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Citation for the original published paper (version of record):

Somerset, E., Lancz, K., Baumann, H. et al (2025). Transparent or hidden choices: Exploring perceptions and practices of LCA in building projects. Building and Environment, 285. http://dx.doi.org/10.1016/j.buildenv.2025.113439

Building and Environment 285 (2025) 113439

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Transparent or hidden choices: Exploring perceptions and practices of LCA in building projects

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ARTICLE INFO

Keywords:
Sense-making
Sustainable built environment
Life cycle management
Denmark
Transparency
Choice awareness

ABSTRACT

This study investigates the alignment between methodological considerations and the perceptions of Life Cycle Assessment (LCA) practitioners, and how these factors shape the role of LCA in driving sustainability in the construction sector. Taking a social constructivist approach, the study employs a mixed-methods design, analysing the communication of methodological choices and results in 16 Danish building LCAs, complemented by eight interviews with LCA practitioners. The findings reveal that practitioners struggle to effectively communicate LCA results, particularly balancing the need for transparency with delivering clear, actionable information. In particular, none of the 16 cases adequately communicated their functional unit, system boundary, or impact assessment method, nor did they report impact categories beyond Global Warming Potential (GWP). Moreover, semi-structured interviews with eight LCA practitioners revealed that current LCA practice is focused on complying with legislation and certifications, rather than environmental performance. These findings show that LCA is often reduced to a compliance tool, with a narrow GWP. This limits LCA's potential to foster broader sustainability objectives, as its effectiveness depends on the understanding and use of the method by stakeholders. By linking to Choice Awareness Theory, we argue that practitioners experience an "illusion of choice" which may reduce trust in LCA results. Future research could investigate communication strategies suitable for presenting LCA-results and how validation of LCAs could be enhanced, including who should validate them.

1. Introduction

The construction sector has a pivotal role in accelerating the transition to a sustainable future, as it was estimated to account for approximately 21 % of global greenhouse gas (GHG) emissions in 2019 [1]. According to the IPCC, 50 % of the emissions stem from energy use in residential buildings and around 18 % stems from the embodied emissions from materials such as cement and steel [1,2]. For example, Denmark, which is globally recognised as being an industry front-runner with respect to decarbonisation, is no different. Its construction sector accounts for approximately 35 % of Denmark's waste generation and 10 % of its greenhouse gas emissions, arising from construction, renovation, and maintenance activities [3].

Life Cycle Assessment (LCA) offers a method for quantifying these impacts, positioning LCA as a key method for enhancing sustainability in the construction sector [4,5]. However, the application of LCA on buildings differ in important ways from its use in other product assessments, as buildings are complex interdependent systems with evolving uses and long lifespans, often subject to considerable uncertainty [6].

While LCA has traditionally been used to inform product design or policy, in the Nordic countries building-level LCA-based climate declarations have become mandatory [7]. Regarding these climate declarations, Denmark was the first country to include GWP limit values for building-LCAs. However, the role of LCA extends beyond regulatory requirements. Many companies use LCA to showcase their sustainability efforts, often presenting results as correct and with high precision on their websites as a competitive parameter. Unlike other sectors, building LCAs thus serve both as a regulatory compliance method and as a means of sustainability communication [8]. However, the perception of LCA providing 'high precision' and 'correct' calculations can be challenged, with the recognition of the inherent relative nature of LCA [9]. Reducing an LCA to a single score raises concerns: Are significant methodological

List of abbreviations: CO_2-eq., carbon dioxide equivalent; BIM, building information modelling; BR, building regulations; EPD, environmental product declaration; GWP, global warming potential; LCA, life cycle assessment; VCBK, danish national knowledge center for buildings climate impact.

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https://doi.org/10.1016/j.buildenv.2025.113439
Received 13 February 2025; Received in revised form 12 June 2025; Accepted 14 July 2025
Available online 7 August 2025

considerations being obscured? Transparent and consistent communication of LCA is essential to ensure models are both robust and valid [9]. Consequently, it is problematic if the interpretation phase of an LCA only includes the quantitative representation, without addressing associated uncertainties and limitations [10,11].

Several studies have found that methodological differences highly affect the LCA results [12,13]. Consequently, the same product or building may garner different LCA results depending on how and by whom it is calculated [14,13]. These could include choices related to the method used, the scope of study including e.g. life cycle modules, impact categories, and data, all of which can influence the results [15,16]. Zhang et al. [17] argue that uncertainties in building LCA stem from input-related issues such as system boundary definitions and modelling choices. This view is supported by Warrier et al. [18], who, through a comprehensive literature review, categorise four key sources of uncertainty in building LCAs: the LCA methodology itself, early-stage design decisions, data quality, and assumptions related to future scenarios.

The influence of practitioner decisions on LCA outcomes has been examined by, for example, Scrucca et al. [19] and Andersen et al. [14], both of whom demonstrate how differing choices by practitioners can lead to significantly varied results when assessing the same case. Goridkov et al. [20] found that it is common for practitioners to face problems with how to communicate results, and that a common strategy is to simplify the language. Key challenges include time constraints and difficulties in interpreting results beyond whether they meet limit values [21]. However, while much research focuses on improving LCA methods and tools by identifying uncertainties and sources of variation, relatively little attention has been given to exploring practitioners' perceptions and reasoning.

From a social constructivist perspective, it can be argued that LCAs are shaped by subjective human decisions influenced by socio-technical factors such as culture, norms, and politics [22]. How practitioners understand and frame LCA results directly influences how these results are communicated to stakeholders [11]. This framing can determine whether the findings are translated into actionable information [22]. Therefore, effective understanding and communication are critical to driving meaningful change [23].

This study is informed by Choice Awareness Theory, which emphasises how discourse, power dynamics, and organisational interests shape perceptions of technologies. Originally developed in the context of energy planning [24,25], the theory offers a valuable lens for examining how truth claims are constructed and contested in LCA by introducing concepts such as 'half-true statements and illusions of choice. Inspired by this theoretical framework, this study explores its application beyond energy planning by investigating how LCA case studies and practitioners' perceptions align to shape its role in the construction sector's sustainability transition. By examining how methodological choices and communication strategies influence the use of LCA, this research provides insight into the extent to which LCA serves as a meaningful sustainability tool or a regulatory checkbox.

