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LIFE CYCLE MANAGEMENT

The myth of informed decision-making: explaining the substantive effectiveness of LCA use in a building product development project

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Abstract

Purpose This study aims to better understand the substantive effectiveness of life cycle assessment (LCA) in practical settings. While LCA has aspired to inform decision-making for decades, it is clear that many good LCA studies are not followed by tangible reductions in product environmental impacts. This raises the question whether the underlying model of LCA use does justice to the practical reality of decision processes in projects and organisations.

Methods An ethnographic study of a building product development project has been conducted, with a special focus on its use of LCA. Rather than assuming that LCA results lead to more sustainable decisions, actual events have been analysed where LCA influenced the development project over a period of 3 years. The data come from interviews (32), first-hand observations (18 days), and project documentation (> 100 documents), including five LCA studies. The analytic process followed an empirically grounded research approach, leading to a detailed process-based description of LCA use in the development project and an analysis of the substantive effects of each LCA study.

Results and discussion Studying a single case in detail enabled the identification of effects from LCA use that normally remain invisible. The analysis revealed that the use of LCA in the development project deviated from common expectations. Rather than a straightforward causal relationship between a commissioned LCA study and a specific design decision, LCA use followed a complex sequence of events, including a diverse set of LCA studies, activities, and project outcomes. Together, six deviations from the conventional model of LCA use were identified: (1) multiplicity, (2) partial effects, (3) displaced effects, (4) activity-based effects, (5) heterogeneous actors and activities, and (6) a two-way directionality of effects. These effect types have been grouped into knowledge- and activity-based models of LCA use.

Conclusions Viewing LCA use as informed decision-making does injustice to the manifold ways in which LCA leads to substantive effects in the studied development project. Relying solely on the conventional linear model is likely to disappoint as it guides LCA practices toward producing accurate information efficiently, rather than focusing on the substantive actions, events, and mechanisms that reduce product environmental impacts. Recognising these limitations, practitioners are recommended to consider a wider spectrum of effect mechanisms by drawing on the proposed knowledge- and activity-based models of LCA use. Given the importance of reducing product environmental impacts, more research is needed to understand the substantive effects of LCA.

Keywords Life cycle assessment · LCA use · Decision-making · Effectiveness · Substantive effect · Product development · Building · Ethnography

1 Introduction

For decades, LCA has been used recurringly for producing information intended to reduce product environmental impacts. To the disappointment of many, it can be difficult to translate calculated LCA results into real reductions in product environmental impacts (Baumann et al. 2002; Keoleian 1993; Kisch et al. 1992; Peace et al. 2018; Rebitzer and Schäfer 2009; Rex et al. 2020). Although accurate

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environmental information is important, it is not a sufficient condition to change product systems (Boons and Howard-Grenville 2009; Cohen-Rosenthal 2000). To have substantive effects on a product system, an LCA has to influence decisions and actions along the product chain that reduce the environmental burden of resource and energy use.

Substantive effectiveness is demonstrated when LCA use leads to environmentally beneficial changes in a product system. It can be differentiated from the accurate and efficient use of LCA as an assessment method, which by itself does not need to lead to any substantive changes. While symbolic uses of LCA for 'greenwashing' and 'science-washing' may limit the substantive effectiveness of LCA, there is a different issue at stake when sincere LCA applications remain analytic exercises without clear environmental course of action. Tracing back the term to environmental assessment (EA) (Bond and Morrison-Saunders 2013; Sadler 1996), the LCA community has been remarkably silent about the substantive effectiveness of its own practice. From an environmental perspective, it is troublesome that effectiveness is primarily treated in terms of accurate, well-communicated, and efficiently conducted LCA studies (c.f. Hauschild 2018; Martínez-Blanco and Finkbeiner 2018). To increase the tangible environmental benefits of LCA use, we need to give more attention to questions of substantive effectiveness and how it is achieved in LCA.

When attributing substantive effects to LCA, it is tempting to assume that the results of a commissioned LCA study are used to make decisions that reduce the environmental burdens of a product system. This idea underlies popular views on LCA and rational decision-making (c.f. Hertwich et al. 2000; Palazzo et al. 2020; Pryshlakivsky and Searcy 2021) and can be called a linear model of LCA use. Management scholars and a few seasoned LCA practitioners have criticised this conventional view for underestimating the complexity of actual decision processes in industry (Blass and Corbett 2018; Vermeulen 2006), indicating that more comprehensive environmental information does not always help decision makers act effectively (Baitz et al. 2013; Rex et al. 2020). Despite doubts about the validity of a linear model to explain the substantive effects of LCA use, it is difficult to present a better alternative because research on the topic is currently lacking.

As ambitions to use LCA are growing in business and politics (e.g. Freidberg 2015; Lazarevic 2018; Sala et al. 2021; Sonnemann et al. 2018), so is the urgency to better understand the entire spectrum of mechanisms by which LCA use may have substantive effects on product systems. To this purpose, an ethnographic case study was conducted of a building product development project where LCA use played an important role. Product development has traditionally been an area for influencing product environmental impacts (Bakker 1995; Baumann et al. 2002; Bhander et al. 2003; Keoleian 1993; Klöpffer 2003), with building design becoming a rapidly growing subfield of LCA due to the significant life cycle environmental impacts of buildings (Fnais et al. 2022; Roberts et al. 2020). This makes building product development a good context for studying the substantive effectiveness of LCA use.

Following an observation period of 3 years, actual sequences of events were analysed where LCA was used to develop a more environmentally sustainable building product. Two main questions guided this research: (RQ1) Which substantive effects followed the use of LCA in the studied product development project? (RQ2) Can the presence of substantive effects be explained by a conventional linear model of LCA use or do they follow other effect mechanisms? Currently, few studies empirically examine LCA use in practical settings (e.g. Lazarevic and Martin 2018; Niero et al. 2021; Rex et al. 2020) and even fewer rely on an ethnographic research design (Freidberg 2015). Studying a single case over an extended period of time allows for a rigorous empirical examination of the phenomenon (Atkinson 2015; Ragin 1992), enabling the systematic identification of effects from LCA use that would normally remain invisible. This article presents novel insights by using an ethnographic research design to study the substantive effects of LCA use in a practical setting.

2 Background

2.1 The linear model of LCA use as informed decision-making

A conventional way to account for the substantive effects of LCA is that they follow linearly from the results of an LCA study through informed decision-making. According to the linear model, an LCA study is commissioned to produce environmental information for a decision maker to make a decision that changes the environmental performance of a product system (see Fig. 1). According to linear logic, better LCAs should produce better environmental information and thus lead to better decisions. Although rarely explicitly acknowledged, the linear model shapes popular expectations

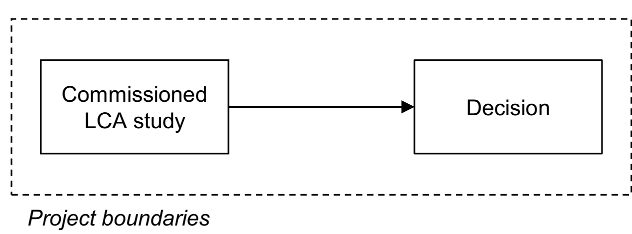

Fig. 1 A schematic depiction of the conventional linear model of LCA use

on LCA and decision-making (c.f. Hauschild et al. 2018; Hertwich et al. 2000; Palazzo et al. 2020; Pryshlakivsky and Searcy 2021) and steers how LCA is planned and carried out in projects and other organisational settings.

The linear model of LCA use is attractive because it reduces a complex chain of substantive effects to a simple rational picture of informed decision-making. Like other linear approaches, it places science and expertise first in a causal chain, leading to technological development (c.f. Godin 2006) and environmental measures (c.f. Beck 2011; Pielke 2005). In doing so, the linear model guides popular perceptions that LCA should efficiently produce credible environmental information that is well communicated to a decision maker. This is reflected in common strategies for improving LCA use by developing methods, tools, data, communication, and the capacity of decision makers to understand LCA results (c.f. Bach and Finkbeiner 2017; Laurin et al. 2016; Sala et al. 2020; Sonnemann et al. 2015; Stucki et al. 2021).

Despite their straightforward theoretical appeal, the conventional idea of LCA use as informed decision-making has been criticised for doing injustice to the complexity of real decision-making processes (c.f. Blass and Corbett 2018; Boons and Howard-Grenville 2009; Niero et al. 2021; Vermeulen 2006). In product development, it is not always possible to await the results of a commissioned study, as the opportunities to make environmentally relevant decisions decrease when a product design matures (Baumann and Tillman 2004; Bhander et al. 2003). Similarly, LCA practitioners have expressed difficulty in balancing credible and useful environmental information (Baitz et al 2013; Freidberg 2015; Rex et al. 2020), indicating that better knowledge is not always desirable for decision makers to act.

