Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 29 (2015) 550 – 555

www.elsevier.com/locate/procedia

The 22nd CIRP conference on Life Cycle Engineering

Effective Integration of Life Cycle Engineering in Education

E.J. Oude Luttikhuis[a]*, M.E. Toxopeus[a], E. Lutters[a]*

[a]*University of Twente, Drienerlolaan 5, Enschede 7522 NB, The Netherland*

* Corresponding author. Tel.: +31 53 489 2418; E-mail address: e.j.oudeluttikhuis@utwente.nl

Abstract

In practice, applying life cycle engineering in product design and development requires an integrated approach, because of the many stakeholders and variables (e.g. cost, environmental impact, energy, safety, quality) involved in a complete product life cycle. In educating young engineers, the same integrated approach should be strived for, because a mono disciplinary approach is often less effective. Therefor, direct application of the theory in practical cases is necessary. This paper describes experiences with effective LCE education using the advantages of project-led education. This is illustrated by describing LCE relevant courses and evaluation of graduation assignments including successful integration of LCE elements.

Peer-review under responsibility of the scientific committee of The 22nd CIRP conference on Life Cycle Engineering

Keywords: Life Cycle Engineering; Project-led education; Product development

Introduction

Although it is not the panacea for all ills, Life Cycle Engineering (LCE) can certainly contribute to the development of products in a manner that is more effective as well as more efficient. This is all the more relevant in contexts where the environment of product development becomes increasingly complex and changes at ever-increasing speed. Moreover, multiple disciplines are involved and organizations have to develop products in shorter time-frames taking many aspects into account in order to survive in a competing market.

When applying LCE, the entire life cycle is taken into account, in order to avoid unnecessary iterations in later stages of the development trajectory due to sub-optimization. Such iterations require significant resources while not being instrumental in increasing the efficiency of the product development process. Some reticence, however, is required in using the notion LCE: its focus is often on sustainability, whereas the definition of the concept sustainability in the context of product development is ambiguous, to say the least. Therefore, the term LCE is ambiguous as well. A clear definition is hard to find in literature.

According to the United States Environmental Protection Agency (EPA), life cycle engineering is 'a process to develop specifications to meet a set of performance, cost, and environmental requirements and goals that span the product, system, process, or facility life cycle.'[1] Alternatively, within CIRP, LCE is depicted as: 'engineering activities, which include the application of technological and scientific principles to manufacture products with the goal of protecting the environment, conserving resources, encouraging economic progress, keeping in mind social concerns, and the need for sustainability, while optimizing the product life cycle and minimizing pollution and waste.'[2]. In other words: Life Cycle Engineering is the optimal development of products, whilst minimizing the economic, environmental and social impacts over the entire life cycle of the product.

These definitions give a rather idealistic depiction of the complex reality in industrial practice. As such, they therefore align more with the orderly context of academic educational programmes. Consequently, allowing students to bridge the gap between academia and industry is a significant educational challenge. After all, students have to imbibe knowledge about many different and diverse subjects. Simultaneously, they have to obtain experience in applying this knowledge in a multi-disciplinary and realistic product development environment. To allow for the adequate integration of theory and practice of Life Cycle Engineering, educational programmes need to take into account both a theoretical background and a practical approach.

Peer-review under responsibility of the scientific committee of The 22nd CIRP conference on Life Cycle Engineering

doi:10.1016/j.procir.2015.02.040

This publication aims to demonstrate why teaching LCE is essential and how LCE education is implemented at the University of Twente in the Netherlands. In this, focus is on project-led education as applied in the undergraduate programmes of Mechanical Engineering and Industrial Design Engineering. Also, individual courses related to LCE are discussed. To assess the effectiveness of the educational programmes, the outcomes of LCE related graduation projects are evaluated, as these projects represent the impact of the LCE related projects and courses.

