26TH INTERNATIONAL CONFERENCE ON ENGINEERING AND PRODUCT DESIGN EDUCATION
5-6 SEPTEMBER 2024, ASTON UNIVERSITY, BIRMINGHAM, UNITED KINGDOM

LCA AND DESIGN THINKING: HOW TO INTEGRATE LIFE CYCLE ASSESSMENT IN EARLY-STAGE PRODUCT DEVELOPMENT?

Mário BARROS and Linda Nhu LAURSEN
Aalborg University, Denmark

ABSTRACT
Life Cycle Assessment (LCA) is a comprehensive tool that supports sustainability by assessing products' environmental impacts. It is both analytical and systemic. However, its integration in the early phases of product development remains challenging for industrial designers. How do industrial designers make sense of it? How do you move from LCA into the early stages of design? Particularly, the clash between the analytical, deductive, delimiting, and multi-criteria parameters of LCA with the divergent abductive reasoning of the fuzzy front end of concept development.
In the paper, we present an example of an LCA design course, which was structured to meet the challenge of how to redesign a product. The course serves as an experimental example of integration and conversion from deductive, quantitative, and analytical LCA to an abductive, qualitative, design thinking process of reconceptualisation. In this context, we identify patterns in the disparity across the level of design work. Two approaches, in particular, made a difference: 1) when SWOT factors were categorised according to life cycle stages, circular economy stages and/or circular product design methods, then it qualified the transition to mind mapping, 2) when the mind-map unfolded complexity in 4 or more levels, it enabled deeper insights on factors itself, implementation, relationships and trade-offs to other life stages, specific strategies and circular value propositions. In the case of both, the mind map served as a dynamic tool, used throughout concept development, to bridge the problem/solution space, as well as facilitate framing, rather than pre-stage guiding concept development.

Keywords: Life cycle assessment, product development, pedagogy, industrial design, sustainability

1 INTRODUCTION
Designers must synthesize several types of data when conceptualising a new design. Considerations about usability, materials, production, form, strategic positioning, and other dimensions must drive decision-making into actionable steps in the product development process. Life Cycle Assessment (LCA) is a comprehensive tool that supports sustainability by assessing products' environmental impacts. It is both analytical and systemic. However, its integration in the early phases of product development remains challenging for industrial designers. Particularly, the clash between the analytical nature and multi-criteria parameters of LCA with the divergent abductive reasoning which characterises the fuzzy front end of concept development.
This paper reports the structure and results of a BSc in Industrial Design course where students learn about LCA and use it to develop product concepts. To overcome the identified challenge of LCA usage, the course adapts a framework defined by da Luz et al. [1] and simplifies it into three phases for pedagogical purposes. The goal is that students learn how to use LCA, while understanding patterns in product categories; and how to identify hotspots and creatively act upon them.
In the *first phase*, students select a reference product to perform a LCA in the following categories: home appliances, small appliances or consumer electronics. LCA is used to assess impact categories and identify hotspots that will guide the planning of the second phase. The *second phase* correlates hotspots with new product design. Its development is based on a SWOT analysis of the life cycle stages and mental models of solutions which define new approaches for strategic environmental goals based on the estimation of benefits on the identified hotspots. Finally, the *third phase* concerns the redesign of the product. The results show how students ideated on one or more areas defined in the previous phase, depending on the selected reference products. The reflection and comparison of new solutions against

the reference product supported students in understanding the value of LCA as a support tool that elevates the debate around sustainable product development. The discussions of sustainability became more tangible regarding specific parameters on which to ideate and identified areas that could be addressed by traditional product-focused perspectives or product-service systems perspectives.
The novelty of the research is threefold. First by presenting a pedagogical approach to using LCA in the fuzzy front end of industrial design. Second, by integrating LCA information to guide early-stage decision-making in product development. Lastly, reducing the complexity of LCA usage by identifying hotspots where concept development can focus on tackling environmental impacts across the full life cycle of a product.