Considering these observations, it can be questioned whether the linear model provides a valid explanation of the substantive effects of LCA use in practical settings. Guiding attention to efficient and accurate LCA applications, the linear model risks to promote environmentally ineffective LCA use, while simultaneously misguiding efforts to improve the substantive effectiveness of LCA.

2.2 Understanding LCA use in practical settings

To better understand the substantive effects of LCA use, it is informative to empirically study LCA use with the help of qualitative research methods. Qualitative case studies aim to provide detailed analyses of LCA use that go beyond the practice of sharing expertise and experiences from LCA projects (c.f. Baitz et al. 2013; Hauschild et al. 2018; Sonnemann and Margni 2015). Qualitative studies allow for a deep understanding of empirical phenomena, which differs from quantitative surveys that generalise such phenomena at the population level (c.f. Almeida et al. 2019; Glisovic et al. 2018; Testa et al. 2016).

Earlier qualitative case studies on LCA use have highlighted the importance of personal, organisational, and institutional influences on the adoption of LCA in specific contexts (Bakker 1995; Baumann 1998; Frankl and Rubik 2000; Freidberg 2015; Heiskanen 2000b; Lazarevic and Martin 2018; Poikkimäki 2006; Rex and Baumann 2007; Testa et al. 2017; Testa et al. 2022). With the spread of LCA throughout industry, more attention has been given to the effects of LCA use on individuals and organisations (Coelho and McLaren 2013; Heiskanen 2000a, 2000b; Rex et al. 2020; Testa et al. 2022). Actors are known to have unequal abilities to make use of LCA results to instigate changes in product systems (Baumann et al. 2011; Lazarevic 2018). In recent years, an empirical focus on LCA use has expanded to include corporate life cycle management (Nilsson-Lindén et al. 2018; Poikkimäki 2006), product-chain collaboration (Freidberg 2020; Goldstein and Newell 2020; Nakano and Hirao 2011; Nilsson-Lindén et al. 2019b; Seuring 2011), and sociomaterial networks of consumption and production (Baumann and Lindkvist 2022; Niero et al. 2021; Suski et al. 2024; Walker et al. 2024).

While considerable differences exist between empirical studies of LCA use, they share the insight that LCA knowledge and environmental product changes materialise through the complex actions and organising of different actors. By closely examining LCA use in a practical setting, it becomes possible to look beyond informed decision-making and explain other mechanisms through which LCA has substantive effects on product systems.

2.3 LCA use in a building context

In recent years, building design has become an important area for LCA use. Buildings are composite products whose environmental performance is strongly influenced by the volume of building materials and by operational energy demands during their long use phase (Lasvaux et al. 2017; Röck et al. 2020). Traditionally, environmental work in building design has been strongly connected to energy performance regulations (Economidou et al. 2020; Georg and Justesen 2017) and the use of environmental certification schemes (Schweber 2013; Thomson and El-Haram 2019). Despite the rapid rise in building LCA studies (Fnais et al. 2022; Roberts et al. 2020), little is known about how to use LCA effectively in building processes (Francart et al. 2022).

In practice, buildings are planned, designed, and constructed in individual building projects that enable a closer fit to local market conditions and the physical conditions of a building site (Dubois and Gadde 2002; Winch 2010). The planning phase puts in place initial goals and requirements for a new building. On the basis of these conditions, a rough programmatic building design is created and further refined into a detailed design. Currently, most LCA studies are conducted late in the design process even if it is well known that early project stages are better placed to reduce the environmental impacts of buildings (Hansen et al. 2023; Meex et al. 2018; Roberts et al. 2020; Soust-Verdaguer et al. 2022).

In line with the conventional model, ineffective LCA use is frequently viewed as a technical problem for building LCAs. Ambitions to improve the situation have spurred the development of simplified LCA tools (e.g. Malmqvist et al. 2011; Zabalza Bribián et al. 2009) as well as more advanced modelling techniques using automated coupling with building information models (BIM) (e.g. Hollberg et al. 2020; Najjar et al. 2022) and parametric optimisation techniques (e.g. Kiss and Szalay 2020; Ostermeyer et al. 2013). For now, it remains unclear whether these recent advances in building LCA research have improved the substantive effectiveness of LCA use in building projects.

3 Method

An ethnographic case study was carried out to investigate the effects of LCA use in a building product development project executed by a large Swedish construction company. Building products are standardised designs that have been developed with the intention of being sold to clients throughout the country. A successful building product can be used in more than 100 construction projects. As the studied company wished to remain anonymous, the developed case description uses fictitious names for the product development units and building products involved. From an analytical perspective, the studied building product development project was selected to maximise information gain (c.f. Flyvbjerg 2006). LCA use was a central part of the development project, which at the time represented a best-practice case for building LCA at a construction company at the forefront of the sector.

3.1 Data collection

Data collection for the case study took place between 2016 and 2021 and was structured in three different phases: a pre-study, a development project, and a project follow-up (see Table 1). The pre-study aimed to become familiar with the company and its LCA use. During the development project, data collection focused on LCA use in relation to the development of a building design. Two years after the project ended, key project members were interviewed to reflect on the project outcomes and to identify additional effects from LCA use in the development project.

Following an ethnographic research design (Atkinson 2015), data were collected from first-hand observations (18 days), interviews (32), and project documentation (> 100 documents). In addition, contact with the case company was maintained through phone calls and informal meetings with a research and development coordinator. All data collection was conducted by the first author of this manuscript.

Observational data were gathered from project activities and meetings that were relevant for understanding LCA use in the project and the environmental performance of the building design. Observational data collection benefited from a project requirement to work physically together 2 days a week. At the end of each day, fieldnotes were transcribed into a day report, culminating in 135 pages of documented observations.

Semi-structured interviews were conducted with project members to learn about aspects that could not be observed directly. The interviews covered the planning stage, interaction with strategic management, and events that took place after the project ended. In addition, the interviews allowed project members to share their thoughts on the development project and on specific events related to LCA use. Important project members were interviewed twice, i.e. the internal LCA analyst, project leader, and technical coordinator. The interviews lasted between 45 and 75 min, were recorded, and were transcribed verbatim.

Documentation about the development project and its LCA use was primarily gathered from a digital project platform that was used to structure the design process. In the case study, project documentation was used to complement or triangulate information gained through observations and interviews. Documentations about LCA studies were obtained directly from relevant project members.

3.2 Analytic process

The analytic process followed an empirically grounded research approach (Alvesson and Sköldberg 2009; Atkinson 2015). Given the importance of empirically describing LCA

Table 1 Data collection for the ethnographic case study

	Time	Observations	Interviews	Documentation
Pre-study	2016/06–2017/11	2 days (6 h)	14	10
Development project	2018/11–2019/05	16 days (> 100 h)	12	> 100
Post-project	2021/01–2021/06		6	
Total		*18 days (> 106 h)*	*32*	*> 100*

use before analysing its effects, a two-step analytical process was chosen. A primary analysis of the empirical material was conducted to create a process-based case description of the product development project and the LCA studies that appeared in the project. Following an inductive method, key events were ordered chronologically in different project stages: planning, programme design, detailed design, and post-project. The empirical case account describes in detail how the development project unfolded over time and how LCA was used during this process (c.f. Section 4). With a detailed case description at hand, a secondary analysis was carried out to answer the research questions by (1) zooming in on the substantive effects that each LCA study had on the development project and (2) identifying deviations from a conventional linear model of LCA use (c.f. Section 5). Discussing the outcomes of this qualitative analysis, the identified effect mechanisms were thematically grouped to propose three alternative models for LCA use (c.f. Section 6).

4 The case of LCA use in a building product development project

The case study followed the development of a multifamily residential building product executed by a product-development unit of a large Swedish construction company. Building products are standardised designs that can be used across projects with minimal adjustments to reduce costs and simplify the design and construction process. At the time of the study, a portfolio of four different residential building products existed at the company, developed by two regional building product groups. North Town building products offered a mid-rise rectangular slab block for up to six stories (Slab6) and a more squarish tower block for up to eight stories (Tower8). West Town building products offered a low-rise building product of up to four stories (Slab4) and a matching two-story terraced housing concept (Terrace2). In this context, the manager of the West Town building products unit considered the initiation of a new building product development project.

4.1 LCA use prior to the development project

Historically, the studied construction company was an early adopter of LCA in the Swedish construction sector. During the 2000s, the company was involved in the development of an innovative LCA tool for the assessment of residential buildings. During the early 2010s, the company's LCA focus shifted from residential buildings to infrastructure projects, as the national transport authority started to demand LCA-based climate declarations in its infrastructure projects. In anticipation of a legal mandate requiring LCA-based climate declarations in residential building projects, a renewed interest in building LCA emerged.