1. Application of LCE in industry

In industry, many initiatives and approaches related to the implementation of LCE are discernable. Nevertheless, an unequivocal, far-reaching and structured methodology is lacking. A variety of methods, tools and techniques have been developed to integrate the economic, environmental and social aspects in product development cycles. Software tools like Simapro [3] and Gabi [4] perform Life Cycle Assessments (LCA) [5]; Life Cycle Costing (LCC) [6] aims at economic impacts, whereas e.g. checklists focus on the social aspects. However, many of these software tools and other approaches are not exploited to their fullest extent in industry. The main reason for this is the sheer fact that their practicability depends on the availability of adequate input on the product under development. Obviously, such information is scarce, incomplete and uncertain in the early phases of development trajectories [7]. Besides, experience with and knowledge of LCA and LCC is required to accurately interpret any results. In many organisations, building and maintaining knowledge and experience in this field is a challenge on its own, especially as concerns the early phases of the development process, where the balance between certitudes and underpinned assumptions can be fragile.

To bypass the difficulties related to lacking information and the limited experience and knowledge, eco-design guidelines are developed. Eco-design guidelines are based on experiences with previous LCAs and give designers guidance on environmental, economic and social impacts. However, as such guidelines are generalisations of several specific product life cycles assessments, there is no guarantee that the results are applicable and valid for all product life cycles. Consequentially, still a certain amount of experience and knowledge are prerequisite to interpret and apply the guidelines to achieve a minimal environmental impact.

Additionally, the environmental impact is certainly not the only factor that has to be taken into account in product development. Unavoidably, this leads to sub-optimisation. This is all the more true, as, for most organizations the economic aspect is the main (yet sometimes privily) driver in decision making. Although it often seems that environmental and economic benefits go hand in hand, in reality it is often easier to find acclaim for cost engineering than for environmental engineering.

For adequate application of LCE in product development, many aspects need to be taken into account simultaneously, considering the entire life cycle - from extraction of raw materials until final disposal. Important is an integrated approach between all disciplines involved in the development of a product in order to align and accomplish the goals efficient and effective.

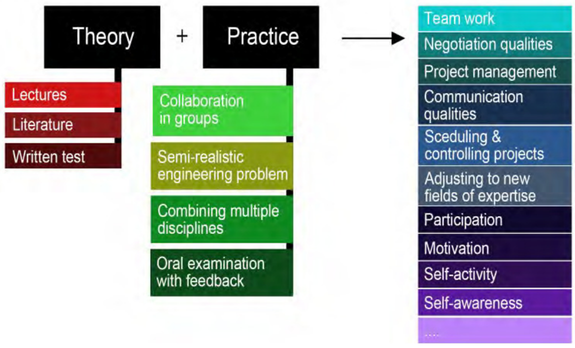

Fig. 1. Elements of project-led education

2. Project-led education

Adequately applying Life Cycle Engineering requires knowledge, experience, collaboration skills, understanding of adjacent disciplines, presentation skills, communication skills, qualities in scheduling and obviously some creativity to come up with new ideas or innovative solutions. Consequentially, coaching young engineers in applying Life Cycle Engineering is a challenge.

The undergraduate programmes for Industrial Design Engineering and Mechanical Engineering at the University of Twente are based on a project-led education system. This educational approach was introduced in 1994 with the aim to integrate e.g. educated theories, methods and techniques in product development by focusing on the direct application of theory in practice. In a more traditional education system, students have to adopt knowledge by listening to a lecturer and studying the literature provided. Sometimes the theory is clarified by definite examples and exercises. Written tests are used to assure that the students acquired sufficient knowledge, often resulting in testing if students can swiftly reproduce the study material. In a project-led education system, focus shifts from the delivery and reproduction of theory to the maturation of the students and their competences as well as on their ability to acquire knowledge and experience [8] (figure 1). In project-led education, separate courses allow students to strengthen their theoretical backbone, while exposing their field of studies from different perspectives.