In the following sections we analyse 16 exemplary LCA case studies of construction projects and evaluate them against two LCA Standards; DS/EN ISO 14040 Environmental management - Life cycle assessment - Principles and framework [26]; and DS/EN ISO 14044 Environmental management - Life cycle assessment - Requirements and guidelines [27]. This reveals mismatches between what should be done and what is done in practice, and these results form a basis for interviewing a panel of practitioners to identify perceptions about LCA in the industry.

2. Methods

2.1. Theoretical framework and research design

This study adopts a methodological framework rooted in a social constructivist perspective. The study explores how LCAs are applied and understood in the construction sector, addressing the overall research question (RQ): *To what extent do LCA case studies and professionals' perceptions align and shape the role of LCA in the construction sector's transition to sustainability?* This is approached in two steps. First, we explore how LCA results and methodological considerations communicated in building projects. This is investigated through 16 LCA building case studies in Denmark and a document analysis of two LCA standards; DS/EN ISO 14040 [26]; and DS/EN ISO 14044 [27]. The European building standard was initially included in the study. However, during the analysis, it became evident that the standard does not directly address transparency, robustness, or communication of LCA results. Instead, it builds upon and refers to the more general standards already analysed. For this reason, it was omitted from further analysis. In the second step we explore LCA practitioners' perceptions in building projects, which is investigated through eight semi-structured interviews with individuals who conduct LCAs. By integrating these findings from these two steps, the study provides a comprehensive analysis of LCA practices and perceptions. Together, these steps are illustrated in Fig. 1.

2.2. Analysis of LCA standards

Two LCA standards were analysed to provide an analytical framework for the subsequent examination of the LCA case studies (SQ1). These standards were: *DS/EN ISO 14040 Environmental management - Life cycle assessment - Principles and framework* [26]; and *DS/EN ISO 14044 Environmental management - Life cycle assessment - Requirements and guidelines* [27].

The LCA standards were used to identify LCA principles, elements necessary to ensure these principles, various modelling considerations, and aspects related to their communication by which the case studies could be cross-examined. The extracted information was coded through content analysis and formulated into 17 analytical questions. These questions provided the analytical framework for the LCA case analysis and are shown in Table 1.

2.3. LCA case studies

Examination of 16 Danish building LCA case studies was conducted based on the 17 questions in Table 2. These cases were published by the Danish Knowledge Centre for Buildings Climate Impacts (VCBK) (Videns Center om Bygningers Klimapåvirkning). It should be noted that the case studies were published before the institutionalisation of LCA requirements in the Danish Building Regulations (BR18), which set out the regulatory requirements for buildings, including aspects of sustainability, health, and safety. They may therefore not comply with the legislative requirements outlined in BR18. However, the case studies are still considered representative for the current LCA-practice in the sector, and thus suitable for this study. The library originally contained 23 case studies, but seven were excluded from the analysis due to issues with LCA model file compatibility. The LCA case studies spanned various building types and were conducted by different companies, as illustrated in Table 2.

The available material for each case study was a case description and the original LCAbyg file, which was exported into an LCA-report though LCAbyg. LCAbyg is a building sector-specific LCA software used widely in Denmark [28]. Consequently, it was possible to investigate all modelling choices, used data and product amounts for all cases. The case descriptions were generated by the original practitioners as part of the publishment of the cases on VCBK with the aim of being examples of how to conduct LCAs in the Danish construction sector. The case descriptions provided general information such as building type and year of construction. However, the level of detail and information varies across cases with no structure provided by VCBK. Both the LCAbyg files and the case descriptions were reviewed as part of this study.

A matrix was developed to guide the analysis, with rows representing case studies and columns corresponding to 17 analytical questions derived from the document analysis of LCA standards. As the matrix was

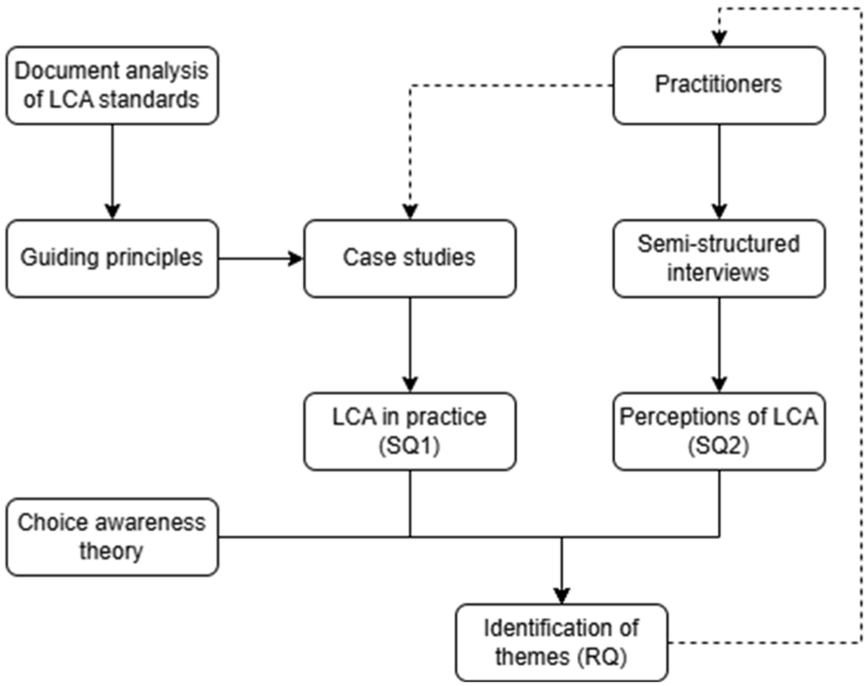

Fig. 1. Research design showing the use of LCA standards to analyse LCA case studies, and the practitioner interview process. Together these address the research question (RQ) and two sub-research questions (SQ1 and SQ2). Dashed lines represent possible learning and improvement opportunities from this study.

Table 1
Questions based on LCA standards that were used for analysis of LCA case studies [26,27].