2 INTEGRATING LCA WITHIN DESIGN THINKING

Table 1. LCA and Design Thinking

	LCA	**Design(erly) Thinking**
Aim	LCA's main aim and focus is on **quantifying** the potential environmental impacts [2].	The primary focus of design thinking is to create new **qualified** artefacts, that make sense in the context for which they were intended [3].
Problem conception	**Definable system problems** In LCA, defining the goal and scope are critical for modelling the boundaries of the reality conception. Thus, to evaluate the merit of a LCA all choices of the assessment should be clearly defined, including: problem definition, intended applications, study recipients, system boundaries, assigned function, functional unit assigned to quantify the system and inventory data [2]. *"Life Cycle Assessment (LCA) is structured according to ISO14040 standards (ISO 14040, 2006; ISO 14044, 2006) with the objective of assessing the potential environmental impacts of a product, a service, or a system, including all its related activities."* [4]	**Undefinable wicked problems** In designers' conceptions of reality, problems are understood as complex, indeterminate and ill-defined. They are wicked problems in the sense they can never fully be understood, nor defined ([5, 6,7]. *"Design problems are 'indeterminate' and "wicked" because design has no special subject matter of its own apart from what a designer conceives it to be. The subject matter of design is potentially universal in scope because design thinking may be applied to any area of human experience. But in the process of application the designer must discover or invent a particular subject out of the problems and issues of specific circumstances."* [8, p.16]
Mode of reasoning	**Deduction** is described as the logic of necessity. It starts with a set of premises or statements, and then applies logical rules to derive a conclusion. This process ensures that the conclusion is necessarily true, but only if the premises are true [9].	**Abduction** is described as the logic of possibilities. It starts with a set of propositions or qualified guesses, that needs subsequently to be empirically tested to arrive at 'better' propositions. It forms a conclusion from the information that is known [10, 11].
Process	**Defining and delimiting to quantify** According to the standards LCA is conducted through four steps: 1) goal and scope definition, 2) life cycle inventory, 3) life cycle impact assessment and 4) interpretation. All entails systematic definition, delimitation, and quantification of information.	**Framing propositions to qualify** As problems are characterized by incomplete, changing, contradictory and interdependent information, designers tend to abductive reasoning to manage them. Propositions of potential futures are created through framing to be qualified empirically [8].

In the paper, we present an example of an LCA design course which was structured to meet the challenge of how to do a redesign of a product, based on an LCA. The course studied is titled "Strategic Material Choices" for industrial design-engineers. The course covers 5-ECTS on the last semester on the Industrial Design bachelor's program Aalborg University in Denmark based on a Problem-Based Learning (PBL) model. The learning objectives determined that students must develop competencies regarding the sustainability consequences of product materials choices, allowing them to conduct LCA in project scenarios. These sustainability considerations are deemed significant both during concept development, influencing solution direction and strategy, and during product detailing, where specifications for manufacturing, materials and finishing are determined.

We position the course as an experimental example of integration and conversion from deductive analytical LCA to an abductive design thinking process of reconceptualisation. In this context, the course represents a field experiment where we are particularly interested in the transition from LCA, as an analytical, quantitative, and deductive approach, to design thinking as a creative, qualitative and abductive approach. Table 1 summarises the framework used to clarify the aims, problem conception, mode of reasoning and process of both LCA and design thinking.

3 METHODOLOGIES: THE STUDY SETTING

The course spanned over three weeks and included lectures, supervision sessions and two milestones. The course was coordinated by two faculty members with a background in industrial design, and lectures on LCA in week 1 including the first milestone were delivered by two faculty members with a background in environmental management. Students worked in teams of four members to perform the LCA of the reference product during week 1, and then individually. The academic evaluation included the individual submission of a report based on a given template of three summary sheets plus an appendix.

The summary sheets aim at emulating the three main phases of using LCA in early concept development and were mapped onto the three weeks of the course. Each summary sheet template is designed to work as a spread of two A4 pages, serving as a toolkit that synthesise information and support decision-making in the design process (Fig 1). In the educational setting they facilitate comparison of student work and peer learning. The goals and steps described to students are detailed on Table 2.