2.1. Elements of project-led education

Without doubt, the collaboration amongst students is the most important element of project-led education. Any group assignment challenges students to conjointly discuss and process the theory and examples provided or referenced in lectures. Due to this set-up, students are more actively involved in assimilating the study material. Peer discussions, and especially peer-learning, related to how theory should be applied and on how to assess the appropriateness and applicability of the theory in a certain context are very effective in education.

To enable close collaboration, the student teams need to be challenged with a semi-realistic engineering problem instead of with the usual artificial and arithmetical example problems where the regulative equation must be applied to obtain the single correct answer. The assignments in project-led education should be sufficiently complex. This implies that it cannot be solved by an individual student, thus emphasizing again collaboration. Obviously, the problem should not be too complex, but suited to the level of the participating students. Another characteristic of the project assignment is the open result, the absence of just a single correct answer. In fact, the validity of a variety of solutions, generally unknown by the supervisors too, seems to elevate the students to a higher level of understanding of and competence in the theories studied.

This leads to a third important aspect of project-led education, the final examination. Although courses can still apply written exams to assess the proficiency of the individual students in the subject, projects are examined differently. Since projects have no set results, project exams are not aimed at singling out right or wrong answers. Consequently, the focus in project exams is on argumentation and underpinning of relevant decisions made during the development trajectory. Student teams compile e.g. reports, prototypes and presentations to base discussions in the project exam on. Within this approach, academic staff is still able to determine incorrect applications of the theory. By discussing such flaws and by simultaneously exploring the applicability of the solutions provided by a student team, project exams inherently become learning experiences as well.

A final crucial aspect of project-led education is the combination of multiple subjects, courses and even engineering disciplines. This is not only a consequence of the semi-realistic engineering problems that are provided. Moreover, it also introduces the necessity of integrating theories and subjects from the individual courses. In engineering, for example, mathematics never exist on its own; in practice it is always rather applied to solve problems modelled from other disciplines. By applying the principles of project-led education, students are almost implicitly introduced to the complexity of the engineering practice while integrating acquired knowledge from the different disciplines.

2.2. Project-led education in practice

At the faculty of Engineering Technology, students participate in a project in nearly all quartiles of their programme. Each project has its specific focus, expressed by means of the adjacent realistic engineering problem. The teams that belabour a project range in size from 4 to 15 students, depending on the learning goals of the project. A quartile of 10 weeks is composed of a project, combined with lectures on theory and practical tutorials to get acquainted with the relevant techniques. The theory from the lectures can directly be applied in context of the project. In doing this, student teams immediately encounter the obviousness and refractoriness of any theory, implying that they develop a sense for applicability and feasibility. Additionally, students challenge themselves to acquire new theories or skills they consider to be contributive. In this, they obviously also build on the theories and competences acquired from previous projects.

During projects, students also develop and train practical skills like team work and negotiation skills, project management, communication skills as well as scheduling and controlling the project [9]. Over the nearly twenty years that the University of Twente has implemented project-led education, is has become clear that this educational approach encourages participation, motivation, self-activity, self-awareness and teamwork [10]. Students are able to solve problems efficiently and effectively; moreover, they can purposefully orient themselves in different fields of expertise, as they have developed the ability to understand such fields of expertise more quickly and more targeted.

In the graduate programme (MSc.), the acquired basic competences are extended. Although the implementation of the graduate programme is not founded on project-led education, many courses contain elements thereof. Examples include assignments focusing on integrating multiple theories, developing methods and techniques and actual application of several methods and techniques for product development.

3. Courses on LCE-related subjects

The curriculum at the University of Twente (mainly for Mechanical Engineering and Industrial Design Engineering) gives opportunities to study the field of Life Cycle Engineering from a number of different perspectives. This chapter outlines examples of courses that contribute to the mastering of LCE.