LCA phase		Question
Goal and scope	1	How is the intended application described
	2	How is the intended audience described
	3	How the product system studied described?
	4	How is the functional unit described (including reference period)?
	5	How are the system boundaries described (including building components and life cycle modules)?
	6	How is the LCIA methodology and impacts described (e.g. EN 15978, ISO 14040/14044, etc.)?
	7	How are the data requirements described?
Inventory	8	How is the source of foreground data described?
	9	How is the used database for environmental data described (including share)?
	10	How is the data quality described?
	11	How is the data calculation and validation described?
Impact assessment	12	Which impact categories are calculated and how are they justified?
Interpretation	13	How are significant issues described?
	14	How is a completeness check described (including data gaps and limitations)?
	15	How is a sensitivity analysis described?
	16	How is a consistency check described?
	17	How are the results presented?

populated, patterns such as recurring challenges or common communication practices emerged and were coded using content analysis [29]. This coding process allowed both qualitative and quantitative analysis, transforming large volumes of information into manageable insights while maintaining the depth of the findings. To ensure validity of the findings, the matrix results were cross verified with insights from semi-structured interviews, described below.

2.4. LCA practitioner interviews

Eight semi-structured interviews were conducted for data collection. These interviews were used to address the second sub-question (SQ2).

Table 2
Overview of the 16 LCA case studies.

Case name	Case type
BOFA	Multi-family housing
DTU Science Park	Office building
E.C. Hansens Hus	Office building
Erlev skole	School
JYSK Sødalsparken	Office building
Kongebrohuset	Multi-family housing
Lisbjerg Bakker	Multi-family housing
Markhaven	Terraced house
Pakhusene	Office building
Samsø energiakademi	Office building
Sophushaven	Multi-family housing
Tankefuld	Terraced house
Teglsøerne	Terraced house
Vision Park	Warehouse building
Karolinelund	Daycare facility
Tømmerup Haveby	Terraced house

Interviewees were selected based on their contribution to LCA case studies published in the VCBK-case library [30]. The identity of the interviewees and the companies they represent is not reported in this study.

An interview guide with 16 analytical questions ensured consistency while allowing flexibility to explore emerging topics during the interviews [31]. After each interview, responses were transcribed and coded using content analysis (Steve [29]). The coding process transformed detailed interview data into manageable, comparable codes, enabling the identification of trends across participants' perceptions. Six key categories were identified: the role of LCA in the sector, reasons for conducting it, challenges, strengths, interpretation, and communication of results. The full list of questions is shown in Table 3, and the coded responses can be accessed in the supplementary information file named '*Interview Data*'.

Table 3
Questions used in the semi-structured interviews with LCA practitioners.

	Question
1	LCA experience
2	What is in your opinion the role of LCA in the sector?
3	Why do you conduct LCAs?
4	And is this useful? (following up on question 3)
5	What are the strengths with LCA?
6	What are the challenges with LCA?
7	When do you conduct LCAs in the project process?
8	Do you know of the four LCA phases from ISO and do you use them?
9	What tool and software do you use when conducting LCAs?
10	How do you balance the complexity of LCA?
11	What do you do with LCA-results?
12	How do you interpret LCA results?
13	How do you communicate LCA-results?
14	Do you think an LCA model represent real impacts?
15	How do you manage uncertainties and limitations?
16	How has you understanding of LCA evolved over time?

3. Results

3.1. Exploring LCA methodology in construction case studies

This section presents the results of the analysis addressing the first sub-question (SQ1): "*How are LCA results and methodological considerations communicated in building projects?*" The results are structured according to the four LCA phases: goal and scope, inventory analysis, impact assessment, and interpretation. Based on a document analysis of ISO 14040 and ISO 14044, the considerations outlined in Table 1 were identified as critical for ensuring adherence to the LCA principles of transparency, consistency, and comprehensiveness. Transparency refers to the clear documentation and description of modelling choices to ensure reliable and reproducible results [27]. Consistency involves the application of consistent assumptions throughout the entire LCA, and comprehensiveness involves the inclusion of all relevant impacts and inputs, and outputs to provide a thorough assessment [27].

All LCA models were developed using the Danish software tool LCAbyg, which supports attributional LCA modelling. The tool can use both Environmental Product Declarations (EPDs) and generic data from Ökobaudat as data sources [28]. The files from the software are referred to as the LCAbyg files. In addition to the LCAbyg files, all cases include a case description providing context about the LCA study.

3.1.1. Goal and scope of the LCAs

A clear goal and scope is crucial to ensure that the LCA reflects all relevant environmental issues for the buildings under study, thereby adhering to the principles of comprehensiveness and transparency [27]. However, in 14 out of 16 cases, the goal of the LCA is not described. The two cases with a goal definition, were defined as the aim of achieving a DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen) certification. Besides the description of the goal, this phase includes a description of the product system, functional unit (FU), and system boundaries [27]. Other scoping aspects include allocation procedures, LCIA methodology, and data requirements which were not described in any of the cases.

All case studies provided a case description of the product system studied stating elements such as what building type was assessed and when the building was constructed. Further investigation into the LCAbyg files revealed additional details that were not explicitly mentioned in the case descriptions, such as the heated floor area and the source of heating energy.

None of the 16 cases mentioned the FU in the case descriptions. The FU was identified based on the result presentations of GWP per m^2 per year, and by analysing the LCAbyg files, it was possible to identify that the FU to be predefined as m^2 per year. Critical for such FU is the specific amount of m^2 assessed and the reference period. The square meters were for each case entered in the LCAbyg file, as described under the product system being studied, were not stated in the case descriptions. This was also the case for the reference period of assessment. In LCAbyg it was found that all cases were calculated based on a predefined period of 50 years, but this was also not stated in the case descriptions.

The system boundaries related to included life cycle modules, while not explicitly described in text, were possible to identify through figures in the case description. It was identified that all 16 cases included life cycle modules A1-A3 (raw material extraction, transport, and construction), B4 (replacement), B6 (operational energy), C3-C4 (waste processing and disposal), and D (Benefits and loads beyond the system). This implies that 7 out of 17 possible life cycle modules were included in the assessment. However, no case describes the reasoning for this inclusion and exclusion of life cycle modules.