In 2016, a newly appointed building-LCA coordinator commissioned a few small LCA studies. The main purpose of these studies was to learn how to perform LCA and to understand the $CO_{2\text{-eq}}$ environmental hotspots associated with a building design. After different LCA software options were reviewed, a building-specific third-party software was selected for future LCA studies. Knowledge exchange was stimulated through an internal building LCA forum and by participating in external university-led research projects on LCA. Furthermore, in a master's thesis, an LCA was conducted comparing the environmental performance of West Town's Slab4 building product and North Town's Tower8 building product (LCA study #1). Importantly, it represented an opportunity for the building product development unit to learn about LCA.

4.2 Planning for a development project

The process of developing a new building product started at the end of 2016. To meet future strengthened legal requirements on building operational energy use, a redesign of the Slab4 building product with thicker insulation sheets was needed. Composed of prefabricated stackable concrete–polystyrene blocks, adding extra insulation material to the building product required additional investments in the supplier's manufacturing facility. Technically limited to four story buildings, the product was ill suited for attractive urban markets with high land prices. The reported sales volume of Slab4 had been declining in recent years, financially straining West Town building products. Environmentally, the extensive use of polystyrene as an insulation material had given rise to internal concerns about the environmental performance of the product. In addition, LCA study #1 concluded that the Slab4 product compared unfavourably to North Town's Tower8. Considering all these factors, the manager of the West Town building-product unit decided to investigate the possibilities for developing a new building product.

A small project team was formed by the manager, including an experienced structural engineer and a project leader. Driven by ambitions to develop a more sustainable building, the project team wanted to explore the possibilities for developing a new wood-based building product. The team visited seminars and tradeshows to learn more about wood-based building techniques. Meanwhile, the unit manager commissioned an internal LCA study to assess the environmental performance of the Slab4 load-bearing outer wall (LCA study #2). With LCA capacity still being under development at the building division, the study was carried out by two experienced LCA analysts from the neighbouring infrastructure division. In LCA study #2, the Slab4 wall system with concrete-polystyrene blocks was compared with different concrete and wood-based alternatives. The results supported earlier findings that the Slab4 building system was not an optimal solution from a GWP perspective. Furthermore, the results of LCA study #2 favoured outer wall types with wooden building components.

However, an unexpected loss in momentum for wood-based buildings occurred after a newly appointed executive favoured a more conservative business approach. Henceforth, perceived problems with wood-based building techniques were emphasised in exchanges with senior management. An internal economic cost estimation revealed that a wooden load-bearing system was more expensive than a concrete load-bearing system. In projects with more than four stories, the thickness of wooden structural components increases substantially, potentially reducing the sellable floor area in urban areas. In addition, wood was perceived to be a risky building material in the company, as improper use had previously led to moisture-induced problems.

With a loss in momentum for wood-based buildings, a new opportunity emerged for LCA use in the development project. The project team abandoned a material-based sustainability agenda and decided instead to frame the project around an LCA-based target for $CO_{2\text{-eq}}$ emissions. Aided by knowledge from LCA studies #1 and #2, the method was deemed to be a material-neutral alternative for thinking about sustainability in the project. This enabled West Town building products to start a development project without resolving the tensions around the choice of load-bearing system in advance. Rather than a retroactive legitimation for a material choice in design, LCA became an active player in the design process. For the first time, in the building division, an LCA-based sustainability goal was placed on equal footing with typical economic cost goals in a product development project.

4.3 Organising and formalising the development project

Before the development project began, project management expanded the project team into a larger project organisation consisting of a product design team, a strategic steering group with senior management representatives from the company, and a reference group with representatives from local building units. The product design team consisted of a four-person product development team, a fourteen-person technical design team, and a two-person LCA team.

Over the course of 9 months, the design team was to take the project from rough programmatic sketches to a detailed design that could be sold to local building units. During this period, the project design team met physically every week to work together for a full day on the project. Further collaboration was stimulated by physical colocation another day a week as well as by the use of a digital project work platform. The steering group and reference group provided strategic guidance on key project decisions and were consulted by project management monthly. The involvement of regional building divisions in the reference group was anticipated by project management to improve future sales of the building product.

LCA studies were commissioned for the programme and detailed design stages, with a twofold goal. First, the LCA team was expected to contribute with environmental knowledge to improve the building product's environmental performance. Second, the LCA team had to assess whether the developed building design fulfilled the project's sustainability goal. Prior LCA studies had given project management a rough understanding of the variations in $CO_{2\text{-eq}}$ emissions among different building systems. On the basis of this knowledge but without specifying a technical benchmark for comparison, project management expected that a 30% reduction in $CO_{2\text{-eq}}$ could be achieved in the project.

4.4 Programme design stage

The design stage began with a 2-day event to introduce the development project to the design team. During the event, the environmental sustainability goal of a 30% reduction in $CO_{2\text{-eq}}$ emissions was introduced, together with economic goals to reduce the expected design and construction costs. Framing the sustainability goal as a single indicator metric was accepted without question as it fitted common industry practice. Its quantification as a 30% reduction was open to adjustment during the programme design stage. To a project team that was unfamiliar with LCA, the single indicator sustainability goal quickly became known as the 'LCA goal'.

To improve the understanding of LCA in the design team, the LCA analyst gave a presentation about LCA and building environmental impacts. The presentation drew heavily from an external research paper of a state-of-the-art building LCA study (LCA study #3), for which the company had provided part of the inventory data. This LCA study compared the $CO_{2\text{-eq}}$ emissions of a particular building with those of six different building systems with concrete, steel, and wooden building materials. The presentation highlighted the importance of the load-bearing system and concrete use for a building's environmental performance. Potential sustainability improvements in the building design included the choice of load-bearing system, cement content in concrete, choice of suppliers, product life-span, renewable fuels for transport, installation of solar PV, and reductions in energy use on site.

Environmental design improvements were considered while determining the exact scope for the commissioned LCA study during the programme design stage. Suggestions were made by project management, technical engineers, and the LCA team to expand the scope of the LCA and environmental design work to fit their own perspectives. Driven by the sustainability ambitions of the project team and possible marketing purposes, more ambitious $CO_{2\text{-eq}}$ targets were considered. The expansive phase came to its apex when considering whether the building design should include a solar photovoltaic system and whether the resulting feed-in of surplus electricity to the grid could still be reasonably assessed by the LCA team within the development project.

Gradually, tensions between innovative ambitions and routine design practices emerged in discussions between the LCA team and project management. The commissioned LCA and building design followed a process of narrowing the scope and emphasising uncertainty avoidance. From a construction perspective, environmental targets beyond a 30% $CO_{2\text{-eq}}$ reduction were disliked, as they would require too radical changes in production methods. Furthermore, any environmental improvements in the design should not burden actors downstream in the product life cycle. Consequently, the environmental performance of a project should not be subject to methodological interpretations of the LCA results. Here, an interest in predictability aligned project management with the LCA team and to 'guarantee the results' became a project mantra.

The dominance of structural engineering in the design process and of the load-bearing system for building environmental performance guided the focus of the development project. First, the choice of load-bearing system was narrowed down to three concrete-based options and a cross-laminated wooden option. After consultation with the reference and steering groups, two concrete-based alternatives remained: a filigree slab and a fully prefabricated slab. The chosen load-bearing systems presented the technical alternatives that the regional building divisions had the most experience with, aligning with a company strategy to focus on existing strengths. To improve the environmental performance of the building design, structural engineers aimed to reduce the amount of concrete in the building design by reducing the thickness of the load-bearing system.

During this time, project management and the LCA team continued to discuss how to measure and monitor the building design against the sustainability goal. Ultimately, the technical scope of the programme design LCA was limited to the upstream product modules for the load-bearing system, with the detailed design LCA also including the upstream modules for the climate shell and inner walls. It was a scope the engineers felt comfortable with. Despite a prolonged negotiation process, the initial 30% goal was maintained. The project team agreed on using the company standard technical solutions as a benchmark for the LCA studies. As a side effect of a narrow goal and scoping, those parts of the building design that were excluded from the assessment effectively became environmentally unimportant to the design team.

4.5 LCA deliverable of the programme design

A formal LCA deliverable was planned at the end of the programme design stage, only a week after the LCA team and project management agreed on the goal and scope of the study. With limited time to compose a life cycle inventory (LCI), the LCA analyst opted to make a rough 'shoebox model' of the building by multiplying the area of each building element with information on width and material composition. The LCI was restricted to core materials of the load-bearing system, roof, and non-load-bearing inner and outer walls, thereby excluding, for example, building foundations, windows and doors, façade materials, construction processes, and operational energy use. Three or four alternatives were considered for each building element. While an online LCA software was available, the analyst found it more convenient to perform the LCI calculations in Excel. The environmental data were restricted to $CO_{2\text{-eq}}$ emissions of basic building materials. Emission data for different concrete mixtures were obtained from the structural engineer and existed in the company prior to the development project. Other environmental data were gathered by the LCA analyst from EPD data and generic data from the LCA software database.

The analyst proceeded to construct different scenarios for LCA #4. The new building design was assessed by comparing the company standard technical solution (Scenario A) to the slimmed load-bearing system adopted in the development project (B) and to the possible use of climate-improved concrete in the load-bearing system (C–D) (see Table 2). To account for data gaps, the analyst adjusted the scenario results using data derived from the external LCA study (LCA study #3).