3.1. Cradle to Cradle

Cradle to Cradle® * is a course that is infused by the philosophy of Braungart and McDonough [11, 12]. The course is organised in a rather traditional manner. It consists of lectures provided by a team of Cradle to Cradle specialists from the Environmental Protection Encouragement Agency (EPEA Internationale Umweltfoschung GmbH). Based on the book 'Waste = Food' by Braungart and McDonough [11] and additional material, the students focus on a selected product. The students have to redesign the product, while applying the specific elements from the Cradle to Cradle design paradigm. Aspects in this course that contribute to LCE education are:

- Considering material applications and combinations;
- A strong focus on the end of life scenario to keep the materials in their appropriate technical or biological cycles;
- 'Material health' considering the Cradle to Cradle ABC-X classification.

Despite the broadness of these aspects, the sheer structure of the course inclined towards a focus on a single design approach, leaving hardly any opportunity to discuss the

---

* Cradle to Cradle® is a trademark of McDonough Braungart Design Chemistry, LLC

benefits and problems of this approach on product development from a more academic point of view. Additionally, in course evaluations, students addressed the lack of integration with other design aspects like manufacturing, user perception, cost, etc. Students also indicated that the (observed) rigid character of the course may have caused them to avoid follow-up courses on this topic. Nevertheless, some students managed to integrate the Cradle to Cradle design paradigm in their master projects of their graduate programme. In these cases, the students could usually elaborate significantly on the paradigm, provided they were allowed to develop and pursue their own interpretations. Section 4.3 depicts a case study of such a master project.

3.2. Introduction to LCA

Students of Mechanical Engineering are confronted with aspects of LCE in the first year of their bachelor studies. The course 'Introduction to LCA' explains the different steps of an environmental LCA from goal definition to improvement analysis. The course is integrated with an educational project, next to courses on engineering thermodynamics, material science and mathematical modelling in Matlab. Therefore the lectures of the course Introduction to LCA focus mainly on the theory of life cycle assessment and becoming familiar with LCA support software.

In the adjacent project, the students analyse an existing power plant and devise a more sustainable version of this plant. A typical project addresses for example the application of concentrated solar power to supply the Caribbean island of Aruba of both electricity and fresh water. Besides the obvious engineering thermodynamical aspects, the life cycles of the old and the new situation are compared in an LCA using e.g. the ReCiPe midpoint effects [13]. By modelling the old and the new situations, students are also confronted with the 'standard' problems of data acquisition for existing installations and the uncertainties of the envisaged situation. This highlights the importance of sensitivity analysis and puts emphasis on the interpretation of the results of an LCA.

Even though in the project the final conclusion of the comparison is predictable, since the discontinuation of the use of fossil fuels by applying renewable energy sources will result in an important environmental improvement, the achieved awareness of the relations between the thermodynamic principles, the material properties and life cycle assessments illustrates the importance of an integrated approach and taking multiple aspects into account in determining the optimal solution direction.