Besides the life cycle modules, there are no clear definitions of the scope of how to decide on the level of detail of included processes, such as building components and materials included. It was found that most cases include components of "Heating," "Ventilation and cooling," "Windows, doors, glass facades," and "Electricity". However, the included number of components varies across the cases, ranging from 12 to 73. This variation likely reflects differences in aggregation level rather than completeness, as similar materials may be grouped into fewer or more numerous components depending on the case. Without a clear methodology for aggregation choices, it can make cases appear more detailed without necessarily covering more products.

3.1.2. Inventory analysis

The inventory phase should include consideration of aspects such as types and sources of data and data quality [27]. Other important inventory aspects, such as calculation and validation procedures, were not mentioned in any of the cases. In seven of the 16 cases, the sources of foreground data were not described. In nine cases, data sources were listed as including direct measurements, documents from key stakeholders, and Building Information modelling (BIM) quantity extractions. Furthermore, none of the 16 cases describe any data quality.

3.1.3. Impact assessment

Through analysing the LCA model files it becomes evident that the software by default draws on the impact categories corresponding to the EN 15978 standard [32,28], and the EN 15978 standard in turn, employs CML-IA as the characterisation model [4]. However, this is not clearly described in any of the cases. Following this, it was found that all cases assessed eight impact categories shown in Table 4.

Table 4
Eight impact categories assessed in the 16 case studies.

Impact category	Unit	Description
GWP: Global Warming Potential	kgCO_2-eq	Impact of greenhouse gases on climate change
ODP: Ozone Depletion Potential	kgR11-eq	Impact of emissions on stratospheric ozone layer depletion
POCP: Photochemical Ozone Creation Potential	kg C_2H_4-eq	Impact on ground-level ozone (smog) formation
AP: Acidification Potential	kg SO_2-eq	Impact that leads to acid rain, affecting ecosystems
EP: Eutrophication Potential	kg PO_4-eq	Nutrient pollution leading to algae blooms and oxygen depletion in water
ADPE: Abiotic Depletion Potential for Elements	kg Sb-eq	Depletion of non-renewable mineral resources
ADPF: Abiotic Depletion Potential for Fossil Fuels	MJ	Fossil fuel resource consumption
PEtot: Total Primary Energy	kWh	Energy demand, covering renewable and non-renewable energy sources

3.1.4. Life cycle interpretation

The interpretation phase should consider the robustness of the results, by conducting, for example, sensitivity analysis and documenting uncertainties, as these elements are essential to understanding and interpreting LCA results [27]. None of the 16 cases describe any significant issues, and none of the cases mention sensitivity analysis, leaving the influence of inventory data on results unexamined.

Ten out of 16 cases do not report data gaps. Among the remaining cases, four mention gaps related to missing building materials, one refers to estimated quantities, and other highlights missing historical energy data as a gap. While data gaps pertain to missing information, limitations involve assumptions or exclusions arising from these gaps. Eight cases report limitations, ranging from BIM-model assumptions to exclusions such as parking basements.

Regarding data quality, it is not possible to assess the consistency of the LCAs based on the available information. This is because it was not possible to determine whether the data was representative geographically, temporally, and technically, as the exact products used in the cases were unknown (see *Section 3.1.2*). However, the LCAs appear to be reproducible, as the LCA model files include a detailed list of all EPD's and generic data used in each assessment. Based on this list, it was possible to identify the sources of environmental data to be Ökobaudat (https://www.oekobaudat.de/en.html), followed by Environmental Product Declarations (EPDs). The share of EPDs and generic data in the cases was found to be approximately 70–80 % for generic data and 20–30 % for EPDs.

In all cases, only the GWP result is presented, with no mention of whether it pertains to GWP20 or GWP100. However, it is evident that it is GWP100 when reading the EN 15978 [32]. Furthermore, only reporting the GWP result illustrates that the seven other impact categories which were calculated are not part of the communication of results. Fig. 2 presents the findings from the case studies communication of methodological considerations and results. For further detail on the results shown in Table 4 see the supplementary information named "*Case Studies*".

3.2. Exploring practitioners' perceptions of LCA

Here we present results of the analysis addressing the second subquestion (SQ2): *What are practitioners' perceptions of LCA in building projects?* Drawing on insights from eight semi-structured interviews with selected practitioners, it examines how LCA is understood in this

