Science Education International
Vol. 24, Issue 2, 2013, 150-166

International Council of
Association for Science Education

Life-cycle analysis and inquiry-based learning in chemistry teaching

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ABSTRACT: The purpose of this design research is to improve the quality of environmental literacy and sustainability education in chemistry teaching through combining a socio-scientific issue, life-cycle analysis (LCA), with inquiry-based learning (IBL). This first phase of the cyclic design research involved 20 in-service trained chemistry teachers from elementary to high school level and two researchers. The aim was to collaboratively develop and test teaching concepts that the teachers had created within in-service training courses over a period of two years. The research questions were: (i) How to develop concepts of chemistry teaching that combine IBL with LCA? and (ii) What kind of teaching concepts related to LCA do chemistry teachers develop in their own practice? The study presents a framework for the development process of new practices in chemistry teaching. The findings reveal that teachers can combine LCA with IBL on all school levels in several different ways. The most popular approach was a project-based student-centered inquiry concept, which combined social and personal teaching strategies. The study suggests that LCA-IBL approaches should be implemented into chemistry education at all school levels. The opportunities to foster several modern educational goals, including scientific literacy and sustainability competence, are also discussed.

KEY WORDS: life-cycle analysis, inquiry-based learning, socio-scientific issues, teaching concepts, chemistry education

INTRODUCTION

Understanding environmental issues is more and more important in the education of children and young people around the world. There is a strong need to improve the life-cycle assessment (LCA) education in chemistry, and the overall sustainability education must become more extensive in science (Tundo et al., 2000; UNESCO, 2009). Schoolbooks lack LCA-IBL topics (Juntunen, 2011, 44–46), even though LCA is one of the key objectives in Finnish National Chemistry Curriculum (Board of Education, 2003; 2004). Chemistry teachers themselves have requested improvements to the fields of environmental teaching design and green

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chemistry (e.g. Feierabend, Jokmin, & Eilks, 2011; Lumivaara, & Aksela, 2002), partly due to the fact that at the same time the total interest in chemistry has declined among young people across Europe (Hofstein et al., 2010; the Inter Academy Panel, 2010; Krapp, & Prenzel, 2011; Osborne, 2003; Rocard et al., 2007; Vassiliou, 2011) and Finland (Kärnä, Hakonen, & Kuusela, 2012). In their chemistry studies, Finnish students struggle especially with the applied tasks related to different daily materials (Kärnä et al., 2012).

As an educational approach, LCA is a possibility to include aspects of sustainability (e.g. Tundo et al., 2000) and ethics (Dondi, 2011; Zeidler et al., 2005) into chemistry lessons. From a chemistry perspective, life-cycle analysis (LCA) combines green chemistry (Anastas, & Lankey, 2000; Poliakoff et al., 2002), sustainable chemistry (Böschen, Lenoir, & Scheringer, 2003) and engineering (Eissen, 2012). LCA is an approach that evaluates the environmental burden of a product, process or activity by quantifying the net-flows of different chemicals, materials and energy (see e.g. Blackburn, & Payne, 2004). The assessment of resource use and emissions, and their health impacts, creates possibilities to make environmental improvements on a product life cycle (Anastas, & Lankey, 2000).

The educational applications of LCA in chemistry education have not yet been studied in detail. Somewhat similar approaches have been developed to teach chemistry of different materials, e.g. plastics (Burmeister, & Eilks, 2012), shower gels (Marks & Eilks, 2010) and bioethanol (Feirabend & Eilks, 2008). Similarly to those examples, the analysis of the life cycle of any product is a socio-scientific teaching approach. It is an interdisciplinary science topic, which is complex, contradictory, societal and relevant to the daily lives of the students (Kolstø, 2001; Oulton, Dillon, & Grace, 2004; Sadler, 2011). Linking sustainability issues to the complex field of socio-scientific teaching has been discussed and structured recently by Pedretti and Nazir (2011) and Tytler (2012). Pedretti and Nazir (2012) map out a typology and provide a heuristic that educators can use for critical analysis of discourses and practices in the field. Tytler (2012) reviews papers that provide models for student disposition to utilize science and other ideas to act meaningfully. Future citizens must have skills to act responsibly and sustainably as chemists, consumers, parents, voters, and decision-makers.

