 10. The more detailed results are in **Article II.**

The students extensively expressed the importance of environmental protection or recycling after the intervention. Many of them reflected positively on the development of their life-cycle thinking skills (48%) and consumer behaviour (33%). The majority of them (78%) thought that the most important outcome for them was new scientific ideas and realisations about the world. Majority of them (63%) did think that this type of project could influence other young peoples' behaviour. In the interviews conducted prior to the intervention, the students did not mention any aspects of environmental literacy. However, in the results of the quantitative survey, no significant ($p<0.01$) differences in the students' environmental attitudes or behaviour were observed. Furthermore, almost half of the students (44%) did not think that the project had affected their own environmental behaviour.

The students' attitudes towards studying chemistry developed in a positive direction as a result of the project. They reflected on the inquiry-based life-cycle thinking project in a very positive way. In the interviews conducted after the intervention, every single student reflected on the usefulness of studying chemistry by expressing how they learned beneficial chemistry-related things. More than a third of them (41%) mentioned chemistry literacy as being important to them as part of general knowledge. The chemistry content the students said that they had learned varied from information received from chemical presentations to the substances used in various products. Many of the students mentioned improvement in their communicative abilities (50%), independent working skills (34%) and co-operative skills (14%). The study methods used in the project appealed to both girls and boys.

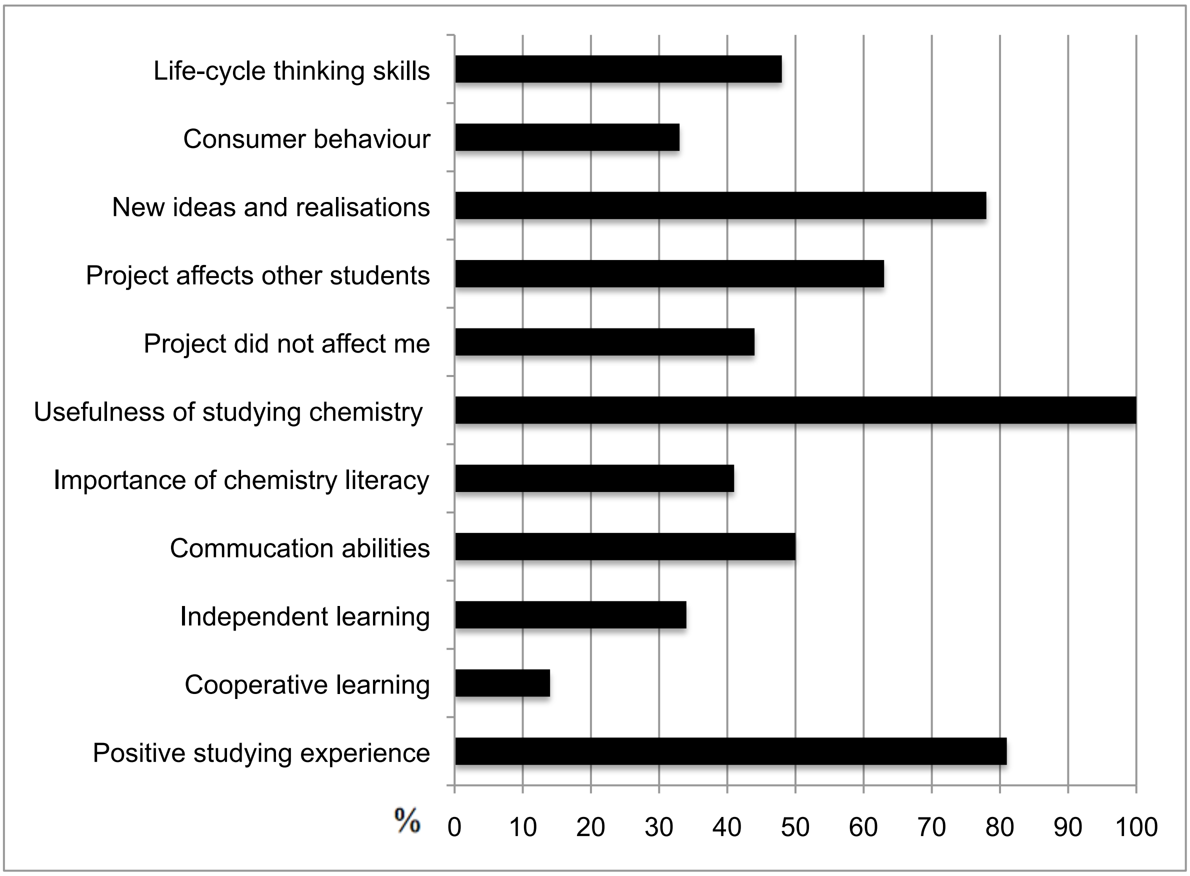


**Figure 10.** The qualitative results about the students' self-reported effects after the IBl-LCA project. The data included either written or oral discussion about students improved abilities, benefits of the project or their feelings. The results are based on questionnaires and interviews explained in more detail in **Article II**.

With regard to argumentation in **Article III**, the results show that the IBL-LCA concept had an impact on the students' (N=8) scientific and ecological argumentation skills. This is illustrated in Figure 11.

The essays, and the pre and post tasks (N=8) were analysed to see if a certain type of argument was presented. In these tasks, the number of times a certain argument was presented by an individual student was not calculated. Before the intervention, only two of the students wrote ecological arguments and one student came up with a scientific argument. After the intervention, all of the eight students wrote scientific and ecological arguments. All students were able to make socio-economic arguments both before and after the intervention, but ethical argumentation was less common. Only four of the students expressed ethical arguments in the pre-argumentation task, and two in the post-argumentation task. One student did not make any ethical statements during any of the study tasks. However, in the essays the students were asked to write, the majority of them, six students, were capable of discussing some ethical aspects related to their product.

In contrast, during the debate after the project work, the total number of arguments presented was calculated. The qualitative distribution of arguments during the role-playing debate with the whole class was in line with the other data. The results of the debate held after the project demonstrate that socio-economical (32%) and scientific (32%) arguments were the most common argument types used. Ecological arguments were almost as common (28%), but ethical arguments were rare (only 8% of all expressed arguments were ethical arguments).