The results of LCA #4 were communicated in a four-page section of the general programme design report. In line with the sustainability goal, the LCA results were presented as improvements relative to the standard technical solution (Scenario A). Absolute values were omitted from the report because of the basic nature of the LCI model. In fact, the LCA analyst also omitted several technical alternatives for which $CO_{2\text{-eq}}$ emissions were calculated. The report briefly explained methodological choices, interpreted the results, and provided suggestions for improving building design and reducing environmental impacts. The document concluded that the suggested design improvement (scenario B) was insufficient to reach the 30% goal, even if climate-improved concrete mixes were used (scenarios C and D). More reductions had to be found in the detailed design stage to reach the 30% goal.

Table 2 Results for programme design and detailed design LCAs according to different scenarios

Scenario	Programme design results (LCA study #4) Reduction in $CO_{2\text{-eq}}$ emissions (A1–3)	Detailed design results (LCA study #5) Reduction in $CO_{2\text{-eq}}$ emissions (A1–3)
A. Base scenario standard solution	0%	0%
B. Slimmer concrete slabs, partially slimmer load-bearing walls, and balcony slabs	~ 10%	~ 8%
C. Climate improved concrete cast- on-site (+ case B)	~ 16%	~ 13%
D. Climate improved concrete cast-on-site and prefab (+ case B)	~ 18%	~ 14%

4.6 Detailed design stage

During the detailed design stage, many project resources were spent to control the secondary effects of the reduced concrete load-bearing system on other parts of the building design. The use of 20% slimmer concrete slabs required heating pipes to be mounted on the walls instead of being poured into the concrete slabs, influencing the available furnishing space of the apartments. Furthermore, a 10% reduction in load-bearing walls led to negative secondary effects on acoustic quality and to some apartments becoming slightly too large to qualify for a potential governmental investment support. In the end, a building design was developed with half of the load-bearing walls slimmed by 10% and the other half remaining as usual.

Owing to these kinds of technical considerations, it has become difficult to create additional environmental improvements in the design of the building. It was difficult for the LCA team to contribute on the spot with information on $CO_{2\text{-eq}}$ emissions of design alternatives. It did not help that the reference group and steering group preferred the use of company-approved technical solutions, or that project management steered the project away from downstream environmental improvements. Despite an urgent need to consider more environmental design improvements, the opportunities to influence the design diminished as the project matured. Somewhat disillusioned, the LCA team shifted its focus towards producing the LCA report for the detailed design deliverable.

Importantly, not all environmental considerations in the development project were connected to LCA and the sustainability goal. For example, operational energy use was seen as a regulatory question and had its own method for calculation. Similarly, trade-offs between building shape, climate shell, and operational energy use were discussed in relation to local energy regulations rather than $CO_{2\text{-eq}}$ emissions. Furthermore, the toxicity of the building materials was discussed in relation to a voluntary environmental certification scheme. While these issues have clear significance for building environmental impacts, they were not discussed in relation to LCA concerns, nor did they influence the project's sustainability goal. In practice, the design team continuously mixed life cycle thinking with other environmental considerations to feed their reasoning, not reflecting on the differences between the underlying environmental instruments.

4.7 LCA deliverable of the detailed design

At the end of the detailed design stage, a second LCA study was completed to assess the chosen design solutions. The LCA analyst spent most of the time waiting for the finalised design to be finished, leaving little time to produce the LCA deliverable to the project team. To make the LCI, the LCA team dropped ambitions to use a BIM model, as its material properties were not sufficiently detailed. Instead, the LCA team used a more detailed material quantification from the economic cost estimation of the design.

The LCA analyst cleaned and converted the data before importing them from Excel into the LCA software program. Afterwards, each line in the bill of resources was matched to an adequate EPD or another form of environmental data. Choosing appropriate EPD data remained an issue for the analyst because many suppliers were not known until later in the design process. After completing these tasks, the LCA software automatically complemented the model with generic data to represent information modules not covered by the analyst. It also automatically produced results for impact categories other than GWP.

Afterwards, the analyst exported the LCA results from the LCA software back to Excel to complete the assessment. First, the LCA analyst complemented the results with internal proprietary emission data for nine different concrete mixes used in the building design. Second, the LCA analyst conducted a scenario analysis in which design solutions were compared to the company's standard building solution. With no new sustainability improvements, the LCA analyst calculated the same four scenarios as in the programme design deliverable (see Table 2).

In contrast to the integrated reporting in the programme design stage, a separate LCA report was produced for the detailed design LCA. Both relative improvements in percentages and absolute impact values for GWP for the product phase (A1–A3) were presented. Projected GWP results from later life cycle stages were included in the report but did not influence its main conclusion. Notably, the $CO_{2\text{-eq}}$ reductions achieved during the detailed design stage were smaller than those during the programme design stage (see Table 2), mainly because the slimmed load-bearing walls were only partially integrated into the design.

4.8 After the development project

Two years after the detailed design was finished, there had been no successful sale of the developed design to a building project. Without a client, there was no practical opportunity to develop the detailed design and realise it through construction. The development project thus produced its final deliverable with the detailed design.

Although the building design did not materialise, the design and its LCAs did not disappear. They remained a resource within the building company. Ironically, the technical coordinator found a way to use the LCA results of the concrete base scenario to further a wood-based design agenda in the company. The LCA analyst responded to two information requests about the environmental hotspots of a building for use in a tender process. Learnings from the development project led to the project becoming a test case for designing a building with reduced concrete slabs and load-bearing inner walls. The technical coordinator believed that these design improvements had become more acceptable in the company.

Key project members also noted that they learned about LCA and the sustainability of building design. The LCA analyst gained LCA competences and used them in subsequent LCA-based building climate declarations. The project leader and technical coordinator considered it positive that wood-based buildings were no longer uncritically viewed as sustainable but needed to be tested with LCA. The unit manager, project leader, and technical coordinator all identified a heightened sensitivity for material quantities in sustainability questions.

5 Analysis

This section presents an explicit analysis of the substantive effectiveness of LCA use based on the case study results. First, the analysis identifies the substantive effects following each LCA study in the studied building product development project. Making use of these instances of substantive effect, the analysis thereafter proceeds to synthesise the most influential effect mechanisms. This enables us to evaluate whether the substantive effectiveness of LCA use in the studied development project can be explained by a conventional linear model of LCA use or if alternative models of LCA use need to be considered. While aiming to remain neutral to the success or failure of the development project, it is worth reminding the reader that the case presents a state-of-the-art LCA use for residential buildings in a Swedish construction company at the time of study.

5.1 Substantive effects of LCA use in the development project

There were five LCA studies and an LCA-based sustainability target in the development project (see Fig. 2). LCA studies #1 and #2 were conducted during the formative planning stage before a formal decision was made to develop a

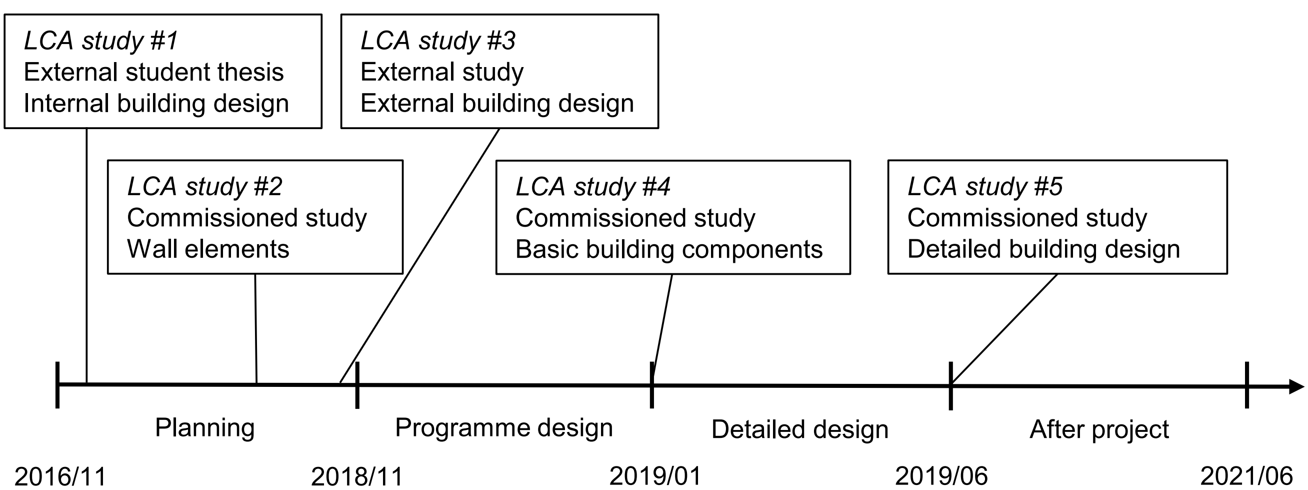

Fig. 2 Five LCA studies used in the studied development project

new product. LCA study #3 consisted of an external research project to which the case company contributed building data. LCA studies #4 and #5 were carried out during the programme and detailed design stages of the project.