This paper illustrates the possibilities of LCA in chemistry education. The possibilities relate to 21st century skills (Fensham, 2004; Palmer, 1998) and to scientific literacy for all (Holbrook, 2010). The objectives of scientific literacy are cross-curricular and closely related to those of environmental literacy. The term 'environmental literacy' refers to skills and motivation to work towards the resolution of environmental problems and active involvement in working toward the maintenance of dynamic equilibrium between the quality of life and quality of environment (Hsu, & Roth, 1998). It is related to knowledge, effects, skills and behaviour on three levels – nominal, functional and operational competences (Roth, 1992). UNESCO includes knowledge, understanding, attitudes and active involvement into their environmental literacy related statements (Marcinkowski, 1991). The effects of LCA teaching on students' environmental literacy have also been discussed previously by Juntunen and Aksela (in press).

Implementing environmental and socio-scientific issues that relate to the daily lives of students can support their feelings of relevance in studying chemistry (Mandler et al., 2012; Van Aalsvoort, 2004; Yager et al., 2006). The selection of topics and teaching methods are of key importance in supporting the declined interest towards studying science (Juuti et al., 2010; Mandler et al., 2012; Van Aalsvoort, 2004). Also inquiry-based learning (IBL) generates positive attitudes towards chemistry in students (Aksela, 2005; Gibson, & Chase, 2002; Juuti et al., 2010; Minner, Levy, & Century, 2010; Rocard et al., 2007). Depending on the skill-level of the student, IBL can be structured, guided, or open inquiry. They require variable levels of teacher guidance and skill demands from the student investigation. In structured inquiry, the teacher gives the student the questions, materials and structure to perform the investigation. The student only formulates the results of the investigation. In guided inquiry, the student gets the questions and the material from the teacher but the structure and the results of the investigation are both open. In open inquiry, the teacher only gives support to the student with the materials if needed. The role of the teacher is to be a catalyst, to facilitate a safe learning environment and to provide support mainly in the form of guiding questions. In IBL, the responsibility of the task is on the students (Colburn, 2000).

Designing chemistry education based on LCA-IBL is a novel approach. The LCA-IBL teaching improves students' attitudes towards studying chemistry (Juntunen, & Aksela, in press). The approach creates possibilities to provoke student discussion, and improve reasoning and social learning skills, and a broad range of other educational goals in personal, cognitive and moral development (Colburn, 2000; Juntunen, & Aksela, in press; Keys, & Bryan, 2001; Kolstø, 2001; Marks, & Eilks, 2009; Zeidler et al., 2005). It also meets the goals of "education through science" thinking in comparison to "education in science" thinking (see Holbrook, & Rannikmae, 2007). Last, but not least, this approach supports the extensive goals for sustainable development (see e.g. Böschen et al., 2003).

METHODOLOGY

Three types of theories can be developed through design research (Edelson, 2002). Categorisation of these theories is: domain theories (descriptive knowledge about the problem to be solved through design), design frameworks (prescriptive knowledge about the properties of a successful design solution), and design methodologies (prescriptive guidelines for a successful design procedure) (Juuti, 2005). In this first phase of the cyclic design research, the research questions focused on (i) design methodologies: How to develop concepts of chemistry teaching that combine IBL with LCA? and (ii) design frameworks: What kind of teaching concepts do chemistry teachers develop in their own practice related to LCA?

To support the work of teachers, fee-free in-service training courses about sustainable development, green chemistry (Anastas, & Lankey, 2000), LCA and IBL approaches were arranged in Finland during the years 2010 to 2012. During the courses, a total of 20 chemistry teachers collaboratively developed new LCA-IBL teaching concepts for their own needs (Joyce, & Weil, 1986; Juntunen, & Aksela, in review). The 20 teachers were from elementary to high school level across Finland. They were randomly selected to the in-service training courses. Over the period of two years, the participants created, together with a researcher, teaching concepts on LCA-IBL during a few-day-long in-service training courses. The used collaborative design setting was closely related to the participatory action research described in Marks, Bertram and Eilks (2008), as it also involved a group of teachers designing new teaching concepts together with researchers. According to their experiences, Marks and Eilks's (2009) have outlined a conceptual framework of the socio-critical and problem-orientated approach to chemistry teaching. There, objectives include multi-dimensional literacy role of science knowledge and the promotion of evaluation and communication skills. Their criteria for socio-critical science approach are authenticity, relevance, open discussion and evaluation, as well as its societal, chemical and technological dimensions. In this study, as a goal and criteria for the teachers, the novel LCA chemistry teaching concept should:

- use inquiry-based, student-centered approaches that emphasize students' own ideas and questions (Colburn, 2000; Joyce, & Weil, 1986)
- develop skills for cooperative studying, critical thinking, problem solving, communication, and evaluation (Colburn, 2000).
- reveal the relevance of chemistry in environmental protection, sustainability, in value-centered discussion and decision-making using LCA as an approach (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 1, the teachers participating in the in-service training in 2011 further developed the teaching concepts designed in 2010. Similarly, in 2012 the in-service trained teachers developed the concepts from 2011. After that, all concepts (N=20) were content analyzed (Tuomi, & Sarajärvi, 2006) by two researchers parallel to improve the validity of the results. This analysis is called researcher-triangulation, when another researcher independently conducts a similar analysis of the entire data to validate the results.

Depending on their structure, the LCA-IBL chemistry teaching concepts were classified according to Joyce and Weil (1986), who have described the differences between personal, or social teaching models. They used the term 'model' (Joyce, & Weil, 1986), but here the term 'concept' is used to better describe the design solutions (see Marks, & Eilks, 2009). Personal teaching concepts utilize individual learning processes that affect student achievement in basic areas, such as in recalling information. It can be non-directive and person-centred. Social teaching concepts may involve cooperative learning approaches, peer-teaching-peer and group investigations. The more complex the outcomes – higher-order thinking, problem solving, social skills and attitudes – the greater the effects of social teaching concepts are in contrast to the personal ones (Joyce, & Weil, 1986).

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

RESULTS

The results are presented according to the research questions.

(i) In-service training courses are practical means of developing chemistry teaching concepts that combine IBL with LCA. As design research typically develops its own practices, also here it governed the length and content of the in-service training course evolved. At the beginning of the research, the first in-service training course lasted 4 days. The course feedback indicated that the topics were suitable, but the time frame could have been shortened. The teachers preferred in-service training courses lasting no more than 1 or 2 days. Thus, the length of the course was shortened for the next courses, but the topics stayed similar. The framework for the in-service training course is presented in Figure 1. During the course, guest lectures were invited about *chemicalisation* of the environment, recycling of electronics and green chemistry. The teachers discussed in small groups about sustainable development, socio-scientific issues, LCA of consumer products and IBL methods. A key task for the course participants was to develop collaboratively, together with the researcher, novel student-centered LCA-IBL teaching concepts, which also were to be classroom tested in schools. The researcher gave direct support to the teachers by attending the lessons and consulting them by phone or e-mail, if the teachers needed advice.