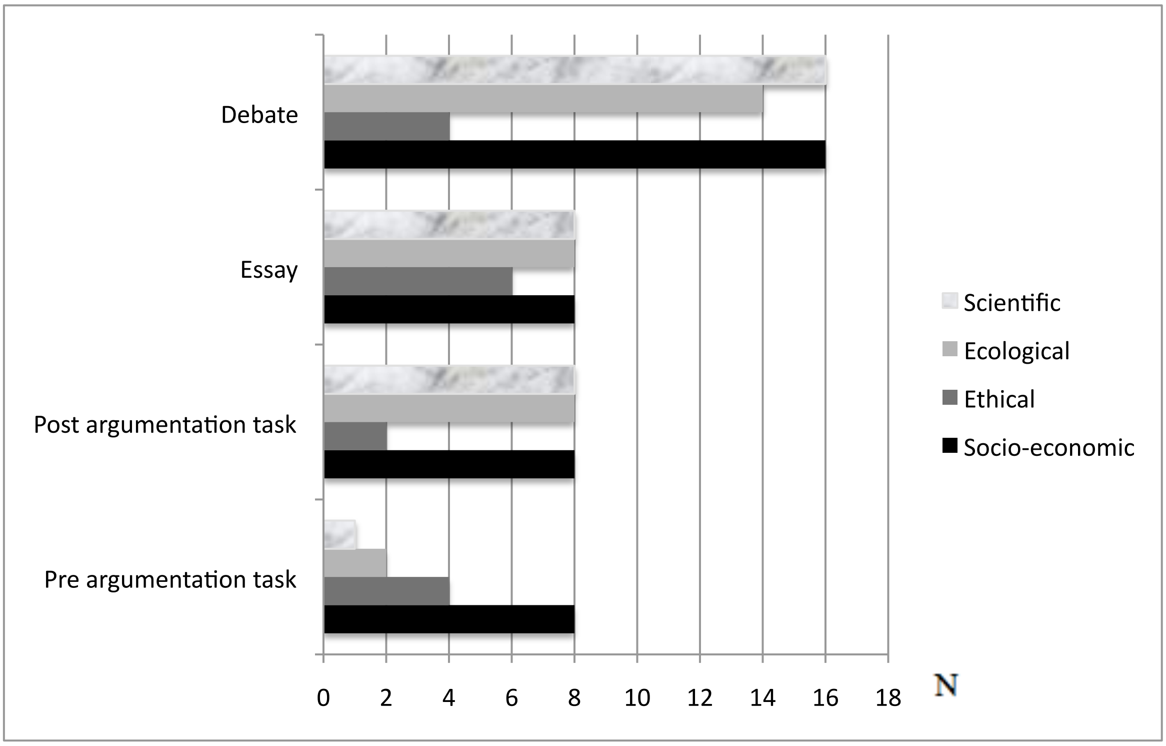


**Figure 11.** The qualitative results of the impact of the IBL-LCA concept on students' argumentation skills. The essays, and the pre and post tasks (N=8) were analysed to see if a certain type of argument was presented. However, the number of times a certain argument was presented by an individual student was not calculated. In contrast, during the debate after the project work, the total number of arguments presented was calculated. The results are explained in more detail in **Article III**.

# 6. VALIDITY AND RELIABILITY

The characteristics of good design research (Pernaa, 2013, 20) have guided this design process. The conducted design research was holistic in how it included both theories and models for guiding and describing the research. The models and theories were based on cyclic design and the testing and evaluation of the research. This design research project produced transferable and authentically-tested educational solutions through well-documented cyclic phases in Section 4. (Pernaa, 2013, 20)

The particular epistemic values guiding scientific research are: reliability, testability, accuracy, precision, generality, simplicity of concepts and heuristic power. These values define the character of science as a distinct way of knowing (Allchin, 1999). This chapter first discusses the validity aspects and then the reliability aspects of this dissertation, both of which were considered throughout the problem analysis and other phases of this design research project (Edelson, 2002).

Validity refers to how well an instrument measures what it is purported to measure. In this thesis, accuracy was considered by inspection of the research frame and how the chosen methodology corresponded to the nature of the studied phenomena and the research questions that were set. The accuracy is explained in terms of internal, external, structural and content validity.

Internal validity dictates how an experimental design is structured and encompasses all of the steps of the scientific research method (Anttila, 2006). In this thesis, internal validity was increased by using methodological triangulation on the qualitative and quantitative research tools. Besides methodological triangulation used in **Articles I–IV**, the multiple levels of analysis were drawn from the mixed methods used in **Article II**. These levels touched upon the individual, the community and the global society. Such a multi-level approach increases both the validity and the reliability of the conclusions.

Content validity (relevance) is the extent to which the measurement method covers the entire range of relevant factors that define the construct being measured. The structural validity (consistency) of the analysis concerns the question of whether the variables provide information on the relevant aspects mentioned in the theoretical framework. (Anttila, 2006) Content and structural validity were both increased by extensively analysing cross-curricular educational research material. In this dissertation, the theoretical problem-analysis represents mainly well-known and significant educational theories, leaving out single articles and weaker theories that may well be of interest in their own right. The theoretical basis seems to be well-saturated. It is limited to the core concepts of this thesis. Because the measurement tools used in this thesis are selected and formulated on the basis of the theoretical problem-analysis, it is assumed that the used tests assess the main domains of the selected criteria.

To improve internal and content validity, the cyclic design process was visualised (see Figure 6.). The visualisation clarifies the decision-making and progression of the thesis.

External validity refers to generalisation of the findings (Anttila, 2006). The group of participants in this study was rather small, which makes quantitative generalisation of the results impossible. However, the collaborative design of the teaching concepts together with the chemistry teachers and the testing of the concepts in authentic school settings partly answer the challenge of testability and generalisation. Representative conclusions can be drawn at least in the context of the research problem of the dissertation.

The results also seem to corroborate previously published educational research and, therefore, have a high face-validity. In other words, the results logically support the usefulness of product life-cycle analysis in particular as a cross-curricular approach to ESD in chemistry.

In terms of reliability, the aim was to select reliable research tools from the reviewed literature. Reliability is the degree to which the assessment tools produce stable and consistent results. The reliability of a method is assured if it produces reproducible results when applied to a sample. Reliability stems from the individual instruments used, and the high quality of the analyses and arguments presented in a study. (Anttila, 2006) The individual empirical methods that were selected for this study are briefly presented in Section 4. and analysed more deeply in **Articles I**–**III**. The logical design of suitable measuring tools was based on the extensive review of previous interventions found in the theoretical framework (see Juntunen, 2013). Qualitative and quantitative approaches were applied to answer the explorative research questions **RQ1–3**. The review process and a consultation with the author who had developed the quantitative instrument (Yavez et al., 2009) formed the basis for framing the design process and choosing a reliable assessment method for the case studies. In the quantitative epistemic analysis conducted in **RQ2**, the statistical factor analysis focused on the significance of the change in students' thoughts. In the structural analysis of qualitative tools in **RQ1–3**, reliability was assured as the method was based on exact counting of defined structural elements.

The guidelines for conducting educational design research by McKenney, Nieeven and Van den Akker (2006) were considered in this dissertation when addressing the reliability of the selected research tools and the gained results:

i) Systematic documentation of the design was carried out throughout the project.
ii) Contextual frameworks were based on the extensive review of literature.
iii) Previous interventions were used in the design of the project.
iv) Triangulation of data sources and data collection methods were used, as well as member checks.
v) Full, context-rich descriptions of the context, design process and research results were provided.

One of the weaknesses of the case study method is often the subjectivity of the results (Cohen et al., 2007). The potential challenges or biases associated with design research may stem from the dual roles of the authors as implementers and evaluators. In order to improve the inter-rater reliability of the results, researcher triangulation was used. Another researcher independently conducted a similar analysis of all of the data in order to validate the results.

Then, a more objective consensus of the results was gained. The triangulations supported the validity and consistency of the results.

To test the stability of the results, the attitudinal and behavioural changes should be monitored in the long-term. That was not a point of focus in this thesis. Instead, the analysis focused on the teachers' current concepts of teaching life-cycle analysis in schools and the students' views and argumentation skills related to life-cycle thinking. Synthesising the reviewed research literature was also important. It seems that the qualitatively saturated results reliably and logically illustrate effectiveness (desired outcomes) and practicality (usability of the intervention in the design context). The utilisation of the results is a fundamental test of the quality of the conclusions of the thesis.