Figure 1. Example of template of summary sheet 1

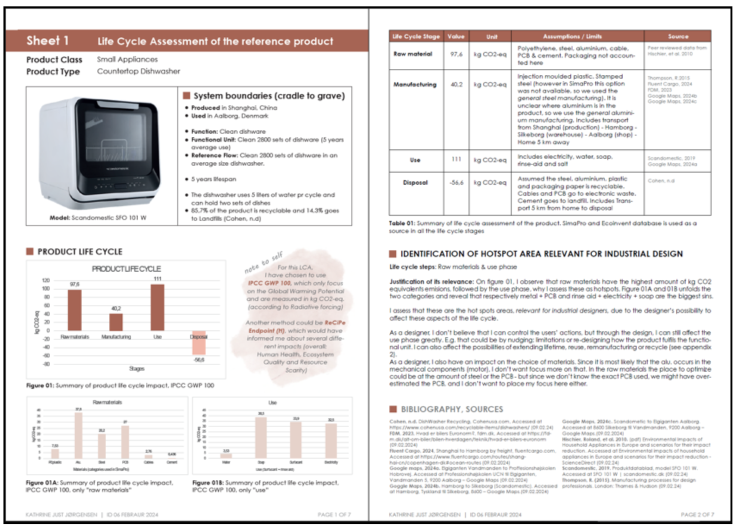

Table 2. Activities and goals of summary sheets

Week	Activity	Goals/Instructions	Information structure of the summary sheets
1	Highlights of the LCA of a reference product	• Summarise the LCA of the reference product to serve as an actionable tool for the design process. • System boundaries: fill in the critical aspects to understand the scope of your analysis. Identify the most significant issues. • Explain the assumptions and limitations behind the values and the sources of information. • Identify the life cycle stages with the highest environmental impact (hotspots). • Understand the systemic relationships in life cycle stages. • Identify potential hotspots for industrial design improvement.	1. <u>Identification</u>: a) Product class; b) Product category. 2. <u>Overview</u>: a) Product image; b) System boundaries. 3. <u>Product Life Cycle</u>: a) Bar chart with product life cycle impact; b) Table with life cycle stage, Value, Unit, Assumptions/Limits, Source. 4. <u>Identification of hotspot relevant for industrial design</u>: a) Life cycle stage;

			b) Justification of its relevance.
2	Correlate the identified hotspots in the previous LCA with new concept design	• Define new approaches for strategic environmental goals. • Define a SWOT (strengths, weaknesses, opportunities, and threats) analysis on the LCA, with a particular focus on the identified hotspot(s). Begin by asking critical questions to the reference product to understand internal and external factors affecting the product. The goal is to analyse the current situation. • Create a mind map of your reasoning in brainstorming potential solutions. The mind map is the visual summary of your brainstorming sessions in envisioning a solution space. The goal is to improve the situation. • Show ideation sketches visualising possible solutions on one or more areas (from the SWOT analysis and mind map)	1. Identification: a) Product class; b) Product category. 2. SWOT: a) SWOT diagram; b) Summary of potential improvement areas. 3. Mind Map: a) Mind Map diagram; b) Brief explanation of the reasoning behind the most promising solutions. 4. Ideation on Configurations and Materials: Annotated sketches. 5. Selection of viable concept reflection: a) Life cycle stage; b) Justification of its relevance.
3	Compare the new proposed solution with the reference product	• After performing an LCA of the concept developed, compare it with the reference product by creating a bar chart showing both the values of your solution and the reference product. The goal is to provide a straightforward illustration of the improvement you propose. • Describe the system boundaries. • Calculate the improvement rate of your solution. Also explain assumptions and limitations behind each value. • Reflect on the overall process of designing with LCA in the forefront of design problems. • Consider the challenges encountered in understanding the systemic dimension of the complete life cycle of a product. Discuss the complexities and insights gained in the process. • Provide recommendations to improve the process (if you had additional time and resources).	1. Identification: a) Product class; b) Product category. 2. Overview: a) Concept rendering; b) System boundaries. 3. Product Life Cycle Comparison: a) Bar chart with reference product and new concept life cycle impact; b) Table with Life Cycle Stage, Value of reference product and new concept, Unit, Improvement rate, Assumptions/Limits. 4. Reflection on the use of LCA in industrial design

4 RESULTS

Students were able to successfully apply LCA and develop concepts of products aiming at improving the identified hotspots whilst reflecting on each step and the overall process. This section unfolds this claim by providing examples taken from positive submissions and reflecting on observed pitfalls.

Regarding the ***summary sheet #1 (LCA of reference product),*** the example illustrated in Figure 1 demonstrates the student's ability to reflect on the metric used in the LCA, by considering that using the ReCiPe method [12] would account for factors beyond just global warming potential. In the identification of relevant hotspots to be addressed by industrial design, the student reflects on potential approaches to raw material selection and nudge of user behaviour to improve the use phase. This transition signifies a shift from deductive reasoning, starting with the identification of hotspots, to breaking down the problem into manageable segments (e.g., nudge user behaviour to minimise resources in the use phase) that can be addressed through new product development. Some students who had multiple potential hotspots, further detailed specific product life cycle stages. An example can be the search for additional granularity of information regarding raw materials to clarify which material or component contributes most to the global warming potential.