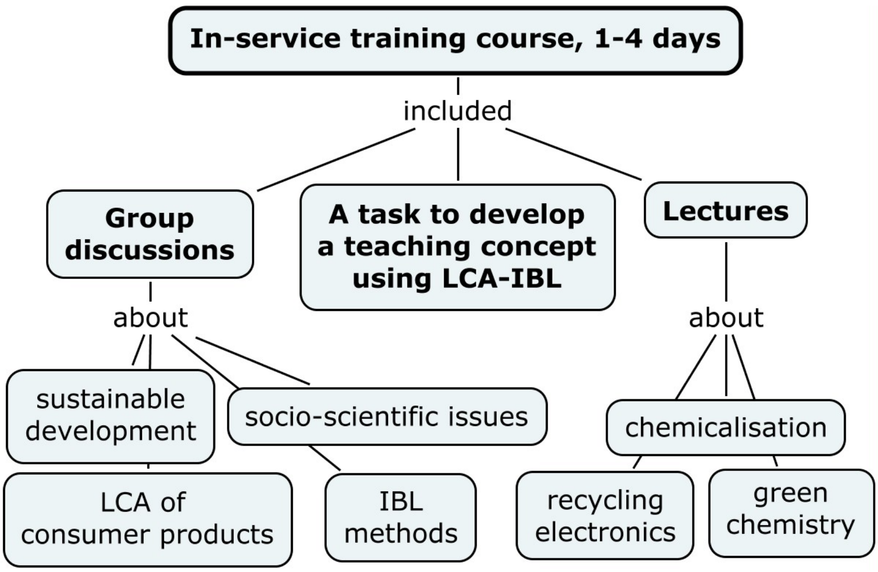

Figure 1. The framework for the in-service training course

The framework for the cyclic design process to develop novel LCA-IBL concepts for chemistry teaching is presented in Appendix 1. The 1st problem analysis related to chemistry teachers, textbooks and curriculum started the research process. Based on problem analysis, in-service training courses were organized in order to develop novel LCA-IBL teaching. First, the teachers created individual mental concepts that were developed further according to collaboratively expressed concepts to better meet the needs of schools. The 2nd problem analysis was undertaken by the researcher and three teachers, who tested these collaboratively developed concepts in their schools. It resulted in a consensus concept about teaching LCA-IBL in schools. To broaden the view, the consensus concept was tested in practice by a chemistry teacher, who did not attend any of the in-service training courses. The 3rd problem analysis was undertaken after this testing. More LCA-IBL concepts were designed during the following in-service training courses to obtain more saturated research material for the content analysis. The 4th problem analysis related to these concepts resulted in the consensus concept presented in Appendix 2. The future phases of the cyclic design research are also presented there to better illustrate the whole design process.

(ii) The chemistry teachers developed variable teaching concepts related to LCA-IBL for all school levels. The concepts were content analysed (Tuomi, & Sarajärvi, 2006). The teaching concepts created by the 20 in-service trained chemistry teachers are shown in the Table 1. They were classified in terms of their topic, learning level, time consumption, working method and the number of teachers using the concept. The concepts placed LCA into the chemistry curriculums at all school levels. The approaches involved a certain theme, project work or special course. The 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 skill-level of the students (Colburn, 2000).

Table 1. The teaching concepts created by the 20 in-service trained chemistry teachers in terms of their topic, learning level, time consumption, working method and the number of teachers using the concept

Teaching concept	Life-cycle topic	Learning level	Time consumption	Working method	Number of teachers preferring the concept
One theme on a chemistry lesson	Drinks and tobacco, plastic bottle	Basic school, high school, college, or university	1–2 h	Alone or in a small group	2
Project work	Optional product, paper, food or cotton	Basic school, college, or university	4–10 h	In a small group	16
Environmental chemistry course	Water	Upper secondary school or high school	n. 30 h	Alone or in a small group	2

The more detailed content analysis related to the topics and working methods is shown in Figure 2. It revealed that the suitable working methods were either social or individual, or had elements of both (see Colburn, 2000; Joyce & Weil, 1986). The topics they used included the life-cycle of cotton, water, drinks, tobacco, plastic bottle, paper, food and an optional subject (Figure 1). The most common approach (N=16) was the social, project-based investigation of an optional product chosen according to the interests of the students. This was influenced by the social, project-based consensus concept 1 (see App. 2, which is a developed version of consensus concept 1), as the teachers who designed the mental concepts 4–20 (see App. 1) reflected their ideas on it. Thus many of the teachers adopted the idea.