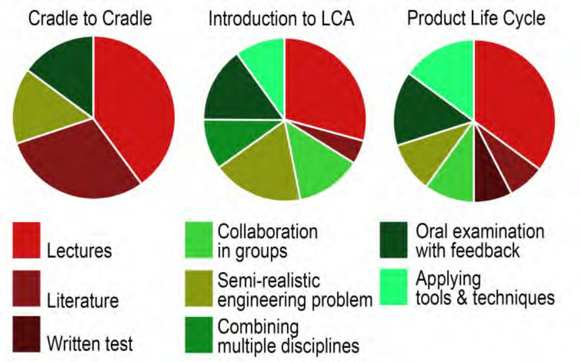

Fig. 2. Contribution of project-led elements in achieving learning objectives

3.3. Product Life Cycle

The vast majority of the graduate students in Industrial Design Engineering take the course 'Product Life Cycle' [14]. Although these students usually did not have explicit prior training in LCA, they did get acquainted with the broad range of different aspects in product development during their undergraduate programme. As mentioned, the students are also trained to familiarise themselves with new fields of expertise. In this graduate course, basic elements of project-led education are employed, addressing the adaptation of theory during lectures and the application in practice in a team assignment. The implicit integration is perhaps not obvious, but nevertheless key to the course. This starts with understanding the theory of LCA and actually modelling a product life cycle to assess the environmental impact. It is elaborated in the main objective of the course: understanding how to apply the general LCA theory on different engineering aspects and to develop an appropriate method to assess the impact of a product on that aspect. An example is the development of an Impact Assessment Method (IAM) for safety [15]. Each year, multiple teams develop an IAM for their selected aspect, ranging from maintenance to employment. The developed IAMs have to be integrated in appropriate support software. Therefore, existing products can be analysed against the developed IAM. During the final evaluation session, the teams assess each other's results, creating awareness on the differences and similarities in developing methods for different aspects.

Although in this course the focus is on a single LCE aspect, similar to the course on Cradle to Cradle, students are stimulated to discuss and review the applicability of LCAs. However in the course, products are not redesigned or developed, but merely assessed. The structure of the course assignment puts a strong emphasis on the total product life cycle and its relation to different engineering aspects, achieving integration of LCE elements.

The three described courses contribute in a different way to an effective LCE education. All courses apply several elements of project-led education. Figure 2 indicates the contribution of the different project-led elements in achieving course learning objectives.

4. Master projects

Every Master project is an individual graduation assignment of circa 9 months. Students combine the knowledge and experience gained from courses and projects to demonstrate that they are individually able to adequately solve a realistic engineering problem in a complex environment. The project content is aligned by the student, the mentor from the educational programme and the organisation that provides the engineering problem. The majority of the students work on their project in an industrial organisation in order to gain experience with the practicalities of product development and to ensure that the outcome of the project is not too elusive. Since many organizations encounter difficulties in addressing sustainability in development trajectories (or in other words, to adequately apply life cycle engineering), many projects are related to this. The inherent challenge of such projects is the fact that students have to deal with intricate business structures. Consequently, they often have to act at the transition area between different departments instead of within one department.

4.1. Integrating LCE in packaging development

The project addressed the development of a more sustainable packaging for a large organization in the fast moving consumer goods market. The company also aimed at the expansion of their knowledge about the integration of sustainability tools into development trajectories. The basis for this was a stage gate model; the company also considered adaptations of their software tool regarding assessing the environmental impact. The existing software tool within the organization was an Excel sheet, containing outdated data on carbon footprints of several processes. As is more often the case, it turned out that the student had more experience and knowledge about sustainability and life cycle engineering than had been formally established by the company's employees. A number of commercial LCA tools were evaluated, based on the usefulness and reliability of the results, the required knowledge and experience necessary to apply the tool and the feasibility of implementation in the product development process of the corresponding organization. Within this master project, LCAs of the packaging that had been selected for optimisation were executed using different LCA tools [16]. In parallel, a consumer perception research project aimed to investigate the consumer's perception of sustainability for both graphical and structural designs. Both research projects were used to develop a packaging with a lower environmental impact and a more sustainable appearance. Retrospectively, an evaluation of the feasibility of the new packaging concepts was done by a commercial packaging development expert.

4.2. Integrating end-of-life guidelines for conceptual design

A second example of effective integration of LCE in a product developing process is a case of a large consumer electronics manufacturer [17]. Here, the master student acted as an intermediary between disposal companies and the product developers. By acting on the boundaries between these two rather dissimilar types of stakeholders, the student could increase the mutual understanding between the companies involved. As a result, expert knowledge from daily practice in waste treatment could be embedded into a practicable decision support system for the product developers. With this system, the developers were supported in relating design decisions to the disposal phase at an early stage of the development process. The main added value of this system was that the support could be realized without relying on material data that usually is not available before the end of the conceptual design phase.

4.3. Developing Cradle to Cradle compliant packaging

The project was defined in co-operation with Van Houtum, a paper mill producing tissue paper. Although the company had already several Cradle to Cradle certified products in their portfolio, there was a need for a compliant packaging for their top-end toilet paper in the cash and carry market [18]. In the project, theoretical knowledge on Cradle to Cradle with experiences from industry were integrated. This resulted not only in a new packaging design, but also in a method for developing Cradle to Cradle compliant packaging. Even though packaging development was not a core business, the topic was considered important enough to start the research project.