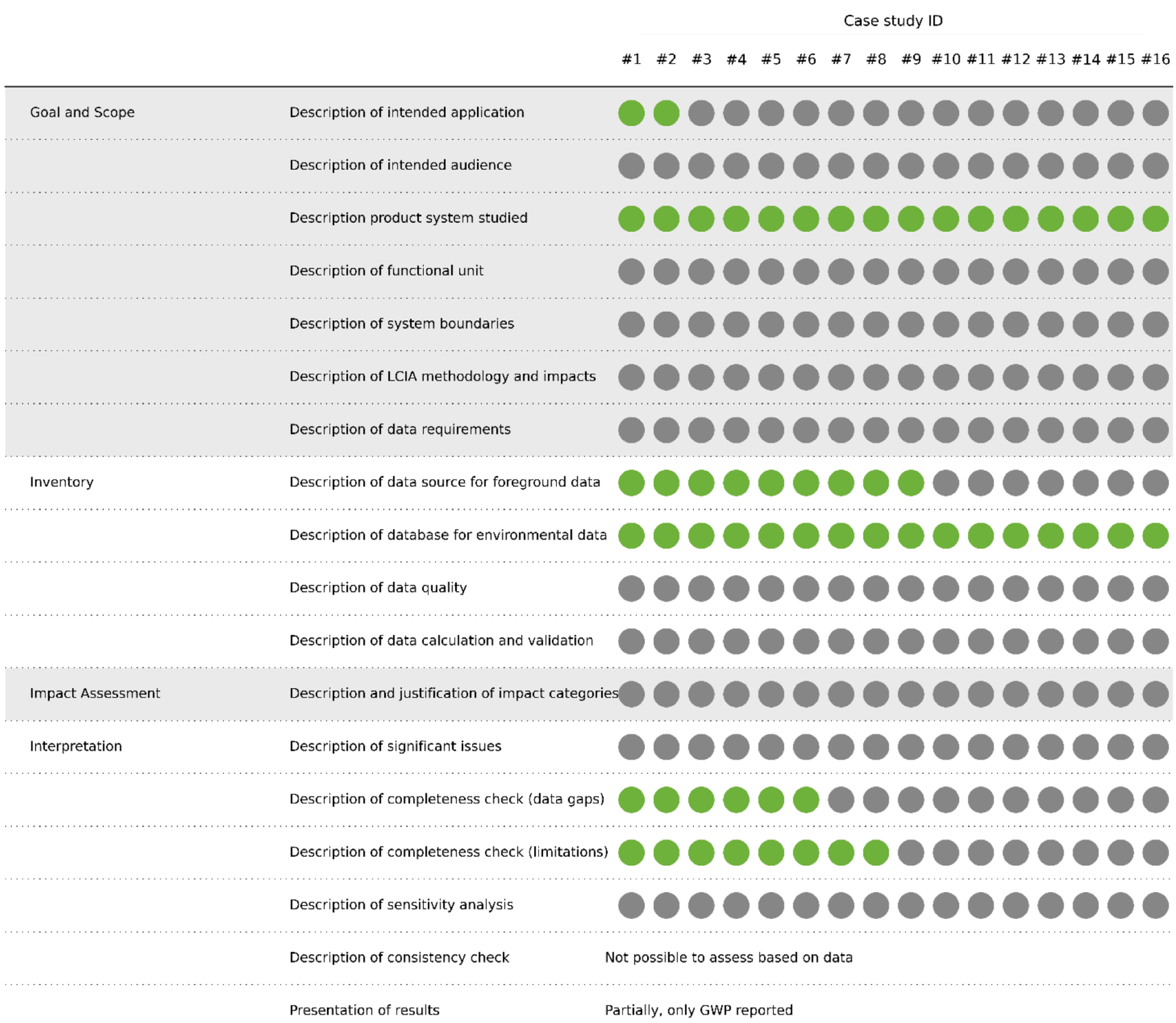

Fig. 2. The results show how many cases describe the central LCA considerations from ISO 14040/44. Each row represents a specific aspect of LCA, and the coloured cells indicate whether information is provided for each of the 16 cases. The green cells signify relevant information mentioned, dark grey cells indicate information not mentioned.

context. Their responses were grouped into six themes based on the question design: the *role* of LCA, the *reason* for conducting an LCA, *strengths* and *challenges* of LCA, and how LCA is *interpreted* and finally *communicated*. These and the frequency of responses are show in Fig. 2 and described in the following paragraphs.

The perceived *roles* of LCA in the building sector are based on practitioners' responses to the interview question: *"What, in your opinion, is the role of LCA in the sector?"*. These roles range from compliance and measuring impacts to creating baselines and minimising impacts. The most frequently perceived role is ensuring compliance with regulations (five responses), followed by using LCA as a competitive parameter (three responses).

Fig. 3.

The perceived *strengths* and challenges of LCA in the building sector are based on practitioners' responses to the questions: *"What are the strengths with LCA?"* and *"What are the challenges with LCA?"*. Most practitioners perceived LCA's strength to be optimising design (six responses), followed by the strength of providing knowledge and awareness of building impacts (four responses).

The most frequently identified *challenge* is time constraints (three responses). However, the challenges vary, including data-related, knowledge, process, and communication challenges. The latter encompasses difficulties in communicating results meaningfully, as well as providing nuanced interpretations of the results.

Theme	Responses	Frequency	Interview ID #1	#2	#3	#4	#5	#6	#7	#8
Role	Compliance with regulation	5			●	●	●	●	●	
	Competetive parameter (attracting investors)	3			●	●		●		
	Documenting that what is agreed, is delivered	2	●					●		
	Meet companys own ambitious targets	2						●	●	
	Minimise impacts	2		●			●			
	Creating baseline	1	●							
	Measure impacts	1								●
Reason	Comply with legislation	6	●		●	●	●	●		●
	Comply with certifications (e.g. DGNB)	3			●	●			●	
	Meet company's own target	2						●	●	
	Competitive parameter	2		●				●		
	It can shape design decisions early on	2	●	●						
	It is a service provided as part of the agreement	1								●
	Documenting delivery of agreed-upon commitments	1						●		
	There is an unwritten culture, that this is important	1					●			
Strengths	Optimise design	6	●		●	●	●	●	●	
	Knowledge and awareness of building impacts	4				●		●	●	●
	Competitive advantage	2			●	●				
	Documentation that helps trace products with issues	1	●							
	Being part of regulations, with consequences if not followed	1		●						
	Quantifiable metrics	1						●		
	Easy to evaluate costs against environmental impact	1							●	
Challenges	Time constraints in conducting and analysing LCA	3		●	●				●	
	Challenges in providing nuanced interpretations of results	2	●							●
	The requirement for specialist knowledge	2			●				●	
	High costs associated with conducting and applying LCA	2				●			●	
	Ensuring the accuracy and reliability of data	2					●	●		
	Primarily used after design decisions are finalised.	1	●							
	Communicate results in a meaningful way	1	●							
	Unable to recommend specific products (procurement law)	1		●						
	Challenges in distributing responsibility for LCA recommendations	1			●					
	Challenges in obtaining Environmental Product Declarations (EPDs)	1					●			
	Receiving data in time to prevent unexpected increases in results	1						●		
	Overcoming the 'business as usual' culture that resists change	1							●	
Interpretation	Determine whether the results are over or under the specified limit value	3	●					●		●
	Results are shaped by modeling assumptions	3				●			●	●
	No interpretation of results is conducted	2			●		●			
	Interpretation relies on industry norms	1		●						
Communication	Communicate results through comparison	4	●					●	●	●
	Do not communicate results	2			●		●			
	Communicate results thorough hotspot analysis on building components	1		●						
	Communicate results by visualing screening vs. final results	1		●						
	Communicate by writing a note (no details to simplify message)	1				●				

Fig. 3. Six thematic groups of responses by the practitioners. Darkness of the blue represents higher frequency of responses, while the green marks represent which of the eight interviewees gave a particular response.

When asked *"Why do you conduct LCAs?"*, practitioners responded with eight *reasons*. The most frequent reason behind conducting LCAs is to comply with regulations (six responses), followed by using LCA to comply with certifications (three responses).