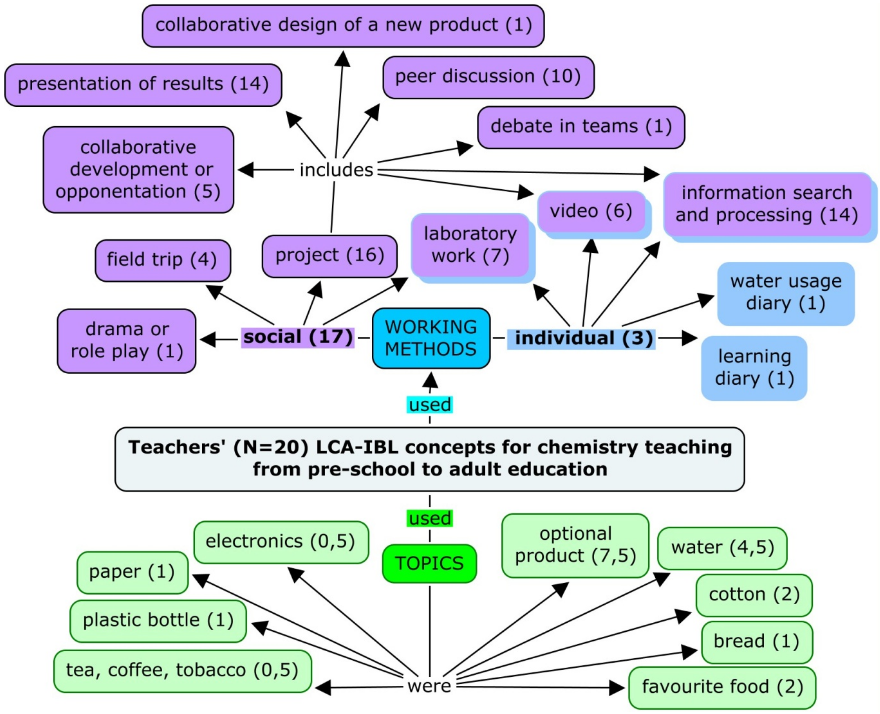

Figure 2. The frequencies of the topics and working methods used by the 20 teachers as they taught LCA. All of them either used social working methods or combined these with individual learning approaches.

All teachers, except one, either used social working methods only or combined them with individual learning approaches (Figure 2). Social concepts most often involved presentation of the results, peer discussions and information search. Less often, the concepts involved peer opponent review, designing a new product or classroom debates. A third of the teachers included laboratory work in their teaching. Four teachers arranged a visit to waterworks, or a science centre. Interestingly, one of the project concepts suggested a conference-type gala evening to conclude the students' work (see App.2). The individual approaches – learning diaries, drama or debate – were each used only in one concept among the social learning methods. Only one teacher taught LCA by lecturing, which was classified as an individual, personal concept of learning (Joyce, & Weil, 1986). Then, the IBL dimension was connected to students' personal learning via water usage diaries.

In the elementary school science lessons, my favourite food was a popular topic for investigation. One teacher even built a 3D-life-cycle of bread with the pupils using Lego. They also photographed the construction and presented the pictures to other pupils of the school. In polytechnic adult education, the presentation of the LCA of cotton was informatively constructed into big cardboard boxes in the hallways. One teacher used drama or role play to engage the students in the LCA of a plastic bottle. Another teacher wanted to limit the students' information search to the LCA of paper. Two teachers wanted to include more than one topic in their LCA-IBL concept. One started with the common task related to the LCA of electronics and then, extended the students' investigations to optional products. Another used laboratory activities on the LCA of tea, coffee and tobacco at first and later connected it generally to water consumption.

Social, project-based LCA-IBL education is the most popular. Thus, the consensus concept 2 is collaboratively developed (see App. 1 and 2). The structure of the consensus concept 2 is presented in Figure 3. After a short engaging introduction by the teacher, the students start their own project through peer collaboration by inquiring into the life-cycle of a product. The students choose the product according to their own interests. During the project, the students are involved in setting their own research questions, searching information, discussing in teams, reviewing the work of other teams, and presenting the results. The students collect data about the raw materials, manufacturing processes, usage, and recycling and waste management. If the student team succeed in this, their investigation may also include precise information or estimations about the product's lifetime, footprints, health effects and environmental impacts. The students are encouraged to make a presentation about their life-cycle studies in the form they consider to be the best. After the project, students are encouraged to debate their views of product lifecycles, responsibility and their own possibilities to take action.

The aim of the concept is that the students discuss in small groups about the pros and cons of the lifecycle of a product. It is crucial that the students are given the responsibility to decide what is important to them to investigate and how. The content of the work is up to the students themselves. They become dedicated and learn to take responsibility for their own learning. Depending on the teacher, the student group and the product of interest, the intervention takes about 10–15 hours within 2–3 weeks. During the whole project, the role of the teacher is being the facilitator who supports the students, providing them with ideas, whenever they need help or encouragement. The teachers expressed that in their concepts they focus the formative assessment more on the student research process and LCA-IBL related discussion than on factual chemistry knowledge.