During this assignment, information on the Cradle to Cradle design paradigm, already studied in the corresponding course, was integrated into a method for packaging development. Next to the obvious elements from the Cradle to Cradle design paradigm, other important issues - ranging from production process to management tools - were integrated as well. This integration is visible in the underlying structure of the method. The method consists of three distinct layers: one for the packaging development itself, one for the required material research and one dedicated to all activities involving external parties. The method is developed for use in manufacturing companies that do not have a dedicated packaging development department. It can be either used for in-house packaging development or as a management tool to create design briefs and to supervise the progress if the packaging development is outsourced.

The packaging concept that has been developed in the project surpassed the requirements that made it Cradle to Cradle compliant. Moreover, an easily adjustable concept was developed in order to align the final product definition with manufacturing requirements.

4.4. Evaluation graduation assignments

The three master projects introduced in the previous sections are distinctive as concerns the way in which students have developed the ability to familiarize themselves with addressing Life Cycle Engineering in a purposeful and integrated manner. From these (and many other graduation projects), it is clear that the competences and knowledge that was obtained from the different projects and courses during both the undergraduate and graduate programme are useful in integrating LCE in product development in industry. Many graduation projects show that students can decisively cross the boundary between academia and industry by simultaneously addressing both perspectives – often implicitly and unknowingly. From a broad evaluation of many graduation projects, a set of preconditions is compiled that evidently allow students to adequately integrate LCE in product development. Examples of relevant competences include:

- Understanding the theory of LCA, including application, report requirements, knowledge about IAMs and experiences in using LCA software.

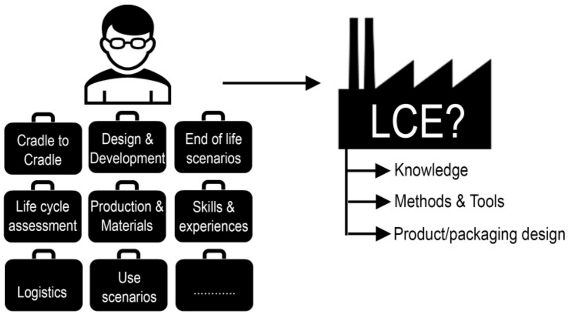

Fig. 3. Successful integration of LCE in practice

- Considering products in their entire life cycle including the possible (consequences of) end-of-life scenarios.
- Understanding relevant LCE specific design paradigms and guidelines like Cradle to Cradle in order to evaluate its applicability and integrate the theory adequately within the organisation.
- Understanding other disciplines and the quality to communicate with different fields of expertise, prerequisite in product design and development and of utmost importance in integrating LCE in daily practice, since acting at the transition area between different departments is necessary in LCE.
- The ability to obtain and translate expert knowledge from industry practice into appropriate and univocal tools and methods that match the requirements of the target group.
- Adequately adjusting to new fields of expertise, which is useful in integrating important (and new) aspects in the development trajectory, depending on e.g. the strategy of the organisation and the type of product.

5. Concluding remarks

Essential in applying LCE in developing products is taking into account multiple aspects like cost, environmental impact and the social impact over the entire product life cycle. Effective application of LCE in industry is lacking, partly due to the complex reality in industrial practice and limited relevant knowledge and experience.

Preparing students for adequately functioning in this environment is a challenge, since both a theoretical background and experience are required for effective integration of LCE in practice.

The project-led education approach introduced in 1994, proved to be successful in integrating theory into practice. Project-led education includes group assignments on realistic engineering problems to apply the theory obtained from lectures and literature directly to practice. This results in relevant competences in product development like communication skills, negotiation skills, scheduling and controlling projects and adequately adjusting to new fields of expertise.

As can be concluded from evaluating master theses and reviews by industry, competences obtained from both project-led education and LCE related courses enables students to successful integrate LCE aspects and cross the boundaries between academia and industry.