5.1.1 LCA study #1

The first LCA study related to the development project was a master's thesis that compared the environmental performance of the Slab4 building product at West Town with that of another building product at the company (LCA study #1). The study was not carried out specifically for the building development project but provided general insights into the current building product (Slab4). This contributed to a growing dissatisfaction at West Town building products, which would culminate in a decision to develop a new building product. LCA study #1 also contributed to learning about LCA and the idea of setting an LCA-based project target.

Despite being influential, LCA study #1 deviated from a conventional linear model of LCA use, as it was conducted outside the boundaries of the development project. Being commissioned and conducted elsewhere in the company, a direct causal connection could not be established between LCA study #1 and the development project. Instead, the effects of LCA study #1 were indirect, mediated through learning about LCA and a growing dissatisfaction with the existing building product at West Town building products (see Fig. 3).

5.1.2 LCA study #2

The second LCA study was commissioned by the West Town product-development unit to better understand the environmental performance of their products in relation to upcoming legal requirements for energy use. LCA study #2 compared the outer wall of the Slab4 building system with other concrete and wood-based alternatives. It was conducted during the formative planning phase of the project by an internal LCA consultant from the infrastructure division. The study concluded that the Slab4 concrete-polystyrene outer wall was not an optimal solution from a GWP perspective, especially compared with wood-based alternatives.

LCA study # 2 aligned partially with a linear model of effect (see Fig. 4). The LCA results were used by the project manager in deciding to develop a new building product rather than investing in an upgrade of the existing Slab4 product. Importantly, the evidence shares the decision space with other legal, technical, economic, environmental, and managerial considerations. Furthermore, LCA study #2 provided evidence to support wood-based building products. The evidence aligned with the personal ambitions of the initial project team and legitimised a focus on wood-based building techniques during the early planning phase of the project. While an interest in wood-based building remained visible in the project—e.g. two external acoustic consultants were hired in anticipation of handling acoustic questions in wooden designs—the project ultimately went for a concrete-based load-bearing system that fitted the cost-estimation and the preferences of the steering and reference groups. Hence, the results of LCA study #2 did not fully materialise in the development project.

Additionally, LCA study #2 contributed to indirect learning effects within the development project. Learning about LCA allowed project management to set a material-neutral $CO_{2\text{-eq}}$ sustainability goal in the project, even if the 30% reduction could not be attributed directly to LCA study #2. The outcomes of LCA study #2 were first transformed into learning about LCA by the project team, after which they led to a sustainability goal that differed from the results of LCA study #2. Rather than a direct linear casual effect on the sustainability goal, the effects are mediated through a learning process.

5.1.3 LCA study #3

A third LCA study used in the project was an external research paper published just before the design phase had started. LCA study #3 compared the $CO_{2\text{-eq}}$ emissions of a building design with those of six different building systems with concrete, steel, and wooden building materials.

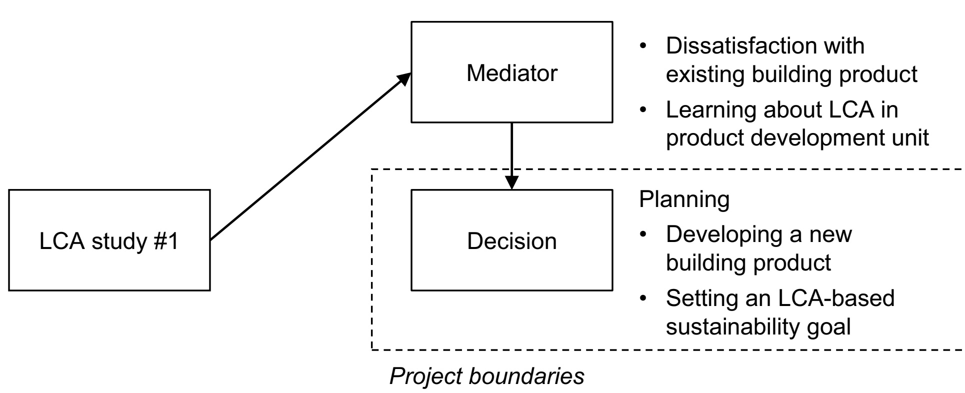

Fig. 3 Visualising the effects of LCA study #1: displaced effects and learning

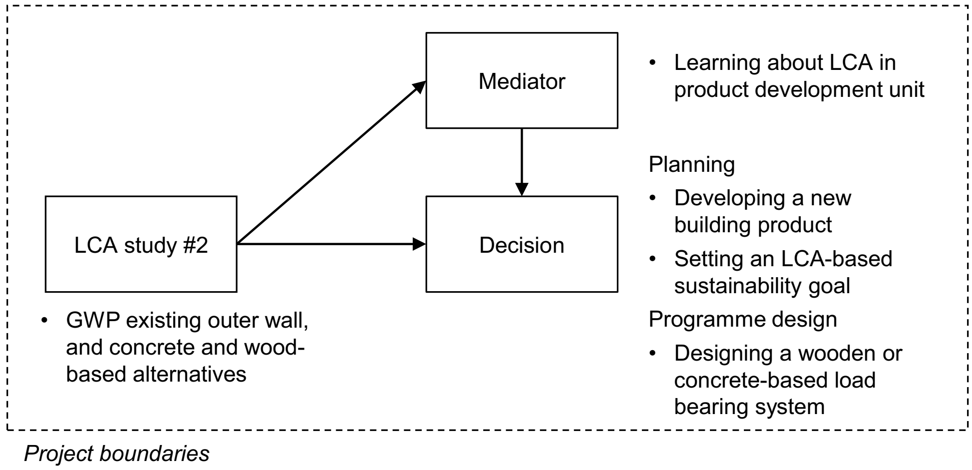

Fig. 4 Visualising the effects of LCA study #2: linear effects and learning

Although the study was not commissioned by the development project, LCA study #3 was very influential as a source of environmental improvements to the building design.

Early in the programme design stage, LCA study #3 was used by the LCA analyst in a presentation that introduced LCA to the design team and highlighted the importance of the load-bearing system for the environmental performance of the building. Additionally, the report featured several sustainability improvements that were communicated to the design team. Not all sustainability improvements were derived from LCA study #3 alone, as the senior structural engineer and company concrete expert played key roles in developing a slimmed load-bearing system and suggesting alternative concrete mixes. Finally, LCA study #3 was used as methodological guidance by the LCA analyst in conducting LCA study #4 and handling data gaps in the LCI.

Despite its importance for the development project, LCA study #3 deviated from the other studies, as it was conducted outside the boundaries of the development project and the building company. As there was no direct relationship between LCA study #3 and the development project, its influence on the project did not follow a linear model of effect. The influence of LCA #3 was displaced and travelled across organisational boundaries (Fig. 5).

5.1.4 LCA study #4

The fourth LCA study consisted of a formal project deliverable and was carried out by the LCA analyst during the programme design stage. LCA study #4 assessed the GWP benefits that could be achieved in the designed building by adopting a slimmer load-bearing system and by using different concrete mixes for cast-on-site and prefab-concrete elements. The report also suggested design improvements that could be considered during the detailed design stage to reduce the environmental impacts of the building.

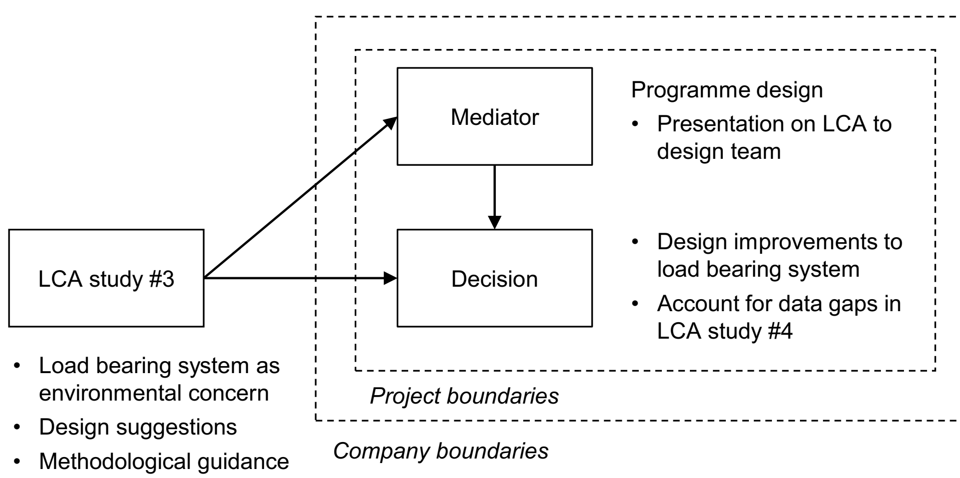

Fig. 5 Visualising the effects of LCA study #3: displaced effects and learning

Theoretically, LCA study #4 should have been the most influential LCA in the development project. Commissioned and carried out within the boundaries of the development project, the linear model of effect suggests that the LCA study would inform decision-making in the project. Furthermore, as LCA study #4 was carried out during the early design stage, it would be easier to make environmental improvements in the building design.