When asked *"Is this reason useful?"*, six interviewees found LCA valuable, while three said its usefulness depends on its impact on decision-making. Responses highlighted that the value of conducting an LCA depends on whether it is used for documentation or as a design tool. For example, one respondent cited concerns about LCA's usefulness, stating 90 % of the and LCAs are for documentation and only 10 % provide valuable information as a design tool. This is influenced by developers' ambitions. If the goal is regulatory compliance, LCA is often implemented early. Without clear goals, it is typically done later, serving more as a reporting tool than a proactive design tool, which hereby limiting the effectiveness of LCA.

The reason behind conducting LCAs is closely related to the four LCA phases, such as the goal definition and scope. Therefore, the interviewees were additionally asked: *"How familiar are you with the four phases of the LCA process outlined in ISO 14040?* The responses revealed varying levels of familiarity, where some had heard of them, others had no knowledge, and only two were somewhat familiar but did not actively apply them. As a result, none of the interviewees actively incorporate the four phases into their work, as they found them to be overly technical and not relevant.

When asked: *"How do you interpret LCA results?"*, four responses were noted. The two most frequent understandings of *interpretation* are to determine whether the results are complying with a specified limit value (three responses), along with the understanding that results should be interpreted as shaped by modelling simplifications (three responses).

This indicates that some interpret the face values, while others express awareness of simplifications in the modelling. An interviewee who perceived results as being shaped by modelling simplifications noted that LCA results are abstract, rather than definitive real-world facts and depend on assumptions and the quality of inventory data. Further, two interviewees do not interpret results. They argue that there is no need for interpretation, since the LCA is only made to comply with regulation, and thus only put in a folder and sent to the municipality with no further interpretation or communication.

The interpretation of results is linked to the practitioner's understanding of uncertainties and limitations. Based on the interviews it was evident, that uncertainties and limitations are not something that has a central role in current LCA practice, as not all interviewees answered the question: *How do you manage uncertainties and limitations?* Two interviewees articulate the uncertainties related to the LCAs being made from 3D models, making them 'as drawn' instead of 'as built'. Consequently, material waste during construction is not included. Three practitioners accommodate such uncertainties using a 'buffer'. The buffer serves as a safety margin, where they try to calculate a conservative results beginning with, for example, 15 % extra buffer on results in a screening phase, and reducing this to 5 % buffer in a final result. Based upon this it is found that limitations are understood as data limitations, which create some uncertainty which is then handled by conservatively including a buffer.

Two interviewees articulate that they do discuss uncertainties internally with fellow sustainability colleagues, but it is not something that is communicated externally. They argue that it is not communicated since it is not something that is required, and it necessitates a high level of knowledge for the developer to understand such.

Part of the interpretation is further the *communication* of results. Interviewees were therefore asked: *"How do you communicate LCA-results?"*. Interviewees find it difficult to communicate the complexities of LCA results and cope using various strategies. Some interviewees try to communicate results by comparing the GWP result (five responses), for example to the average GWP results on previous projects. The responses highlighted that practitioners only communicate the GWP result. Communicating more impact categories is perceived as a source of confusion for people who are not LCA experts. Moreover, one interviewee expressed that people do not understand the meaning of units such as CO_2-eq. People are more interested in comparisons to average or limit threshold results for their sense-making. Following this, it is found, that communicating LCA in a simple, actionable, and meaningful way for the audience is of greater importance than generating LCAs that follow scientific principles, because they find that communicating such aspects can make the audience lose interest in the results.

4. Discussion

4.1. Insights from exploring LCA case studies

4.1.1. The domino effect of undefined goal and scope

The document analysis of ISO 14040/44 revealed that an undefined goal and scope cause cascading issues throughout the LCA process [26,27]. Only two cases explicitly defined a goal, complicating assessment of other LCA aspects, since scope must align with the goal., [26,27].

An undefined goal and scope often lead to missing system boundary descriptions [33]. Although seven modules were consistently considered, exclusion of others modules (e.g., maintenance, repair) lacked justification, undermining transparency and comparability [34,35].

All cases lacked a clearly defined FU, which depends on the goal and is critical for interpreting the LCA [33]. FU defaults from LCAbyg (m2 per year over 50 years) were assumed, but such defaults and such reliance on GWP100 limit transparency and adaptability without justification [36,37].

Undefined goals and scope influence modelling choices, data selection, impact categories, and interpretation, yet none of the cases reported data quality, despite its crucial influence on LCA results [38]. Most data came from generic databases like Ökobau.dat and product-specific EPDs, which vary in reliability due to verification and methodological differences between providers [13,33]. The lack of data quality reporting reduces transparency and validity.

4.1.2. Interpretation and communication of LCA results

Through the document analysis of ISO 14040/44 [26,27], it was found that the results are interpreted based on the goal and scope, which consequently stresses the challenges with the domino effect of an undefined goal and scope in the case studies. Although all studies calculated eight impact categories, only GWP was reported. This is a common, but limiting practice, that risks neglecting important impacts and burden-shifts between impact categories [39–41].

Another critical aspect is found in the description of results as the "total climate impact," such as some specific amount of kg CO_2-eq. per year, as this can mislead readers. Based on the interviews with practitioners, results were often presented with no statement of uncertainty, in order to simplify the core message, and enhance the recipients understanding of LCA. The term "total" suggests completeness, which is further strengthened by the use of decimals. Omitting words like "potential" might simplify the message, but using excessive precision can create an illusion of accuracy and robustness. As the studies lack sensitivity and uncertainty analyses it undermines their robustness, stressing why results should be presented with uncertainty and as potential, not as precise results [42]. These analyses are crucial for assessing the reliability of LCA findings and understanding how varying assumptions or data might influence outcomes [9,42]. Without them, stakeholders lack vital information and context for identifying limitations.

4.1.3. Case study approach

The examination of LCA in practice relied on limited publicly available case studies from VCBK's library, conducted prior to the implementation of requirements for LCAs in the Danish Building legislations. Practitioner interviews confirmed that the case studies remain representative of current practices of building-LCAs in Denmark. While all cases available were conducted through the LCAbyg tool, this may limit the generalisability of these findings to other contexts. However, as LCAbyg is the dominant tool for building-LCAs in Denmark, the results have internal validity in the reflection of the Danish practice. Future studies should include other LCA tools for broader insights. All cases reviewed in this study, were conducted using the LCAbyg tool, which aligns with the EN 15978. However, the tool does not enforce full compliance with ISO 14040/44 standards, particularly in terms of documenting goal and scope. Therefore, LCAs conducted solely within LCAbyg without supplementary information are unlikely to meet ISO requirements.