References

[1] Smith Cooper, J., Vigon, B., Life Cycle Engineering Guidelines. November 2001. Access date 7 november 2014, available from http://nepis.epa.gov/

[2] Jeswiet, J., Szekeres, A. Definitions of critical nomenclature in environmental discussion. In Proceedings of the 21st CIRP Conference on Life Cycle Engineering, Lien, T.K.(ed), Trondheim, 2014, p14-18

[3] Simapro 7.23 LCA software; PRé Consultants b.v., Amersfoort, The Netherlands; 2012

[4] Gabi 6 LCA software-System and Databases for lifecycle Engineering. PE International AG, Stuttgart, Echterdingen, Germany, 2014

[5] Wenzel H, Hauschild M, Alting, L: Environmental Assessment of Products, Volume 1 methodology, tools and case studies in product development. London, Chapman & Hill, first edition, 1997

[6] Norris, G.A., Integrating life cycle cost analysis and LCA. In International Journal of Life Cycle Assessment, Vol 6, 2001, 2: 118-120

[7] Lange J, Oude Luttikhuis E, Klooster R, Lutters E. Towards Integrating Sustainability in the Development of Product/Packaging Combinations. In: CIRP Design Conference, Abramovici, M. and Stark, R. (ed.), 11-13 March 2013, Bochum (D) p. 855-864, ISBN:978-3-642-30816-1.

[8] Ponsen, Hans J.M., and Kees C.T.A. Ruijter. 2002. "Project oriented education: learning by doing". In Proceedings of the first CIRP International Manufacturing Education Conference, edited by Hubert J.J. Kals, 135 - 144. Enschede, The Netherlands: University of Twente.

[9] Oude Luttikhuis, E.J., de Lange, J., ten Klooster, R., Lutters, E., Project-led education in packaging development and management. In Proceedings of the 24th CIRP Design Conference, Moroni, G., Tolio T.A.M. (ed), 14-16 April 2014, Milano

[10] Dankers W, Schuurman-Hemmer H, van den Boomgaard T, Lutters E. Bringing practice to the theory: project-led education in industrial design engineering; 2nd International Conference for Design Education Researchers 2013. Oslo.

[11] Braungart M, McDonough W. Cradle to cradle, remaking the way we make things. London Vintage 2009

[12] Braungart M, McDonough W. The Upcycle. New York: North Point Press; 2013

[13] Goedkoop M.J, Heijungs R, Huijbregts M., De Schryver A., Struijs J, Van Zelm R. ReCiPe 2008, A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level; First edition Report I: Characterisation; 6 January 2009. Access date 5 November 2014, available from http://www.lcia-recipe.net

[14] Toxopeus, M.E, Lutters, E, Meijer, M, Houten, F, van: Teaching LCA Back to Front, in: Proceedings of the 12th CIRP International Conference on Life Cycle Engineering , Grenoble, France, 2005

[15] Toxopeus M.E., Lutters, E. Developing IAM for life cycle safety assessment. In Proceedings of the 20th CIRP International Conference on Life Cycle Engineering, Heidelberg, Springer, 2013

[16] Lutters, E., Oude Luttikhuis, E.J., Toxopeus, M.E., ten Klooster, R., Appropriateness of life cycle assessments for product/packaging combinations, COMA Conference, 30 January-1 Februari 2013

[17] Peters, H.A.R. Toxopeus, M.E, Jauregui-Becker, J.M, Dirksen M.O. Prioritizing 'Design for recyclability' guidelines, bridging the gap between recyclers and product developers. In Proceedings of the 19th CIRp international conference on life Cycle Engineering, Berkely. Heidelberg, Springer, 2012

[18] Toxopeus M.E, de Koeijer, B.L.A, Meij A: Cradle to Cradle; Effective vision vs efficient practice. Submitted for 22nd CIRP International Conference on Life Cycle Engineering, Sydney, 2014