On the basis of these notions about validity and reliability, it is concluded that the question of used methods is adequately resolved, at least to the extent that the most important conclusions are supported by the data.

# 7. DISCUSSION AND CONCLUSIONS

This dissertation answered the main research question: **What are the main features of holistic and inquiry-based education for sustainable development in chemistry?** In this concluding Section of the thesis, the results are discussed according to the subquestions of the dissertation. These include the perspectives of teachers, students and scientific research. Three types of new knowledge generated:

**RQ1.** (**Article I**)**:** What kind of teaching concepts related to product life-cycle analysis do chemistry teachers develop in their own practice? This case-study resulted in new chemistry teaching concepts for ESD that use life-cycle thinking and inquiry-based learning methods. From these models, a *design solution* the IBL-LCA concept was collaboratively-developed. Chemistry education that uses the created concepts and the IBL-LCA concept is evaluated in Section 7.1.

**RQ2.** and **RQ3.** (**Articles II** and **III**)**:** How does an inquiry-based, product life-cycle analysis project in chemistry education affect students' attitudes towards chemistry and environmental literacy? How do students use scientific, ecological, socio-economical and ethical argumentation in the life-cycle analysis of products? These two case-studies generated knowledge about *the effects of the design solution*. Students' attitudes towards chemistry, their perspectives on environmental literacy and their argumentation skills after the project are discussed in Section 7.2.

**RQ4.** (**Article IV**)**:** How to teach education for sustainable development in chemistry? The theoretical study formulated *domain knowledge* about holistic and inquiry-based ESD in chemistry. These approaches are discussed in Section 7.3.

The design research project of this study is discussed in Section 7.4. In Section 7.5., which is the final chapter of this thesis, a summary of how ESD can be implemented into curricula, teacher education and the wider pedagogical culture is presented. This summary provides implications of the findings and provides suggestions for further research on how chemistry education should be developed based on the results and the new knowledge gained.

## 7.1. Inquiry-based learning of life-cycle analysis – A teaching concept for ESD

The collaborative and cyclic design of a teaching concept resulted in a novel approach for inquiry-based infusion of LCA into chemistry lessons (see **Article I**). The results demonstrate that the design solution, the IBL-LCA concept, supports holistic and social chemistry learning.

The learning theories favoured in the teachers' concepts were socio-critical (Feierabend & Eilks, 2011; Marks & Eilks, 2010), socio-constructivist (Robottom & Hart, 1993; Tani, 2008) and context-based learning theories (Gilbert, 2006). In the theory and the concepts developed, students are allowed to socially construct their understanding, to participate in and influence their own learning process. The context in focus was a life-cycle of a product, which can touch the students' personal, vocational, technological or societal contexts (De Jong, 2008).

The design solution, the IBL-LCA concept, demonstrates how teachers combine inquiry, ESD, daily-life issues, collaborative studying and ethics in chemistry. This practical approach is a consensus developed by the teachers (see Section 5.1.). There are other collaboratively developed learning concepts, which have partly similar structures (e.g., Marks & Eilks, 2009; Rohweder, 2008b) and pedagogical features (e.g., Holbrook & Rannikmae, 2007; Sadler et al., 2007). The pedagogical features of the IBL-LCA concept may touch upon six possible learning contexts (Louhimaa, 2002): knowledge, feelings, experiences, values, attitudes and actions. Therefore, the learning aspects may involve:

i) knowledge about the relationship between humans and nature,
ii) development of various skills and abilities, and
iii) development of responsible attitudes and values.

The social, project-based IBL-LCA concept was the approach the teachers preferred the most. They utilised various learning materials, topics and ways of working, including pair work and small group work. This is similar to the socio-scientific teaching concepts in chemistry developed and described by Marks and Eilks (2009) and Mandler *et al.* (2012). The socio-critical and socio-scientific issues discussed in the LCA project presented here included water footprint, resource scarcity and the use of different types of materials. Similar approaches to chemistry teaching have previously discussed plastics (see Burmeister & Eilks, 2012), diet chips (Marks et al., 2008) and water (Mandler et al., 2012). The setting of the IBL-LCA concept is very similar to previous socio-critical and problem-oriented approaches to chemistry teaching (Feierabend & Eilks, 2011; Marks & Eilks, 2010). The product LCA approach lacks the laboratory working phase, which is common in previously published approaches. Jig-saw (Feierabend & Eilks, 2011) or learning-at-stations (Burmeister & Eilks, 2012) methods are also not used. Another specific feature of the product LCA method is the fact that it is a project-based approach.

As Marks and Eilks (2009) point out, at the most practical level, consumer products may be used to provoke open discussion and support individual decision-making during chemistry lessons. If there are contradictory aspects or improvements needed in the life-cycle of a product, the students can discuss them and suggest needed actions (see Dondi, 2011; Fensham, 2004; Kolstø, 2001). These kinds of skills are also referred as action competence skills (Jensen & Schnack, 1994; 1997; Paloniemi & Koskinen, 2005). Thus, LCA as a studying context is student-centred, as the topics touch upon the students' daily lives and are chosen by the students themselves. It presents students with an interdisciplinary science topic that is complex, contradictory and societal (Kolstø, 2001; Oulton et al., 2004; Sadler, 2011).

The teachers managed to make space for the students' empowerment and transformation by teaching socio-scientific and critical reflexive chemistry (Sjöström & Talanquer, 2014). The focus of teaching with the IBL-LCA concept is on the students' own experiences with research in daily-life contexts. Most of the teachers let the students choose which product's life-cycle to investigate. Life-cycle analysis of any product will lead the students to think about socio-scientific issues. By using relevant and contradictory socio-scientific topics and issues in chemistry teaching, it is possible to foster the students' views on science-based issues and how they relate to the moral, social and physical world around them (Van

Aalsvoort, 2004; Vilches & Gil-Pérez, 2013; Wilmes & Howarth, 2009; Yager et al., 2006; Zeidler et al., 2005).

The effects of social teaching concepts are greater than those of personal ones when considering complex learning outcomes such as higher-order thinking, problem solving, social skills or attitudes (Joyce & Weil, 1986). The IBL-LCA concept emphasises social, co-operative and open-ended information seeking, critical discussions and presentation of the findings. Thus and according to the results, this design solution seems to promote multidimensional skills, e.g., life-cycle thinking (Wylie et al., 1998), critical systems thinking (Hogan, 2002; Zoller, 2012) and ethical responsibility (Dondi, 2011; Holbrook & Rannikmae, 2007; Saloranta & Uitto, 2010).

The level of complexity within the IBL-LCA concept may be adjusted in similar ways as in other SSI education concepts (e.g., Kolstø, 2001; Sadler, 2011). The results indicated that LCA can be studied through inquiry-based learning at all school levels. Depending on the skill level of the students and the time available, the teacher can meaningfully adjust the difficulty level of the inquiry (Colburn, 2000). An open-ended, social project always places great demands on the students if their previous experiences consist only of guided instruction in their chemistry lessons.