To mitigate researcher bias, a structured ISO 14040/44-based framework was designed. Another bias is the available information, as the cases were published to guide sector practices and provide an LCA file and a case description. However, it is argued that the lack of detailed modelling documentation undermines the cases' utility as learning tools, limiting transparency, consistency, and comprehensiveness in LCA practices. The availability of information is thus a limitation of the study, but due to the LCAs serving as learning tools for the whole sector, they were thus found suitable for this study.

4.2. Insights from exploring practitioners' perceptions

Interviews with eight practitioners revealed LCAs are primarily conducted for regulatory compliance, with strengths like design optimisation underutilised due to time constraints and interpretation challenges. This section explores compliance-driven LCA, knowledge transfer, and practical misalignments.

4.2.1. Compliance driven sustainability transition

Most practitioners view LCA primarily as a tool for regulatory compliance, resulting in a reactive rather than proactive approach to sustainability. From a social constructivist perspective, the institutionalisation of LCA in BR18 may shape practitioners' perceptions, introducing biases in sustainability assessments [22]. While LCA's role in compliance is crucial, it can limit LCAs broader potential to drive sustainable change, fostering a "business-as-usual" mindset. Consequently, LCA is often applied later in project phases, reducing its ability to inform early decisions aligned with sustainability goals [23]. Early integration of LCA could enhance its relevance and impact by tailoring assessments to specific project objectives. However, the compliance-focused approach, emphasising GWP while neglecting other environmental indicators, limits LCA's capacity to identify burden shifts and critical hotspots for a comprehensive sustainability strategy [9,43].

4.2.2. Knowledge transfer across projects

While the compliance-driven understanding of LCA limits its potential, it still holds significant opportunities to support sustainability decisions across projects. The key to unlocking this potential lies in how knowledge sharing is perceived and utilised. Traditionally, LCA knowledge has been viewed as a linear process, where data and insights generated within a specific project serve only to inform decision-making for that particular project [44]. However, there is potential for LCA knowledge to cross individual project boundaries and contribute to broader learning across the sector [23].

LCA practitioners accumulate "expiriri", a term that refers to the combination of experimentation and experience [45]. In the context of LCA, experiri describes practitioners' ability to learn from both ongoing experiments (current LCAs) and past experiences. This continuous learning process enables practitioners to refine their approach over time, improving the quality and relevance of future LCA assessments. Although practitioners often view LCA as project-specific, the knowledge gained from one project can influence the design of future projects, contributing to broader, sector-wide learning. This suggests that LCA has the potential to foster incremental improvements across the construction sector, even when applied primarily as a compliance-driven method.

4.2.3. Misalignment between the strengths of LCA and its practical use

An interesting finding is the disconnect between practitioners' perception of LCA's strengths and its actual use. While LCA is primarily viewed as a tool for compliance, its perceived strengths, e.g., optimising building design, are underutilised. A key factor in this underutilisation can be found in a knowledge-action gap; while practitioners understand LCA's potential to drive sustainability and inform design decisions, external pressures prevent them from taking full advantage of it [23]. This disconnect may stem from the identified challenges such as time constraints, data gaps, and communication barriers [21]. Time pressures, mentioned by three interviewees, likely contribute to LCA being used mainly for compliance rather than for strategic decision-making. Additionally, the limited time allocated for sustainability work within companies, coupled with the compliance-driven focus, leaves little room for innovation.

Another misalignment is found in strength of LCA originally intended to illustrate a comprehensive system perspective with the possibility of addressing burden-shifts, and the practical use when providing simplified and actionable results. The interviewees illustrate a misalignment between the need to balance actionable simplicity with methodological transparency. Freidberg [46] also stress the challenge with communicating LCA results. Practitioners often simplify results, such as presenting precise GWP values, to align with stakeholder expectations and ensure practical application [40,42]. While this approach makes findings more accessible, it risks obscuring underlying uncertainties and limiting stakeholders' understanding of broader environmental impacts [46]. This presentation of results does not align with the general intention of LCA as a holistic approach to assess environmental considerations.

4.3. Choice awareness and the role of LCA

4.3.1. Institutionalisation and the illusion of choice

Drawing on choice awareness theory, a true choice is one where at least two viable options are available, whereas a false choice occurs when practitioners perceive they have a choice, but the options are constrained or predetermined, creating an illusion of choice [24]. Choice Awareness theory, which draws on aspects of both power and discourse theory, was initially developed to explore why radical energy solutions were excluded from the sustainable energy planning agenda. It is used to help explain how the presentation of options shapes societal perceptions of choice, often obscuring available alternatives [24,25]. In the context of LCA, numerous choices must be made, with decisions depending on the purpose of the assessment [47]. When adhering to BR18 requirements, several decisions are predefined to ensure comparability, thereby limiting flexibility. If modelling decisions are not transparent, it could indicate that these choices are not consciously made, instead following a 'business-as-usual' routine. If practitioners are unaware of alternative approaches, this creates a false sense of choice. Alternatively, LCA practitioners may intentionally downplay the variety of choices to maintain the scientific objectivity of their work, and thus preserve their perceived rigour and reliability in decision-making contexts [46]. If the sector does not critically evaluate the compliance-LCA approach, it risks limiting LCA's potential for sustainable change.