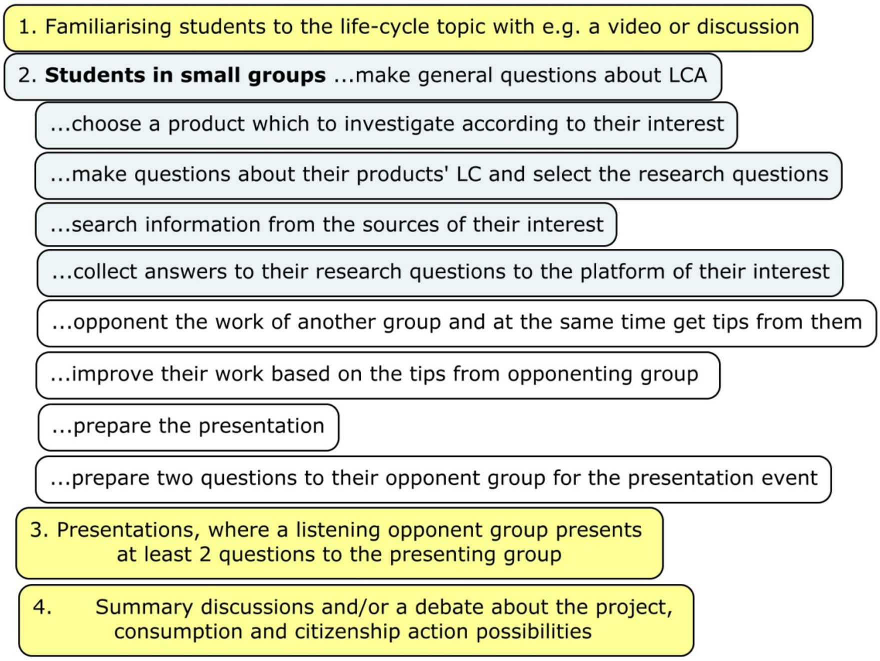

Figure 3. The structure of the consensus concept 2 of LCA-IBL project work

CONCLUSION

The inclusion of life-cycle thinking into chemistry education using inquiry-based learning is a new approach. Thus, the design framework here is developed during cyclic design research (see App. 1 and Edelson, 2002). The design framework evolves during the design process. It is launched via an in-service training course, where chemistry teachers develop novel LCA-IBL teaching for their own needs. The cyclic design process has similarities with participatory action research (see 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 schools' practices together with the teachers (Cohen, Manion, & Morrison, 2007, 297-317). When the teachers need support, the researcher attends the lessons or offers guidance by phone or e-mail.

The framework for the course was developed at the beginning of the design research and it evolved based on the needs of the teachers. The teachers preferred in-service training courses lasting no more than 1–2 days. Their commitment caused minor challenges, because there were teachers, who were too busy to hand in their mental concepts for LCA-IBL teaching. The course was still a functional entity with its key elements: discussion, collaborative tasks and theme lectures.

This study revealed that chemistry teachers could apply LCA-IBL at all school levels and use variable approaches. The social, project-based concept was the most preferred concept. This is in line with the good experiences with concept use in schools, as it affected the students' chemistry attitudes and environmental literacy positively (see Juntunen, & Aksela, in press). More research is needed about the effects of the less common concepts e.g. drama or learning diaries on students.