In reality, the outcomes of LCA study #4 did not influence decisions in the programme design stage, as the results were available only after the programme design had been completed. In the development project, a slimmed concrete load-bearing system was developed before LCA study #4 evaluated its environmental impact. Hence, rather than guiding building design, the outcomes of LCA study #4 retroactively confirmed the design decisions already made. This is a reversal of the causal relation described in the linear model of effect (see Fig. 6). Furthermore, while LCA study #4 identified additional design improvements, these results were not followed up in the detailed design stage.

Instead, LCA study #4 influenced the project in another way: through the activities involved in the process of carrying out the study. For example, to obtain inventory data for concrete materials, the LCA analyst interacted with a concrete expert in the company. From this interaction, the LCA analyst gained support for the idea that alternative concrete mixes could be a design improvement, which was subsequently shared with the design team. Rather than following the outcome of LCA study #4, changes in the building design could be traced back to the activities involved in carrying out LCA and other project work.

Activity-based effects were influential in the development project. By carrying out LCA work, members of the LCA team interacted with other members of the project team in a series of meetings, informal conversations, written communications, and joint project work. Through these interactions, a goal and scope and life cycle inventory were produced for LCA study #4 as well as a goal and scope for the development project. Additionally, these interactions produced a building design containing a range of digital drawings, cost estimations, and environmental improvements such as a slimmed load-bearing system and attention to concrete mixtures. These effects emerged from the interactions and led to a two-way relationship where LCA activities and design activities influenced each other in the work process (see Fig. 6).

5.1.5 LCA study #5

The final LCA study was another project deliverable and was carried out by the LCA analyst during the detailed design stage. As no new design improvements were realised in the detailed design stage, LCA study #5 assessed the same scenarios developed in LCA study #4. The results of LCA study #5 confirmed the design decisions made earlier in the development project, revealing a reversal of the cause−effect relation similar to those in LCA study #4. However, compared with the programme stage, less importance could be attached to the activity-based effects of LCA work during the detailed design stage.

Instead, the effects of LCA study #5 took place mainly after the development project ended. For example, evidence produced in LCA study #5 was requested for use in a tender procedure in another project. Similarly, the assessment results were used as a concrete baseline to support a wood-based agenda in the company (see Fig. 7). Learning effects included a greater sensitivity to describing material quantities in building design and a potential for using LCA in sales and purchasing. Perhaps most importantly, the results of LCA study #5 supported the acceptance of a slimmed load-bearing system as a design option at the company.

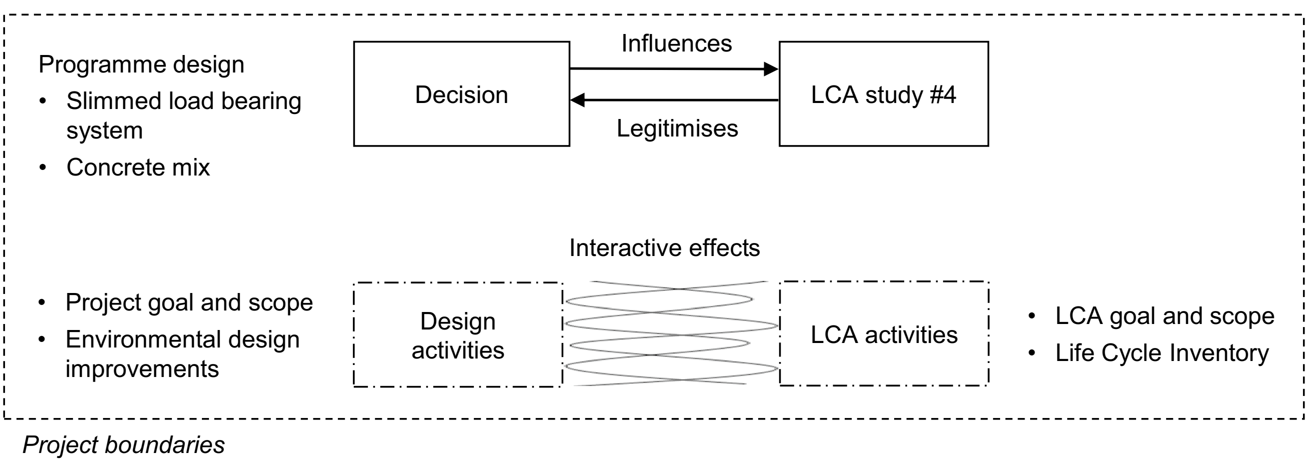

Fig. 6 Visualising the effects of LCA study #4: retroactive legitimation (top) and interactive effects (bottom)

5.2 Deviations from the conventional model of LCA use

Thus far, the analysis highlighted the ways in which LCA studies have made a difference in the development project. This section synthesises the most influential effect mechanisms that deviate from the conventional linear model of LCA use.

5.2.1 Multiplicity

Rather than straightforwardly commissioning an LCA for a specific decision, LCA use was a complex process in which multiple LCA studies coexisted. The case revealed five relevant LCA studies relating to a range of different decisions in the project (see Fig. 2). Only three of the five LCA studies were commissioned by the development project. The studies differed in their technical scopes, building types, LCI details, and involved different analysts and software packages. The results from these LCA studies were typically not aligned with specific decisions but were used more dispersedly across project processes. The project team used results from LCA studies even if the goal and scope were not fitted specifically to the decision at hand. In these cases, there was no direct relationship between a commissioned LCA study and the decision. Being competent practitioners, the project team took a pragmatic approach and accepted knowledge from multiple LCA studies that were imperfectly aligned with project decisions as legitimate form of LCA use.

5.2.2 Partial effects

While LCA was given a central place in the project, LCA results were not the only form of environmental information used in decision-making. In the development project, the LCA results were used together with information from building environmental certification schemes, operational energy calculations, and other environmental practices. An internal dynamic between these different kinds of environmental knowledge emerged in the project, allowing only for a partial effect of the LCA result on environmental design improvements. The internal dynamics resulting from these different types of environmental information complicated LCA-based decision-making in a setting that already had its own architectural, engineering, and management practices.

5.2.3 Displaced effects

Conventionally, it is expected that an LCA study is commissioned to inform decision-making within project boundaries. However, in the development project, LCA results were frequently used outside the project context from which they originated. Many project decisions were based on LCA studies conducted elsewhere, before and outside the development project. The case analysis showed that displaced effects took place across organisational and temporal boundaries in relation to LCA studies #1, #3, and #5. While the presence of displaced effects may appear trivial, it has important repercussions for LCA use. It is hardly necessary for organisations to commission an LCA study in each building project to determine that slimmer concrete slabs and 'green concrete' are environmental design improvements. Similar substantive effects can be achieved more economically by learning from existing LCA studies. This opens space for companies and practitioners to reconsider the organisation of LCA work.

5.2.4 Activity-based effects

The linear model of LCA use focuses on knowledge as a lever for change through informed decision-making. This knowledge-based view on change does not align with the lack of influence that the results from LCA studies #4 and #5 had in the design phase of the development project. Instead, of informing decision-making in the project,

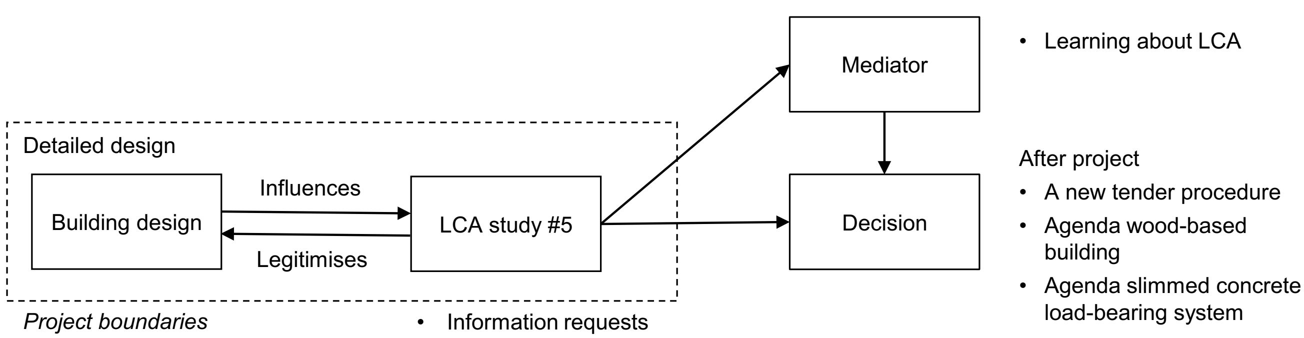

Fig. 7 Visualisation effects LCA study #5: retroactive legitimation (left), displaced effects and learning (right)

these LCA results merely confirmed design choices already made. In contrast to conventional expectations, many environmental design improvements could be traced back to the activities involved in conducting LCAs and not to the outcomes from these studies. Notably, setting a goal and scope and data collection were important LCA activities for the project, leading to substantive effects on the building design.