In the IBL-LCA concept, the teachers' evaluation focused more on the students' research process and discussions related to product LCA than on factual chemistry knowledge, which is in line with previous research (Cantell, 2004; Oulton et al., 2004; Short, 2010). Socio-scientific issues involve different levels of complexity and develop different kinds of competences in science learning (Kolstø, 2001). The key learning objectives in the social, open-ended, inquiry-based concept are the multiple skills involved in how the students continuously evaluate the life-cycle data during the project, how they develop questions, critically discuss the ethical aspects of the product and comment on the findings of their peers. These abilities are crucial in the teacher's formative evaluation of the student. A practical method for evaluating learning outcomes in socio-scientific teaching is suggested by Holbrook (2005), for example, and this evaluation method is also suitable for the IBL-LCA concept.

More holistic and inquiry-based inclusion of teaching LCA is possible in chemistry education. LCA is one of the key objectives in the Finnish National Chemistry Curriculum (Finnish National Board of Education, 2015; 2014; 2003), but the textbooks currently lack inquiry-based LCA topics (Juntunen, 2011, 44–46). In the project discussed in this thesis, the participating teachers easily integrated the IBL-LCA concept into Finnish chemistry education at all school levels. However, the methods they used varied. Until now, when teaching LCA, teachers have rarely utilised decision-making practices, which are considered key pedagogical methods in socio-scientific chemistry education (Holbrook & Rannikmae, 2007; Ratcliffe, 1997; Tani, 2008; Tilbury & Cooke, 2005; Wilmes & Howarth, 2009; Zeidler et al., 2005) Similarly, drama, field-trips, acting as opponents to each other's work, learning diaries and debates are also rarely used methods. These methods could be important in supporting students' ethical decision-making skills and other ESD goals (Grace, 2006; Heimlich & Ardoin, 2008; Hiltunen & Konivuori, 2005; Littledyke, 2008; Paloniemi &

Koskinen, 2005, 29; Sadler et al., 2007). The challenge is to encourage the teacher to use more varied pedagogies.

Thus, some actions are needed. These actions involve including the IBL-LCA concept in chemistry teacher education, as well as in in-service training courses (Kärnä et al., 2012; Eilks & Ralle, 2002). Further collaborative development of the IBL-LCA concept should focus on promoting the students' skills for action (Jensen & Schnack, 1994; 1997; Oulton et al., 2004; Wilmes & Howarth, 2009). The other rarely used methods, such as outside of school activities (e.g., field trips, visitors), could also be implemented into the concept (Juuti et al., 2010). One solution may lie, once again, in teacher training (Aksela & Karjalainen, 2008; Keinonen & Hartikainen, 2011; Kärnä et al., 2012; Lester et al., 2006; Palmberg, 2004; Eilks & Ralle, 2002; Tung, Huang & Kawata, 2002). While learning about novel approaches in ESD in chemistry, the teachers or student teachers could also produce new teaching concepts themselves, which could then be disseminated for use by other chemistry teachers. The innovation of ESD generated in this study, the IBL-LCA concept, has already been disseminated to many Finnish schools and individual teachers. The IBL-LCA concept can also be included in chemistry teacher education. However, the diffusion of an innovation always takes a certain amount of time (see Rogers, 1995, 5–17).

## 7.2. Students' perspectives on IBL-LCA

Teaching life-cycle thinking using inquiry-based methods is a sound option for improving students' life-cycle thinking capabilities, environmental literacy, attitudes towards chemistry and argumentation skills (see **Articles II** and **III**). As an approach for ESD in chemistry, the IBL-LCA concept generated socio-scientific thinking and student-driven discussions in classrooms.

After the intervention, the students felt that the most important outcomes for them were the new scientific perspectives and realisations about the world. Almost all of the students addressed the importance of environmental protection, especially recycling. This is understandable, as recycling is generally the sustainability theme that students are the most familiar with (Asunta, 2003; Tung et al., 2002). A third of the students stated that the project had an influence on the depth of their life-cycle thinking and consumption, although some confusion related to the extent of the issues and the presented contradictory information was observed. While there was some scepticism of the sustainability competence of a single person, the majority of the students who were interviewed believed that, in general, their own behaviour, or that of other young people, could change as a result of this type of project.

In terms of environmental literacy, expressions of environmental awareness and societal views qualitatively improved and increased, but quantitatively significant changes in environmentally oriented behaviour or attitudes were not generated. This may be due to the fact that changes in attitudes and behaviour are a personal and often slow process (Dwyer et al., 1993). The relationships between secondary school students' environmental and human values, attitudes, interests and motivations are also multifaceted and ill-defined concepts to analyse (Uitto & Saloranta, 2010b). However, in this study, gender was observed to have an effect on the students' environmental literacy. This is in line with previous research (e.g., Bogner & Wiseman, 1999; Tikka, Kuitunen & Tynys, 2000; Uitto et al., 2011; Zelezny, Chua & Aldrich, 2000), with girls scoring better than boys in this area. Generally, the students' environmental attitudes appeared to be more positive than their environmental behaviour, which also corroborates earlier research (e.g., Erdogan & Ok, 2011; Kärnä et al., 2012).

With regard to the students' attitudes towards chemistry, the sustainability aspects of the project motivated them to study. After the life-cycle project, all of the students who were interviewed stated that they had learned beneficial things about substances and products during these chemistry lessons. Their previously cautious thoughts regarding the use of chemistry in their daily life became more environmentally oriented. The environmental and societal issues related to the daily lives of the students increased their sense of the relevance of chemistry (see Mandler et al., 2012; Marks & Eilks, 2009; Van Aalsvoort, 2004; Yager et al., 2006). Many of the students also described chemistry as a subject that supports general knowledge or general literacy. The low interest in studying chemistry (Kärnä et al., 2012) can be transformed into interest by using more relevant topics and teaching methods (see, e.g., Juuti et al., 2010; Van Aalsvoort, 2004).

The students valued the novel inquiry-based chemistry learning approach, which was independent but still socially collaborative. The students described the project as more meaningful and diverse than their ordinary chemistry lessons, which most often include only writing and listening to the teacher's lectures. The results support the evidence that the traditional and deductive learning methods are still dominating the chemistry education today when compared to inquiry-based approaches (Anderson, 2002; Kärnä et al., 2012; Rocard et al., 2007; Smithenry, 2010). IBL methods typically generate positive chemistry attitudes in students (e.g., Aksela, 2005; Gibson & Chase, 2002; Juuti et al., 2010; Minner et al., 2010; Rocard et al., 2007). As in the findings of Juuti *et al.* (2010), girls liked the inquiry-based methods more than boys. Most students noticed improvement, especially in their communication abilities or critical thinking skills.

The IBL-LCA concept seems to be a suitable method also for teaching socio-scientific argumentation skills to secondary level students within school chemistry. The product life-cycle analysis project fosters the students' scientific and ecological reasoning skills regarding the life-cycles of various products. It is known that students often tend to exclude scientific knowledge from their personal knowledge (Sadler, 2004). After the intervention, all of the participating students expressed scientific and ecological arguments. It seems that the knowledge the students gained during the project helped them form arguments from scientific and ecological points of view in particular. Socio-economical argumentation was the easiest form of argumentation for the students, which corroborates the findings of Osborne, Dillon and Grace (2004). Socio-economical argumentation is rather in line with the rationalistic reasoning culture that has typically been fostered and honoured in science classrooms (Zeidler et al., 2005). Within the context of life-cycle analysis, there is no severe need for further practise in simply expressing socio-economic arguments. In contrast, ethical argumentation could have been more prominent. All of the students seemed to be somehow restricted or at least shy in expressing moral arguments. Ethical dimensions are still new and uncommon in

Finnish chemistry lessons (Kärnä et al., 2012). If students do not consider ethics to be a part of a chemistry lesson (and something a teacher wants to hear from them), it surely affects the way students engage in ethical reflection. That is why the teachers should focus on developing the quality of the socio-economical argumentation prevalent among their students and take those ideas in a more ethical direction, for example.