The teachers' concepts for teaching LCA using IBL involve variable learning materials, topics and ways of working, including pair or small group work. This is similar to the other socio-scientific teaching concepts in chemistry developed and described by Marks and Eilks (2009) and Mandler et al. (2012). The level of the complexity of these LCA-IBL concepts can be varied (see also Kolstø, 2001). Depending on the skill level of the students and the time available, the teacher can meaningfully adjusts the difficulty level of the LCA-IBL education (see Colburn, 2000). An open-ended, social project places great demands on the students, if they only have previous experiences of guided instructions in their chemistry lessons. The designed teaching concepts emphasize cooperative open-ended information search by the students, critical discussion and presentation of the findings. The challenge is to encourage teachers to use more opponent review, debates, drama, learning diaries and study visits. These approaches could support another important aspect of LCA – ethical decision-making ability. It seems that the decision-making aspect is not yet part of the teachers' teaching about LCA. The students can also design new and better products more often, as one of the teachers let them do. If there are contradictory aspects or improvements needed in the life-cycle of a product, the students can discuss them and suggest the needed action (see Dondi, 2011; Fensham, 2004; Kolstø, 2001). Studying chemistry becomes more relevant to the students when they feel that the scientific dimensions of the topic are important part of the issue and thus close to their personal lives (Van Aalsvoort, 2004; Yager et al., 2006).

All of the topics the teachers chose to use in their concept development task are relevant, contradictory and related to the students' daily lives. In this study, the smaller socio-scientific issues within LCA were e.g. water footprint, resource scarcity, and the use of different types of materials. Similar approaches to chemistry teaching are previously developed about plastics (see Burmeister, & Eilks, 2012) and water (Mandler et al. 2012). By using relevant and contradictory socio-scientific topics and issues in chemistry teaching, it is possible to foster student views on science-based issues and how they reflect the moral, social and physical world around them (Zeidler et al., 2005; Wilmes, & Howarth, 2009). As Marks and Eilks (2009) point out, provoking open discussion and supporting individual decision making processes during chemistry lesson relates on the most practical level to different consumer products.

The teachers focus their evaluation more on the student research process and life-cycle related discussions than on factual chemistry knowledge. Similar outcomes are described in the study by Oulton et al. (2004). The practical concept for evaluating learning outcomes in socio-scientific teaching, suitable for the LCA-IBL consensus concept, is suggested for example by Holbrook (2005). Socio-scientific issues, like LCA-IBL concepts, involve different levels of complexity and develop different kinds of competence in learning science (Kolstø, 2001). The key learning objectives in the social, open-ended, inquiry-based concept are the multiple skills – 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 formative evaluation of the student by the teacher.

More efficient inclusion of LCA-IBL is possible in chemistry education. The study shows that teachers integrate the LCA-IBL concepts easily into the Finnish chemistry education at all levels. As the approach is new, and the LCA is one of the key objectives in Finnish National Chemistry Curriculum (Board of Education, 2003; 2004), but the textbooks currently lack LCA-IBL topics (Juntunen, 2011, 44–46), some actions are needed. These actions could involve including the LCA-IBL methods into chemistry teacher education, as well as into the in-service training courses (Kärnä et al., 2012; Ralle & Eilks, 2002). While learning the novel approach, the teachers or teacher students could themselves produce new teaching concepts, which could be disseminated for use by other chemistry teachers. The innovation of this study, the consensus concept, has already been disseminated to many Finnish schools and to individual teachers. Still, the diffusion of innovation always takes a certain degree of time (see Rogers, 1995, 5–17)

Additionally, the huge sustainability challenges of the Earth address the need for LCA-IBL in chemistry education (see UNESCO, 2009). The findings imply that LCA education combined with inquiry and social approaches can create opportunities to reach several modern goals in chemistry education (see Juntunen, & Aksela, 2013). The goals are related to sustainability competencies (Tytler, 2012) and include the improvement of the students' socio-scientific reasoning skills (Sadler, 2004), active citizenship (Zeidler et al., 2005), peer collaboration (Keys, & Bryan, 2001) and environmental literacy (Yavez et al., 2009).

More research is needed to investigate the kind of learning outcomes the LCA-IBL approach supports in students. Does it advance students' scientific literacy (Holbrook, 2010) and moral awareness (Zeidler et al., 2005)? Does it empower students to act more responsibly (Roth, 1992)? What other means can be used to promote sustainability in chemistry? The future studies will focus on the variety of other advisable approaches, which chemistry teachers use when teaching about sustainable development.

Acknowledgements
We would like to acknowledge the Research Foundation of the University of Helsinki and the association Maa- ja vesitektiikan tuki ry. for the financial support.

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