5.2.5 Heterogeneous actors and activities

Once the leap has been taken to accept LCA activities as a source of change, it is a small step to recognise the importance of a wider range of actors and activities. In addition to the LCA team and key decision makers, the case study showed that routine engineering activities, professional norms, regulatory requirements, and material properties acted as important sources of change in the project. Substantive effects emerged in the project from the interactions between heterogeneous actors. By acknowledging the relations between different actors and activities, it is possible to go beyond a narrow focus on an LCA study and decision-making to consider the effects of more diverse and dispersed networks of life cycle practices.

5.2.6 Two-way directionality of effects

Finally, the conventional model of LCA use expects substantive effects to follow linearly from the communication of LCA results to an informed decision. The substantive effects related to LCA use in the development project deviated from a linear causal model because the LCA team and other project members influenced each other through their daily activities. Given that these interactions were a source of change, the LCA activities and other project activities ended up shaping each other. A two-way directionality of effects explains why practical LCA use did not strictly follow the ISO standard, but was also shaped by a mixture of other professional practices and norms present in the project and organisation. With building design and life cycle assessment being tied together through interactions in the project, they change the course of each other. This interactive process became especially visible when project management tied up ambitions for a predictable building construction phase, with the goal and scope for LCA studies #4 and #5, and the adoption of a slimmed load-bearing system for the building design. Accepting a two-way directionality of effects has important implications for understanding LCA use as well as the substantive effects it may generate. The only way to use LCA to change a product design in practice is by accepting that other relevant actors end up changing how an LCA is carried out.

6 Discussion

An ethnographic case study of a building product development project has been presented to gain a deeper understanding of the substantive effectiveness of LCA use in a practical setting. The empirical material was analysed to identify which substantive effects followed LCA use in the studied development project (RQ1) and evaluate whether these effects can be explained by a conventional linear model of LCA use (RQ2).

6.1 Substantive effects of LCA use

The use of LCA in the studied development project led to several substantive effects. Compared with an internal reference product, the developed product design reduced the expected GWP emissions by 8–14%. These reductions were achieved mainly by slimming the concrete load bearing system and prescribing improved concrete mixtures. Other substantive effects from LCA use could be identified only after the development project had finished. The use of LCA in the development project contributed to a better understanding of LCA as a material neutral assessment tool and a better grasp of quantifying material usage in projects. Ironically, the LCA results of the final building design were used to demonstrate the benefits of slimmed concrete structures as well as articulating the need for wood-based building techniques in the organisation.

The results show that substantive effects are varied in nature and cannot be limited to a single decision or a reduction in environmental impacts alone. The substantive effects of LCA include many small changes in product design as well as project practices. They involve learning about LCA, having an active LCA-based project goal, and other intermediary steps. In short, substantive effects from LCA use emerged from a complicated sequence of events, relating to products, practices, people, and organisations, with the intention of reducing product environmental impacts. These findings are vital for better understanding LCA use in a decision context (c.f. Hertwich et al. 2000; Pryshlakivsky and Searcy 2021) and give credit to the complexity of real decision-making processes (c.f. Blass and Corbett 2018; Boons and Howard-Grenville 2009; Niero et al. 2021; Vermeulen 2006).

6.2 Limitations of a linear model of LCA use

Until now, it has been common in the LCA community to assume that the results of a commissioned LCA study are used to inform decision-making. We have described this way of thinking as the conventional linear model of LCA use, expressing doubts about its ability to explain how substantive effects actually occur. In particular, the varied and sequential nature of substantive effects makes it difficult to believe that such complex mechanisms can be adequately captured through a linear model of informed decision-making.

The case study highlighted the practical difficulties in applying the conventional linear model of LCA to realise basic environmental improvements in product design. Although the project organised its LCA work according to the conventional linear model, the case analysis established that this approach was rarely effective. The two LCA studies commissioned for the design phase were completed too late for their outcomes to inform a decision process, reflecting a classic design paradox (Baumann and Tillman 2004; Bhander et al. 2003). Only one instance was found where the effects of LCA use followed a linear model: LCA study #2 was commissioned for the planning stage and used in the decision to develop a new building product. In all other cases, key environmental improvements in the product design were traced back to the results from an external LCA study, everyday activities involved in carrying out the LCA studies, and other forms of environmental knowledge. In turn, important substantive effects from LCA use took place only after the project had ended, elsewhere in the organisation.

Far from a direct linear relationship between a commissioned LCA study and a specific design decision, LCA use in the development project followed a complex sequence of events including a diverse set of LCA studies and activities. Relying solely on a conventional linear model of LCA use yields false expectations about the contributions of LCA in projects and other organisational settings. It steers LCA practices toward producing accurate information efficiently, even in situations where this is not particularly useful for companies (c.f. Baitz et al. 2013; Freidberg 2015; Rex et al. 2020).

In total, six mechanisms were identified that deviate from a linear model of LCA use as informed decision-making: (1) multiplicity, (2) partial effects, (3) displaced effects, (4) activity-based effects, (5) heterogeneous actors, and (6) a two-way directionality of effects. These mechanisms allow to explain more complex cause-effect paths observed in LCA use in a practical setting and contrast strongly with the naïve image of rationally informed decision-making in the conventional linear model.

6.3 Alternative knowledge- and activity-based models of LCA use

To provide LCA researchers and practitioners with alternatives to the linear model of LCA use, three new knowledge- and activity-based models are proposed (see Fig. 8). These models articulate different ways of achieving substantive effects and can be used to guide LCA use in projects and other organisational settings.

First, a complex knowledge-based model extends the conventional linear model by recognising the importance of (1) *multiplicity*, (2) *partial effects*, and (3) *displaced effects* for LCA use in practical settings. Maintaining the premise that LCA knowledge is used to inform decision-making, the model challenges practitioners to actively consider the usefulness of LCA results in projects and other organisations (c.f. Baitz et al. 2013; Freidberg 2015; Rex et al. 2020). A complex knowledge-based model guides practitioners to pragmatically use LCA knowledge across project, organisational, and temporal boundaries, while accepting the value of other types of environmental information. It guides LCA practitioners to take strategic perspective on knowledge needs, by reusing and learning from existing LCA studies and other sources of environmental knowledge and by conducting new LCA studies only when and where they contribute to meeting knowledge needs and achieving substantive effects.

A complex knowledge-based model involves a strategic use of LCA, which requires practitioners to pay more attention to learning processes (e.g. Baumann 1998; Heiskanen 2000b) and how to organise LCA to achieve such gains (e.g. Bianchi et al. 2022; Nilsson-Lindén et al. 2018). This is especially relevant in a building context, where LCA practices tend to mimic the project-based organisation of design and construction projects and where there is a strong historical precedence of using other sources of environmental information (c.f. Francart et al. 2022; Georg and Justesen 2017; Gluch and Räisänen 2012; Schweber 2013; Thomson and El-Haram 2019).

Second, a linear activity-based model of LCA use articulates (4) *the effects of activities involved in conducting LCA studies*. Challenging the idea that substantive effects come from decision situations, the model suggests that substantive effectiveness can be increased if the activities of carrying out an LCA study are considered as sources of change instead. Because LCA-related activities tend to become invisible after an LCA report has been published, it is easy to undervalue their potential as a source of change. This points to a need for more process-based studies on LCA use (c.f. Lazarevic and Martin 2018; Rex et al. 2020; Testa et al. 2022). The linear activity-based model of LCA use guides practitioners to look closer at the process of carrying out LCA studies, recognising that activities such as data collection, and discussing a goal and scope can be important sources of change.