Summary sheet #2 supported bridging from analytical approach to abduction. We observed that it was the part of the process that accounted for more disparity across the level of student work. Regarding the SWOT analysis, students were instructed on how to perform it, to map life cycle stages as strong or weak and map external opportunities and threats related specifically to those identified life cycle stages. Students who categorised the SWOT factors onto life cycle stages, circular economy stages and/or circular product design methods [13] had a more proficient transition to mind mapping. In these cases, these categories provided the framework to structure the mind map, thereby facilitating an assessment of trade-offs to select preferable perspectives for concept development. Regarding the mind map, some students stated factors as a one-liner and others who developed further the factors. Students who developed further the factors (unfolding complexity in 4 or more levels) were able to reflect on them, gaining insights on both the factor itself (e.g. reuse water) to its implementation in product development, its relationships to other product life cycle stages, specific strategies and their circular value proposition (e.g. disassembly for repairability vs disassembly for recycling), or other industrial design factors (e.g. envisioning different user scenarios, defining working principles). In such cases, such as the one illustrated in Fig. 2, the mind map served as a dynamic tool used throughout concept development that supported bridging problem and solution space and facilitated framing, rather than merely guiding concept development at a preliminary stage.

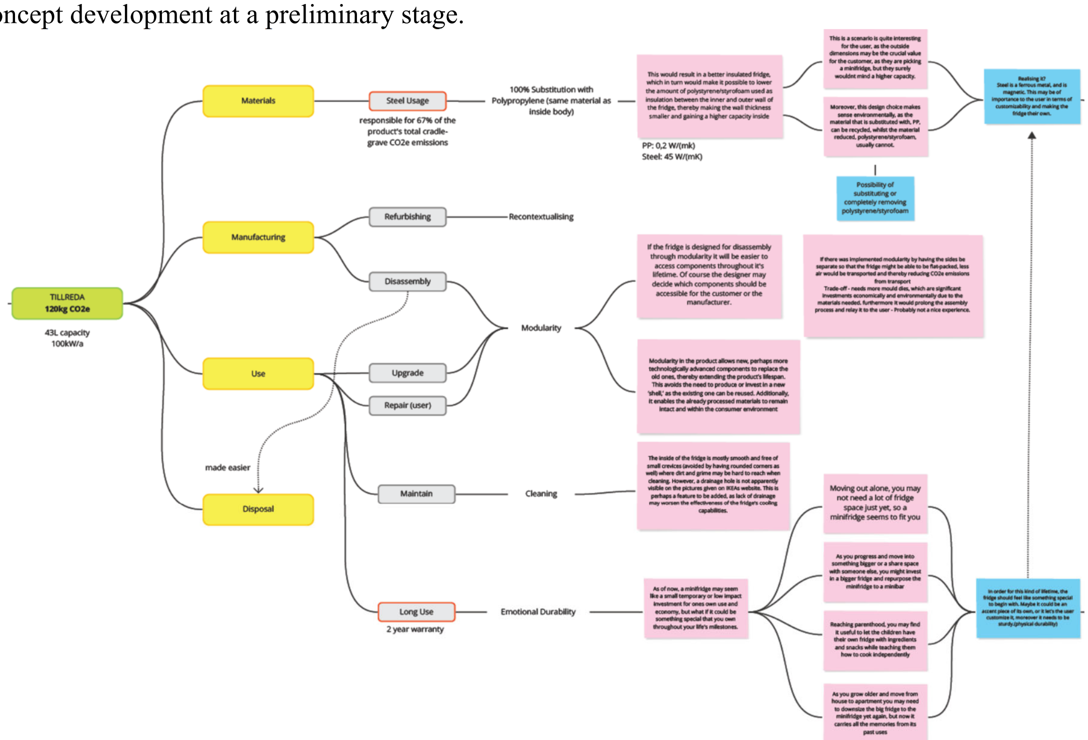

Figure 2. Example of a mind map in summary sheet 2

In the overall reflection on the use of LCA as an important driver for concept development, students' reflections on ***summary sheet #3*** provided insights on the awareness of using LCA as an analytical tool to inform abductive reasoning in design. Students acknowledged that LCA allowed for a focus on hotspots. A few students stated that its use reduces intuition from design as problems and systems complexity (such as number of parameters and interrelationships) are at the forefront of reasoning. Nonetheless, students also reflected on the need for integrating LCA results with other critical factors, including cost, quality, simplicity, or functionality. Furthermore, they reflected on the uncertainties of using approximate data to estimate global warming potential, highlighting the need to critically consider the trade-offs in decision making rather than solely optimising LCA hotspots.

5 DISCUSSIONS

The framework presented in this paper allowed students to use LCA to drive concept development. Most students found the process effective in supporting engagement in both analytical mode and abductive reasoning. Also, they were able to create concepts not only for incremental optimisation of identified hotspots but thinking beyond such a framework of thought. Despite this, some students reported that shifting from deductive reasoning, quantification and systems thinking into designerly thinking is difficult. One student defines this as "a never-ending wicked problem."