Socio-scientific contexts are well-known forums for working on argumentation skills, but simply being exposed to socio-scientific issues does not make students better at reasoning or at analysing arguments. The promotion of argumentation skills is a difficult and multi-dimensional educational goal (Albe, 2008; Sadler, 2004). This was noticed in the context of this life-cycle analysis, as the moral arguments were more present in the individual essay than in the group tasks (the post-argumentation task and the role-playing debate). It might be that the ethical perspectives easily become too personal, which might explain why the students avoided expressing their ethical thoughts during the group activities. It seems the students need encouragement in expressing their emerging moral views to other students. The students also need support in connecting product-related issues and moral perspectives more deeply to socio-scientific issues in chemistry. Similar notions are recognised by Zeidler *et al.* (2005).

In practice, it is important to pay attention to whether the students try to form arguments or not. The flaws in informal reasoning about complex topics are common among students as well as among adults. For instance, Zeidler and Sadler (2004) found no evidence to suggest that individuals with different levels of content knowledge relied on different modes of reasoning (rationalistic, emotive or intuitive). Consequently, with regards to complex socio-scientific issues, the teacher should value all the emerging arguments the students are trying to form. This is why the different dimensions of knowledge (Krathwohl, 2002) or levels of reasoning (Sadler, 2011) found in the arguments were not analysed in this study, but instead the focus was placed on the categories and the number of arguments.

The results are encouraging. The project was short, but it positively affected the students' chemistry attitudes and successfully planted important seeds of environmental literacy. The students' new realisations indicate that their personal process of attitude and behavioural change had begun. There were also significant differences between schools. For the teacher, it is motivating to know that school culture can affect students' environmental literacy (Erdogan, Marcinkowski & Ok, 2009). Negev *et al.* (2008) have previously reported that schools appear to have only a modest effect on environmental attitudes and behaviour among children, relative to other factors. However, even small effects may accumulate as students indirectly influence their families and thus disseminate further what they have learned (Damerell, Howe & Milner-Gulland, 2013).

The group of participants in this study was a rather small one, so the generalisation of the results is impossible. However, it was noticed that as a result of the product life-cycle analysis project, the participants' arguments and thoughts on environmental literacy became more varied. The students who were exposed to the project saw new interesting dimensions of sustainability issues and the subject of chemistry. Life-cycle thinking requires holistic and cross-curricular understanding (Bulte et al., 2006; Mogensen & Schnack, 2010). These students might be more likely to consider not only the dominating socio-economic aspects of issues, but also the moral, ecological and scientific aspects in their future studies and daily lives. The approach supported the views of Sjöströms and Talanquer (2014), who state that: ”*Critical-reflexive chemistry engages students in a reflective analysis of historical, philosophical, sociological and cultural perspectives, as well as in critical-democratic action for socioecojustice*”. The student-centred activities and phases of the IBL-LCA concept fostered the students' reflection in small group discussions (Albe, 2008; Wilmes & Howarth, 2009). Argumentation and environmental literacy in chemistry requires both higher order thinking skills and systems thinking skills for one to be able to understand the reasons, progress, causalities, effects and solutions related to socio-scientific issues (see Hogan, 2002; Wylie et al., 1998; Zoller, 2012). The results indicate that the IBL-LCA concept is a way to promote relevant scientific literacy and 'education through science' to benefit everyone (see Holbrook &Rannikmae, 2009). Through the IBL-LCA concept, it is possible to improve the socio-scientific thinking skills of students and thus meet many of the multifaceted curricular and research-based goals of chemistry education (see, e.g., Holbrook & Rannikmae, 2007; Sadler et al., 2007).

To conclude, the IBL-LCA concept supports the established goals of the Finnish National Curriculum (Finnish National Board of Education, 2015; 2014; 2003), the research communities (Rocard et al., 2007; Vassiliou, 2011) and ESD (Bray, 2012; Tytler, 2012). These goals involve such competences as socio-scientific argumentation skills (Sadler, 2004), self-confidence for active citizenship (Tytler, 2012; Zeidler et al., 2005), action competence (Jensen & Schnack, 1994; 1997), social skills (Keys & Bryan, 2001) and environmental literacy (Yavez et al., 2009). As recognised in previous related research, this approach also promotes students' interest in studying chemistry (Marks & Eilks, 2009) and increases their chemistry content knowledge about product life-cycles (Minner et al., 2010).

## 7.3. Holistic and inquiry-based ESD in chemistry

Eligible pedagogical models for teaching ESD in chemistry are based on socio-constructivist and critical context-based learning theories, which was demonstrated in this thesis with the help of three new pedagogical models (see Figures 5., 7. and 8. and **Article IV**).

The six main elements of a holistic approach to ESD in basic chemistry are repeatedly recognised in research literature (see Figure 8. and e.g., Marks & Eilks, 2009; Watson et al., 2013; Zoller, 2012): interdisciplinarity, topical socio-scientific issues, societal co-operation with stakeholders, social interaction among students, socio-scientific argumentation practices and student-centred IBL methods. Similar elements are also recognised by Zoller (2012), who states: ”*Meaningful chemistry and science education for sustainability is envisioned as a teaching approach that is interdisciplinary, and promotes critical system thinking, problem solving, and decision-making, with the ultimate goal of increasing higher-order cognitive skills learning. Students educated in such a way could develop the capacity of evaluative system thinking and transfer and apply these skills and practices beyond science disciplines' specificities in the complex interwoven STSE systems context.*” Holistic STSE education in chemistry touches upon the moral, political and environmental aspects of daily-life science, technology, society and environment (Pedretti & Nazir, 2011; Zeidler et al., 2005).

The pedagogical approach to teaching SSI in ESD can be divided in three phases (see Figure 5.). The teaching of SSI often seems to begin with the introduction of the socio-cultural causes of an issue and then continuing to the environmental chemistry aspects related to ecology. Subsequently, the co-operative and value-driven practices are fostered through examples of opportunities for action in sustainable or unsustainable future scenarios, possibly involving all three dimensions of sustainable development. However, the economical aspects seem to be the least discussed dimension when compared to the aspects bound to ecology and the socio-cultural dimension. In addition to the empirical student argumentation study presented in this thesis (see **Article III**), there are a few other socio-scientific teaching concepts, which also involve discussions about the economical aspects (see Burmeister & Eilks, 2012, Eilks, 2002, Eilks et al., 2003, Marks et al., 2008, Marks & Eilks, 2010). Additionally, taking green chemistry practices and chemical safety into account right at the beginning of a molecular design process is often also the most economically efficient approach in the long term – a fact that could also be pointed out in the chemistry classroom (Anastas & Lankey, 2000; Böschen et al., 2003).