The role of activities in LCA use can be traced back to a distinction between the LCA procedure and the LCA model (Baumann 1998). In a building context, it is recognised that LCA should be introduced early in the building design process to be effective (Hansen et al. 2023; Meex et al. 2018;

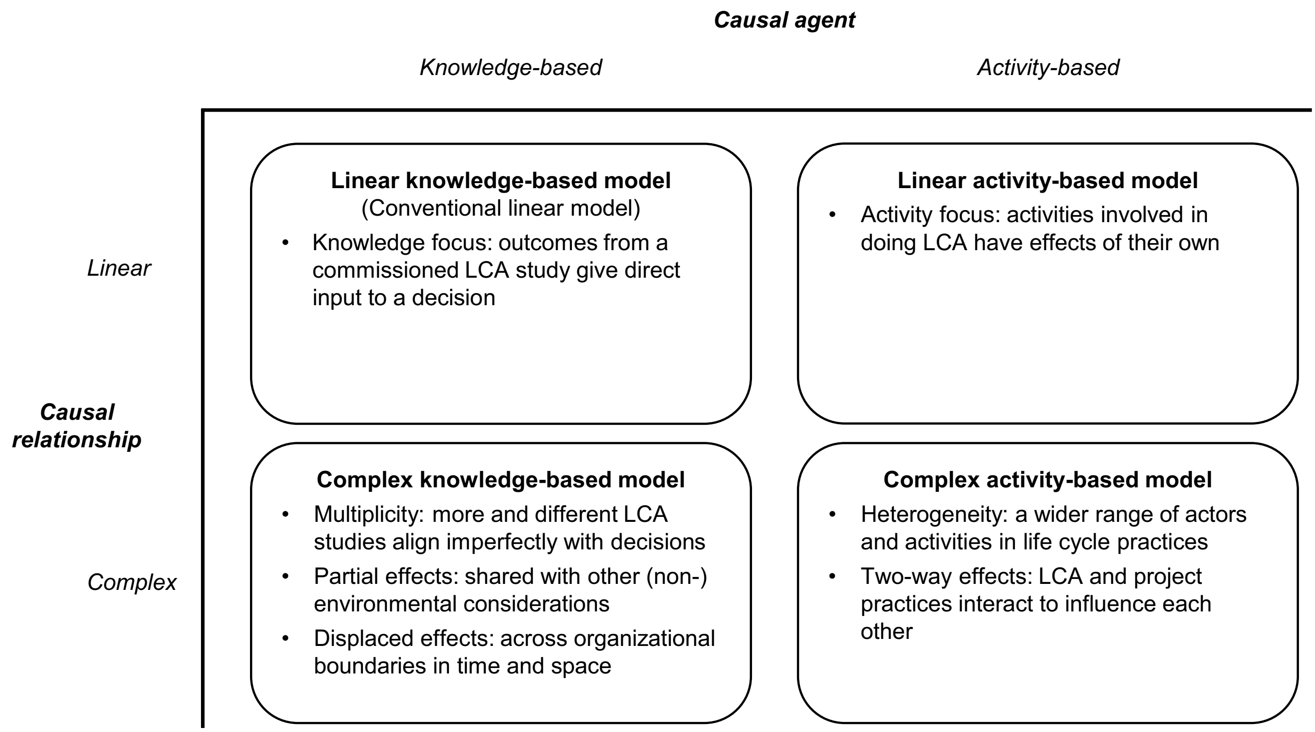

Fig. 8 Four models of LCA use based on different effect mechanisms

Roberts et al. 2020; Soust-Verdaguer et al. 2022). A linear activity-based model of LCA use suggests that early involvement is especially beneficial when practitioners do not wait for the results of a commissioned LCA study to be completed but actively engage in the process of conducting an LCA.

Finally, a complex activity-based model articulates the widest set of effect mechanisms, extending beyond LCA results and activities to include the effects from (5) *heterogeneous actors and activities* and (6) *a two-way directionality of effects*. A complex activity-based model challenges the immediate focus on LCA as the primary method for reducing product environmental impacts. It guides practitioners to look beyond LCA use and consider how substantive effects can emerge from wider networks of environmentally relevant actors and practices. This can be accomplished by reconsidering the relations between LCA and other relevant life cycle practices in companies (Nilsson-Lindén et al. 2018; Poikkimäki 2006), product-chains (Freidberg 2020; Goldstein and Newell 2019; Nakano and Hirao 2011), and sociomaterial networks of consumption and production (Baumann and Lindkvist 2022; Niero et al. 2021; Suski et al. 2024; Walker et al. 2024).

In product development, the interaction between environmental specialists and product developers has been considered an important source of environmental design improvements (Bakker 1995; Poikkimäki 2006). A complex activity-based model suggests that these creative interactions do not need to be limited to LCA and eco-design activities inside the project but can be extended to influences from outside the confines the organisation. Subsequently, LCA practitioners find that their own tools and concepts change as they are situationally adapted to different activities (Heiskanen 2002; Nilsson-Lindén et al. 2019a).

6.4 Research outlook

This study employed a novel ethnographic research design to empirically examine LCA use in a building product development project. The importance of recognising the empirical setting of practical LCA use has been acknowledged previously (e.g. Baitz et al. 2013; Baumann et al. 2002; Freidberg 2015; Heiskanen 2002; Lazarevic and Martin 2018; Niero et al. 2021; Nilsson-Lindén et al. 2021; Rex et al. 2020; Testa et al. 2022) but remains to be better understood. To our knowledge, this article presents the first empirically informed analysis of the substantive effects of LCA use. By conducting a qualitative case study, it became possible to discern the manifold ways in which LCA use led to substantive effects in the development project. The ethnographic research design added empirical depth, enabling for the generation of analytical concepts used in theory building (c.f. Alvesson and Sköldberg 2009; Atkinson 2015).

The empirical descriptions of LCA use are situated in the specific conditions in which the case study was conducted. LCA was made to be part of the development projecting a way that made sense to the involved actors, drawing on a particular set of LCA skills and uses available to the company at the time of study. For this reason, qualitative case studies of LCA use can look different if they are carried out in different settings. Our shared understanding of the substantive effectiveness of LCA use would benefit from similar studies being conducted in other companies, sectors, and use contexts. Such studies can contribute more empirical descriptions of LCA use that help identify additional effect mechanisms and advance the proposed knowledge- and activity-based models of LCA use.

In particular, we recognise a development where LCA is more frequently being mandated by governing authorities (Jegen 2024; Sala et al. 2021). For example, LCA-based climate declarations have become mandatory for new building projects in several countries, with legally enforced emission ceilings anticipated to follow soon (Boverket 2023). These legal requirements greatly reduce the freedom of companies to plan and carry out LCA activities and deserve more attention in future research. In particular, the substantive effects of mandatory LCA use need to be better understood.

Finally, there is a large literature promoting the development of advanced assessment tools to support decision-making, eco-design, and different forms of product and technology development (Laurin et al. 2016, Parolin et al. 2024, Rossi et al. 2016). In building, recent innovations in computational LCA aim for a more interactive real-time environmental assessment (c.f. Hansen et al. 2023; Hollberg et al. 2020). While these are promising developments, the substantive effectiveness of such tools remains poorly studied. The findings of this study suggest that the potential effectiveness of LCA tools may depend on their ability to support a range of different practices and decision processes. More detailed empirical studies are recommended, to differentiate between the rapid assessment of environmental impacts and the actual substantive effectiveness of using advanced assessment tools in projects and other organisational settings.

7 Conclusions

This article presents insights from an ethnographic study on LCA use in a building product development project. To better understand the substantive effectiveness of LCA, this study examined whether a conventional linear model of LCA use as informed decision-making actually explained the tangible effects of LCA use in a practical setting. Following a detailed empirical study of the development project, actual instances were analysed where LCA was used to create a more environmentally sustainable building product.

The research findings made visible a wide range of substantive effects from LCA use, relating to minute and substantial changes in product design, practices, people, and organisations, with the intention to reduce product environmental impacts. Contrary to popular expectations, most substantive effects of LCA use did not follow a linear model of informed decision-making but instead resulted from a complex sequence of events in the project. While the analysis was limited to a single case study, it could be clearly shown that substantive effects go beyond any specific decision moment. On the basis of six identified deviations from the conventional linear model, this research proposed three alternative knowledge- and activity-based models to guide LCA use in practical settings.

These findings have clear implications, compelling researchers and practitioners to reconsider the near mythical status of informed decision-making for explaining the substantive effects of LCA use. Relying solely on a conventional linear model of LCA use is likely to disappoint as it guides LCA practitioners toward producing accurate information efficiently, disregarding whether this is the most effective way to reduce product environmental impacts. To effectively reduce product environmental impacts, it is recommended for practitioners to start using the proposed knowledge- and activity-based models of LCA use in order to complement the conventional linear model. These novel models support LCA practitioners in actively considering the process of conducting LCAs as a source of change, as well as organising LCA in a way that makes best use of existing forms of environmental and LCA knowledge available to organisations.

In the LCA research community, it has been a common strategy to remedy a perceived lack of substantive effectiveness by focussing on the environmental credibility and intelligibility of LCA knowledge. This article has shown that such efforts are essentially based on a misguided linear model of LCA use as informed decision-making, doing little to address the concrete actions, events, and mechanisms by which product environmental impacts are actually reduced. To our knowledge, no other studies have empirically examined the substantive effects of LCA use in a practical setting. Given the importance of reducing product environmental impacts in addressing climate change and other pressing environmental problems, it is recommended that more research is conducted examining the substantive effectiveness of LCA use.

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Data availability The authors confirm that the data supporting the findings of this study are available within the article. Additionally, restrictions apply to the empirical field data from observations, interviews, and other documents, which were used under licence for the current study, and so are not publicly available.

Declarations

Competing interests The authors declare no competing interests.

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