Based on evidence from best examples, we recommend improvements to activities in planning and concept development stage (summary sheet #2). The interdependence of the SWOT analysis and the mind map should be higher. Categorising SWOT factors and following those categories in mind

mapping provides better support from deductive to abductive reasoning. Furthermore, mind maps should branch out into at least four levels. As an example, the ***first level*** should identify *product life cycle stages*, the ***second*** could define different *scenarios of improvement based on circular economy stages,* the ***third*** *design methods* (e.g., modularity, disassembly), the ***fourth***, what *working principles* (or product architectures, or functional requirements) could be established. From then on, potential features or concepts that embody the *working principles* can be defined, and user interaction envisioned. To conclude the mind map, the most promising concepts should end with a brief *clarification of trade-offs* that could be connected back to the identified factors on the SWOT analysis and the hotspots to consolidate the decision-making for further development.
Based on the assessments of the reports we conclude that pedagogically, the selection of mid-range products facilitates learning. Students who either selected very cost-effective products or environmental efficient products faced challenges in improvement: the former because of trying to address the same cost, while the latter due to limited relevant criteria to improve hotspots.

6 CONCLUSIONS

This study highlights the potential of methods that facilitate the shift from deductive to abductive reasoning within an existing framework [1] for sustainable product development. This approach may support professional designers in navigating the complex landscape of sustainability by synthesising knowledge as a set of tangible factors. The knowledge generated at the early stages of product development provides practical insights, empowering decision-making at both strategic and product levels. Moreover, it may enable multidisciplinary teams to maintain a nuanced understanding of the dynamic interplay of factors influencing sustainability goals and supports discipline-based developments to be pursued. Ultimately, such proposed methods foster a holistic approach to addressing real-world sustainability challenges within design-driven processes.

REFERENCES

[1] da Luz L.M, de Francisco A.C., Piekarski C.M and Salvador R. Integrating life cycle assessment in the product development process: A methodological approach. *Journal of Cleaner Production*, 2018, 193, pp. 28-42.
[2] van der Giesen C., Cucurachi S., Guinée J., Kramer G. J. and Tukker A. A critical view on the current application of LCA for new technologies and recommendations for improved practice. *Journal of Cleaner Production*, 2020, 259, 120904.
[3] Krippendorff K. *The Semantic Turn–A New Foundation for Design*, 2006 (CRC Press/Taylor and Francis Group, New York).
[4] Pradel M., Aissani L., Villot J., Baudez J. C. and Laforest V. From waste to added value product: towards a paradigm shift in life cycle assessment applied to wastewater sludge–a review. *Journal of Cleaner Production*, 2016, 131, pp. 60-75.
[5] Rittel H. W. J. and Webber M. M. Dilemmas in a General Theory of Planning. *Policy Sciences*, 1973, 4 (2), pp.155–169.
[6] Lawson B. 2006. *How Designers Think–The Design Process Demystified*, 2006 (Architectural Press).
[7] Cross N. *Designerly Ways of Knowing. Designerly Ways of Knowing*, 2006 (Springer, London).
[8] Buchanan R. Wicked Problems in Design Thinking. *Design Issues*, 1992, 8 (2), pp. 5–21.
[9] Laursen L. N. and Tollestrup C. Design thinking-a paradigm. In DS 87-2 proceedings of the 21st International Conference on Engineering Design (ICED 17) vol 2: Design processes, design organisation and management, Vancouver, Canada, August 21–25, 2017 (pp. 229–238).
[10] Peirce C. S. *Pragmatism as the Logic of Abduction. In The Essential Peirce: Selected Philosophical Writings (1893–1913)*, edited by Nathan Houser and Christian Kloesel, Vol.2, pp. 226–241 (Indiana University Press, Bloomington).
[11] Boland R. J. and Collopy F. 2004. Managing as Designing. Stanford: Stanford University Press.
[12] Huijbregts M. A. J, Steinmann Z., Elshout P, Stam G., Verones F., Vieira M., Zijp M., Hollander A. and van Zelm A. ReCiPe2016: a harmonized life cycle impact assessment method at midpoint and endpoint level. *International Journal of LCA*, 2017, 22, pp. 138–147.
[13] den Hollander M. C., Bakker C. A. and Hultink E. J. Product Design in a Circular Economy: Development of a Typology of Key Concepts and Terms. *Journal of Industrial Ecology*, 2017, 21, pp. 517-525.