Sustainable development in the field of chemistry education is realised in practice through green chemistry and socio-scientific issues. These approaches convey to students an applied, cross-curricular and holistic view of the complex and contradictory nature of sustainability issues. (Nair, 1998; Wilmes & Howarth, 2009) The contexts are related to the daily lives of the students. Simplifying and practicing systems thinking by using examples such as product life-cycle analysis in chemistry education is beneficial. ESD approaches bring socio-scientific argumentation and IBL into chemistry. When intending to empower rather than disempower students in ESD in chemistry, the education should apply features of a student-centred, socio-constructivist pedagogical strategy (Dwyer et al., 1993; Jensen & Schnack, 1994; Marks & Eilks, 2009). In this thesis, IBL was used as an approach because it typically generates positive chemistry attitudes in students (e.g., Aksela, 2005; Gibson & Chase, 2002; Juuti et al., 2010; Minner et al., 2010; Rocard et al., 2007). A socio-scientific issue as a context for studying has also been documented to support the growth of students' interest, ethical awareness and sensitivity in science learning (Albe, 2008; Sadler, 2011; Wilmes & Howarth, 2009). The results achieved with IBL-LCA in this thesis, as well as previous studies, underline that a school's culture can affect the students' environmental awareness in science classrooms (Erdogan et al., 2009; Lukman et al., 2013). More meaningful studying contents and methods play a key role in changing the students' all-too-negative attitudes towards studying chemistry and steering them into a more positive direction (Juuti et al., 2010; Kärnä et al., 2012; Osborne, Simon & Collins, 2003), as demonstrated in this thesis.

In order to learn the holistic action and sustainability competencies, it is important that the students can construct the knowledge together in a social and positive atmosphere (see Figure 7. and Lave & Wenger, 1991; Vygotsky, 1978), get feedback from each other and self-reflect on their own actions and ideas related to the context (Dwyer et al., 1993; Gilbert, 2006). The new pedagogical approaches in ESD in chemistry should more often focus on methods which highlight the students' questions, interests and opinions. As constructivist learning theory (Vygotsky, 1978) suggests, a student's understanding is built on inner and outer influences. Students always modify the knowledge actively and from their own perspective. Thus, the novel teaching needs to holistically foster the cognitive and moral evolution within the unique human personalities of the students (Vilches & Gil-Pérez, 2013; Wolff, 2004b; Zeidler et al., 2005). This makes it possible to support certain prerequisites of sustainable development: higher order thinking skills (Anderson & Krathwohl, 2001), argumentation and decision-making skills (Albe, 2008; Wilmes & Howarth, 2009) and interest in studying greener chemistry (Juuti et al., 2010).

The endless and engaging future possibilities of ESD in chemistry include both new factual contents and new pedagogical methods. The new approaches are bound to daily lives or society in a new, interesting way. This promotes holistic understanding of the importance of chemistry as the students are able to see the relevance of chemistry also outside of their classroom (see Burmeister et al., 2012; Hofstein et al., 2011; Holbrook, 2010). Only by knowing chemistry can one recognise and quantify the different types of pollution in air, water and soil. Chemistry skills are needed when harmful substances are detected in consumer products or raw materials (Brunner & Ma, 2009). The chance to contribute to real world issues will make chemistry more engaging for all students (see **Article II**). The important role of chemistry in contributing to sustainable development should be underlined at all educational levels.

Presently there are various challenges facing chemistry teachers, however. In general, the curricular relevance and importance of ESD in chemistry needs to be improved and several supporting measures are required. Chemistry teachers are already doing small things related to ESD in their work (Uitto & Saloranta, 2010a). They want to teach sustainability (Burmeister et al., 2013) and have called for new approaches (Kärnä et al., 2012), but both teachers and students are still facing multiple challenges in implementing new kinds of holistic ESD in chemistry. The challenges are reviewed and possibilities to address them are presented in **Article IV** and Attachments 2 and 3. It seems chemistry teachers struggle with finding a suitable SSI, which is challenging due to the lack of teaching materials (Grace, 2006). Also, the amount of preparative work (Hofstein et al., 2011) and the complex language and theories (Grace, 2006; Millar, 2006; Reis & Galvao, 2004) that teaching SSI requires cause problems. To address these needs, in-service training courses (Aksela & Karjalainen, 2008; Keinonen & Hartikainen, 2011) and possibly collaboratively re-designed course-materials (Juntunen, 2011; Pernaa, 2011; Pernaa, Aksela & Västinsalo, 2010) are needed. Some teachers also consider the time constraints challenging due to other curricular goals that need to be met (Grace, 2006; Reis & Galvao, 2004). This issue could be addressed with improved interdisciplinary support from their colleagues or community. Presently, interdisciplinary support is described as rare (Hofstein et al., 2011; Kärnä et al., 2012; Pedersen & Totten, 2001), as is the use of inquiry-based approaches (Anderson, 2002; Kärnä et al., 2012; Rocard et al., 2007; Smithenry, 2010).

Another point of interest in developing ESD in chemistry is the field of student evaluation. In ESD, student evaluation is highly complex and multifaceted. It has been suggested that the evaluation of student performance should take into account the following elements: attitudes towards sustainability, behaviour, competence, knowledge (Roth, 1992; Jensen & Schnack, 1997; Yavez et al., 2009; Littledyke, 2008), information seeking skills, critical reflection, argumentation skills, ethical sensitivity and understanding of different opinions and the nature of science (Oulton et al., 2004). These elements were considered in the design process presented in this thesis.

The goal of ESD is to awaken investigation and action skills in students. These skills are both quantitative (e.g., solutions for reducing consumption or emissions) and qualitative (e.g., critical evaluation of knowledge and values, co-operation, decision-making and independent working skills) (see Burmeister & Eilks, 2012; Jensen & Schnack, 1997; Wilmes & Howarth, 2009).

The holistic goals can be reached if the traditional deductive and less ethically-oriented chemistry teaching methods (Kärnä et al., 2012) evolve into a more inquiry-based, social and student-centred direction. The improved holistic and inquiry-based teaching of ESD in chemistry by using SSI approaches has multiple positive outcomes. It is a means of improving both secondary students' attitudes towards chemistry and their environmental thinking skills (see, e.g., Eilks, 2002; Feierabend & Eilks, 2011).

The role of chemistry education is more contradictory than ever before (Bray, 2010). Chemistry creates welfare, but also contributes to massive problems. Technology can be seen as a crucial element in solving these problems. On the other hand, technology is also considered by some people to be elitist and controlled by few. Bray (2010) asks an important question: "*Can sustainable development realise without changing the nature and goals of science into more transparent and open for social participation?*" This is in line with the goal 'education through science' presented by Holbrook and Rannikmae (2009), which emphasises the importance of connecting daily-life science and scientific literacy to skills and values that are appropriate for a responsible citizen.

To conclude, despite the contradictions related to chemistry technology, ESD in chemistry can empower students of different ages in knowledge-based activism (Vilches & Gil-Pérez, 2013). ESD in chemistry aims to empower the students to act. They are citizens, consumers and even educators of their family in their daily lives. By affecting the younger generations, it is also possible to influence the attitudes of the older people who live with them (Damerell et al., 2013). Actions driven by sustainability are needed on the levels of the individual, community, ecosystems and the entire world, and these actions should be based on well-developed and informed personal holistic competences (Jegstad & Sinnes, 2015; Lichtfouse et al., 2005; Salonen, 2010, 9). Through ESD in chemistry, more sustainable habits, practices and skills can spread to all levels of daily life as individuals gain more holistic competences and systems thinking skills for active participation in making a change (Hogan, 2002).

## 7.4. Evaluation of design process

This dissertation stemmed from a deep worry about the critical state of the planet (see, e.g., Barnosky et al., 2012; Rockström et al., 2009). The by-products of our welfare resulting from unsustainable socio-cultural practices are severe issues facing humankind and other species (Peltonen, 1995, 104−105). Thus, this thesis is based on the critical, ”improved-design” oriented attitude that the world acutely needs more actively participating people, or even ”activists” (Lester et al., 2006). One of the starting points for this design research project occurred while teaching chemistry in junior high school. It seemed that both ESD practices and life-cycle thinking skills were inadequately approached in school chemistry (Juntunen, 2011). The need to re-design these areas was value-driven and subjective at first, but it then evolved into a more research-based direction as more knowledge of the issue was gained. However, research is never totally neutral, even though it aims to be. Critical and design-oriented research embraces the following values: responsibility and freedom to foster ecological integrity and diversity, equality of species, democracy, multi-valued society, justice and non-violence. These universal values need to overcome the values of victories or pleasure and they form the basis of this thesis. (Salonen, 2010, 60; Särkkä, 2011, 105)

Another starting point was the expertise of chemistry teachers. They have two kinds of expertise: they are chemists and pedagogists. They understand that both chemistry science and the teaching of it should continuously evolve to better meet current needs.

The learning theories that were eventually chosen as the basis of this design research project were critical contextual learning theories and socio-constructivism (Robottom & Hart, 1993; Tani, 2008). Marks and Eilks (2009) have previously presented their framework for a socio-critical and problem-oriented approach to chemistry teaching, which was a helpful starting point for this dissertation. It seems that through contextual, critical and social approaches, students have the best opportunities to participate in and influence their own learning process. The more complex the learning outcomes – higher-order thinking, problem solving, social skills and attitudes – the greater the effects of social teaching concepts are when compared to personal teaching concepts (Joyce & Weil, 1986).

The general process of conducting a design research project about ESD is challenging, and the concept of sustainable development involves extensive and cross-curricular educational research. This means that the related empirical projects are multifaceted. They are often more context-bound than generally applicable (Lang et al., 2012). Therefore, this design process involved an extensive and cross-curricular theoretical problem analysis (see Juntunen, 2013). The roles of the participants were clear throughout the design process. The researcher was an expert chemistry teacher, who planned and coordinated the research and reported the findings. The chemistry teachers who participated in the in-service training courses designed novel educational approaches for their own needs and tested them in their schools.

The new knowledge generated in this study is limited. For instance, our analysis of the different types of arguments used by the students offers only one lens through which argument quality may be viewed in terms of its effectiveness. In the scope of this study, the students could not look for a consensus. Therefore, one limitation of this study lies in the goals set for the argumentation tasks. In contexts where students value other perspectives as a means of refining and elaborating their own understanding of science, they would construct deeper knowledge. Instead of the competitive debate used in this study, the students could have been engaged in two-sided reasoning and made to look for a consensus together when constructing knowledge. This would have helped the students to form more sophisticated arguments (Garcia-Mila et al., 2013).

Despite the minor challenges faced during the design process, this dissertation succeeds in structuring new interesting and useful results for chemistry education. It analyses the general state of holistic and inquiry-based ESD in chemistry in a cross-curricular way from the perspectives of teachers, students, pedagogical practices and educational theories. The conclusions drawn from the results can therefore be used to suggest precise and much-needed improvements.

## 7.5. Implications

The theoretical and empirical findings of this dissertation encourage the formulation of suggestions for changes in curricula, the pedagogical culture and teacher education. These suggestions are useful for individual teachers as well as entire educational communities. Chemistry teaching needs to take more responsibility for supporting students' sustainability thinking and for providing them with opportunities to participate in relevant personal and societal actions and in open debate with different stakeholders on socio-scientific issues.

At the curricular level, the needs are modest. The current curricula already include sustainability statements and give a signal of their importance. Additionally, various learning methods are used in teaching theory. However, the specific issues of sustainability are not yet mentioned in curricula. Neither are there guidelines for topics or levels of learning in regards to sustainability. The amount and depth of sustainability topics discussed in a chemistry classroom is therefore presently dependent on the teachers' views and students may not be evaluated on sustainability issues at all. It is crucial to incorporate sustainability into the list of required student skills in a more concrete manner. More specific definition of the various learning methods may also be needed. Furthermore, ethical thinking is still absent while instead it should become a point of emphasis. ESD in chemistry stems from educating the students in, about and for the environment. This should be stated more clearly in curricula. When expecting changes in students' environmental literacy, it is good to bear in mind that behaviour and attitudes are highly dependent on the situation and require a long-term-oriented attitude (Uitto & Saloranta, 2010b). Thus, ESD should be interdisciplinary and penetrate all subjects as multidimensionally as possible.

As for the pedagogical culture, a change is needed among chemistry teachers so that the pedagogical methods evolve to be more diverse and the best practices are openly shared among teachers. Co-operation between chemistry teachers and other subject teachers should become more commonplace. Novel chemistry teaching involves real-world problems with contradictory perspectives, local and global value considerations, critical discussions about normative consumer culture, student-centred topics and democratic decision-making practices. The currently predominant deductive teaching methods should become less dominant and be more often replaced with cross-curricular and student-centred methods. This cultural change needs to be supported not only by teacher education, but also by the whole teacher community. In-service training courses, seminars, social web-portals, e-news, camps and all kinds of uniting social activities are very important traditions in supporting and reforming the identity of the chemistry teacher for the 21st century.

When developing new kinds of pedagogical approaches, relevance and social context are central aspects from the student's perspective. The experience of relevance may relate to students' personal, professional, social and societal choices. When students see the relevance of chemistry, their attitudes towards science become more positive and they may even become inspired to choose a scientific career. The IBL-LCA concept is a pedagogical means to address some of the developmental needs about environmental and scientific literacy at all school levels. Student-centred approaches such as the IBL-LCA concept improve the students' holistic understanding and argumentation skills with regard to consumer products. The daily-life context encourages the students to adopt new ideas and make more arguments from scientific and ecological points of view.

Furthermore, chemistry course books should evolve to include more sustainability practices and SSI-based, student-centred pedagogies. Students should be more often provided with more personally relevant and flexible chemistry content and studying methods. In line with previous research, the results of this dissertation support previous findings that inquiry-based and social learning approaches motivate students. Efficient learning of chemistry content knowledge often involves methods based on social inquiry. Novel chemistry teaching involves student-centred approaches where the focus is on the students' personal questions, interests and opinions. The students' participation, capability to act democratically and their feelings of empowerment facilitate a positive personal and cultural change. Inquiry-based methods may feel more difficult for the students at first, but when they get used to them, their appetite for understanding chemistry increases.

Besides the measures related to curricula and pedagogical culture, educators of chemistry teachers also need to support chemistry teachers in overcoming the multifaceted SSI and ESD challenges they face in their work. This may be realised through in-service training, new collaboratively developed teaching approaches, uniting social activities and more holistic chemistry teacher education. The teachers need advice about using cross-curricular and student-centred pedagogical approaches. Socio-scientific issues, sustainability and ethics are becoming more important every day, but they remain rarely used contents in chemistry education.

At the level of teacher education, this dissertation encourages educators to adopt the idea of changing the world in co-operation with non-governmental organisations, companies and local communities. This dissertation suggests that chemistry education should become more open towards society via learning environments and methods, which

- i) consider solutions to socio-scientific issues,
- ii) more often approach chemistry in co-operation with other subject teachers in a cross-curricular fashion,
- iii) hone skills related to decision-making and forming opinions and arguments by also incorporating chemistry knowledge,
- iii) use IBL methods, i.e., generating student-centred knowledge and peer learning,

iv) use collaborative, social and emotionally engaging learning methods, e.g., project work and drama,
iv) welcome visitors from different points of view to the lessons, and
v) expand the learning environment also to the outdoors in the form of field trips, for example.

Furthermore, for ESD in chemistry, four levels of knowledge can be recognised:

i) chemistry knowledge *about* sustainability issues,
ii) knowledge about socio-cultural *reasons* in sustainability issues,
iii) chemistry knowledge on the levels of the individual and the society about opportunities for *action* to steer the worrying trends into a better direction, and
iv) chemistry knowledge about sustainable *solution* perspectives in the future.

Given the increasing severity of global sustainability problems and the public's role in solving them, upgrading ESD programs in Finnish schools should become a central part of future environmental policy efforts at both national and local levels.

In order to achieve the goals of sustainable development, investigations are needed about the range of other advisable approaches that chemistry teachers could use when teaching sustainable development. To change the world, education that genuinely changes behaviour should be found. The best practices should be shared among chemistry teachers. Could chemistry lessons be taken outdoors more often? Which topics related to sustainability does today's chemistry teaching cover and which are left uncovered? Which socio-scientific issues should be taught at which age? Additional research should focus on the variability of existing and experimental pedagogical techniques in ESD in chemistry.

As the culture of chemistry teaching evolves, it would be interesting to study to what extent teachers discuss different aspects while teaching ESD. What level do they reach? How is the teacher's identity as a facilitator of a more sustainable future perceived? Can trained teachers overcome the challenges related to ESD and SSI in their work?

Additional research may also focus on the students and their sense of competence in socio-scientific issues. In which way does the teaching of SSI in chemistry advance students' scientific literacy or moral awareness? Does it empower students to act more responsibly or discourage them from doing so? What is the role of school chemistry education in the formation of a student's identity in the long term? More research is required to investigate what kind of learning outcomes the IBL-LCA concept supports and what kind of knowledge outcomes this type of teaching creates. Subsequent studies could also address the students' argumentation skills outside of the classroom. How do the students talk about products after the product life-cycle analysis project? In this thesis, it was found that after the project, at least some of the participating students considered their material consumption differently, at least for a while.

Future studies should also focus on chemistry education on the vocational or academic levels. What kind of adult education promotes an environmentally-literate chemist's identity –

chemists who are ethically and intrinsically motivated in green chemistry practices (Tundo et al., 2000)? Do all chemistry teachers gain knowledge about ESD during their training?

Understanding all of this is central to improving ESD in 21st century chemistry classrooms and steering our society at large towards sustainable development. Allocating resources to the developmental tasks would push chemistry education to more efficiently strive towards achieving the most important goal of all: transforming the extensive aims of ESD into actions for a more sustainable world. As the challenges in global sustainability are more complex and multifaceted than ever before in human history, future citizens need new kinds of skills so that they can act differently than previous generations – they need to act more responsibly and sustainably as chemists, consumers, parents, voters and decision-makers in this world of complex systems. The realisation of chemistry education that supports these skills is also essential. There are no excuses for not doing it. With every teacher, student and chemistry lesson, the global goal of sustainability is one step closer.

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# APPENDICES

**Attachment 1.** The challenges science teachers face and opportunities for improvements in ESD about SSI.

| **Challenges** | **References** | **Opportunities** | **References** |
|---|---|---|---|
| Group management | Millar, 2006 | Pre-teacher education | Kaivola, 2007 |
| Complex language and theories | Grace, 2006; Millar, 2006; Reis & Galvao, 2004 | In-service training | Aksela & Karjalainen, 2008; Keinonen & Hartikainen, 2011 |
| Lack of teaching materials | Grace, 2006 | Teachers have called for new approaches | Kärnä *et al*., 2012 |
| Amount of preparative work | Hofstein *et al*., 2011 | Redesigned course materials and books | Juntunen, 2011 |
| Finding a suitable socio-scientific issue | Grace, 2006; Reis & Galvao, 2004 | Teachers want to teach sustainability | Burmeister *et al*., 2013 |
| Lack of interdisciplinary support from colleagues or community | Hofstein *et al*., 2011; Kärnä *et al*., 2012; Pedersen & Totten, 2001 | Collaboratively developed teaching approaches | Pernaa, 2011; Pernaa, Aksela & Västinsalo, 2010 |
| Time limitations due to other curricular goals | Grace, 2006; Reis & Galvao, 2004 | School culture affects students' environmental awareness | Erdogan *et al.*, 2009; Lukman *et al.*, 2013 |
| Little curricular relevance and importance | Grace, 2006; Reis & Galvao, 2004 | Teachers already do small things related to ESD | Uitto & Saloranta, 2010a |

**Attachment 2.** The challenges students face in chemistry lessons and opportunities for improvements in ESD about SSI.

| Challenges | References | Opportunities | References |
|---|---|---|---|
| Struggling with practical tasks related to everyday product materials | Kärnä *et al.*, 2012 | Learning of scientific content knowledge and applying it in a societal context | Bulte *et al.*, 2006; Dori *et al.*, 2003; Klosterman & Sadler, 2010; Sadler, 2004; Yager *et al.*, 2006 |
| Connecting chemistry to ethics and morals | Lymbouridou, 2011; Tirri *et al.*, 2012 | Improvement in moral and ethical thinking skills | Belland, Glazewski & Richardson, 2011; Oulton *et al.*, 2004; Sadler, 2004; Ratcliffe 1997; Zeidler *et al.*, 2005 |
| Low levels of interest in studying chemistry<br><br>OR sustainability issues | Hofstein *et al.*, 2011; Kärnä *et al.*, 2012; Osborne *et al.*, 2003; Rocard *et al.*, 2007 OR Zsóka *et al.*, 2013 | Increased student motivation to study chemistry OR make sustainable changes | Albe, 2008; Mandler *et al.*, 2012; Sadler, 2004; Taskinen, 2008; Yager *et al.*, 2006; Van Aalsvoort, 2004<br><br>OR Sund & Lysgaard, 2013 |
| Lack of opportunities to practice new skills (argumentation, participation) | Albe, 2008; Driver *et al.*, 2000; Paloniemi & Koskinen, 2005 | Improved understanding of the importance of science in society and one's daily life | Hofstein *et al.*, 2011; Kolstø, 2000; Oulton *et al.*, 2004; Reis & Galvao, 2004; Sadler, 2004; Zeidler *et al.*, 2005 |