4.3.2. The role of collective perception in LCA practice

Practitioners' perceptions and LCA practices are, from a social constructivist stance, argued to be shaped by the socio-technical context [22]. As all interviewees belong to the same sector, they are subject to a collective perception within that sector [24]. Collective perception refers to the general understanding of a phenomenon that is unaffected by individual expertise [24]. According to the choice awareness theory, the collective perception is shaped by the language used to communicate LCA within the sector [24]. For example, Kanafani et al. [4] positioned LCA as a cornerstone for sustainability. This perception of compliance-LCA as crucial for sustainable development can be argued to be a “half-true” statement [25]. A half-true statement simplifies the truth to make it more digestible, but at the cost of overlooking other possibilities [25]. This does not imply deliberate manipulation but rather reflects how LCA’s institutionalisation in BR18 frames it as a universal solution, shaping the sector’s understanding of its role. This could foster the belief: *We must require LCAs to achieve sustainability* [24]. However, as discussed in *Section 4.3.1*. above, LCA, like energy planning [24], can be conducted in various ways, and its role in the sustainability transition depends on the specific application in each case. Simply conducting an LCA does not inherently contribute to sustainability [23]. While a compliance-driven LCA may seem better than no LCA, it is more complex to argue that it will not produce environmental benefits if based on flawed calculations or not used to drive project changes. As observed in *Section 3.2*, several practitioners simply submit LCAs for compliance without interpreting or communicating the results. By focusing on compliance rather than context-specific decision-making, LCA risks becoming a box-ticking exercise rather than driving meaningful environmental change.

Another reason why "compliance-driven LCA is a crucial aspect of sustainability" could be argued to be a half-true statement is that LCA is not the only factor on which decisions are based. Subal et al. [48] argue that LCA in practice has limited influence on decisions, due to environmental considerations having less importance compared to costs. Besides the lower priority, the complexity of the LCA-results and robustness also limits the role [48]. This aligns well with the findings in *Section 3.2*, where practitioners stress the challenges with communicating complex modelling considerations, as well as the limited time spent on LCAs and the cost of EPDs. This does not imply that current role and practice is inherently flawed, that they represent only one application of LCA. To unlock the full potential of LCA, it is essential to critically evaluate its use and the communication of modelling choices and results. Without awareness of different LCA methods, how can the sector be sure it has made an informed choice?

4.3.3. From enthusiasm to accountability in LCA practices

The increasing attention and development of LCA in regulation are not isolated to the Danish building sector. Several countries in Europe including The Netherlands, France, and the Nordic countries have similarly introduced LCA-regulation [49]. It can be argued, that the LCA development has been characterised by great enthusiasm [50]. In *Section 3.1* it was found that results are often presented as ’face values’, indicating a state of enthusiasm. Enthusiasm for LCA can create false perceptions of certainty [51]. Over-reliance on numerical results risk a "valley of distrust", where stakeholders lose trust upon recognising limitations [52]. Without open discussion of robustness, LCA’s credibility may suffer. While stakeholders can question the presented information, they may not seek or value such details. LCA studies often reinforce pre-existing expectations, potentially creating misplaced confidence that overlooks critical impacts. This "illusion of confidence" risks leading to misguided decisions, although, in some cases, other stakeholders may address the overlooked aspects. This uncertainty may result in the mass production of LCAs that fail to inform meaningful decision-making or contribute to knowledge development, resulting in unnecessary work and the false belief within the sector that simply conducting LCAs will lead to a more sustainable future [23]. Therefore, the sector must move beyond its current ’enthusiastic’ level and come to terms with the relative nature of such assessments [53]. A critical shift is needed, focusing on the validation and robustness of findings. Here, *validation* refers to assessing whether the LCA results are credible and fit for their intended purpose, while *verification* denotes an independent check of data quality and methodological compliance.

4.3.4. Compliance-driven LCA: implications and recommendations

The current role of LCA as a compliance-driven method limits its potential to enhance understanding of trade-offs, such as between impact categories and life cycle stages. Hidden modelling assumptions, the cascading domino effect of undefined goal and scope, and insufficient attention to data quality undermine the robustness of LCA. This reduces its value to "half-true statements" and risks creating a false sense of sustainability. Many of these challenges could be addressed by adhering to the general LCA principles of transparency, consistency, and completeness [26].

Based on the findings of the first sub-question (SQ1), it is recommended that detailed reports should accompany all LCAs. These reports should explicitly outline modelling considerations to avoid cascading domino effect caused by undefined goals and scopes. Encouraging the development of affordable, third-party verified EPDs and standardising methodologies across programme operators would improve the robustness and comparability of inventory data. Additionally, the interpretation and communication of results should use terms like "potential" rather than "total" to highlight uncertainties, and greater emphasis should be placed on qualitative insights, such as trade-offs between impact categories, rather than relying solely on quantitative metrics.

Based on the findings of the second sub-question (SQ2), it is recommended that the understanding of LCA as a means for compliance-driven sustainability should be optimised by incorporating LCA during the planning and design stages to maximise its potential in reducing environmental impacts. Following this, the use of LCA should move beyond compliance to instead provide information with the possibility of optimising design and potentially foster innovation. This will further ensure the knowledge is transfers across projects and not isolated to single projects. To accommodate the misalignment between the strength of LCA in optimising building design and providing knowledge and awareness related to building’s impacts and its practical use, it is recommended that developers understand the importance of this type of knowledge and consequently allocate sufficient time for LCA work.

4.4. Limitations and future research recommendations

This study is limited by the small sample size of both case studies and interviewees. It is known that LCA is deployed in the building design process in a number of contexts and applications, and in combination with other tools. These considerations fall outside the scope of this study but may offer further nuanced perspectives for subsequent research enquiries. Furthermore, future research should investigate different communication strategies suitable for presenting LCA-results, including an investigation of developers’ perceptions of LCA, their willingness to pay for LCA work and how they can formulate project specific goals for LCAs. It should further include an investigation of how validation of LCAs could be enhanced, including who should validate them.

5. Conclusions

This study explores to what extent building LCAs and practitioners’ perceptions shape the role of LCA in the construction sector’s transition to sustainability. In doing so, it uncovers a critical gap between LCA result communication and practitioner perceptions. The study first examines how LCA results and methodological considerations are communicated in building projects.

None of the 16 case studies adequately communicated key modelling considerations such as the FU, system boundaries, LCIA methodology and data requirements. Nor did any of the case studies report results of life cycle impact categories beyond GWP or justify the selection if this impact category or its time horizon. Over 40 % of the case studies do not describe the source of their foreground data, and none provide information about data quality, validation, nor do they report any sensitivity analysis results. This compromises the transparency, robustness of the results, and compromise comparability between studies. The current LCA practice in the construction sector frames LCA as a method for definitive or objective results, rather than recognising it as modelling output influenced by methodological considerations.

Second, the investigation of practitioners' perceptions of LCA in building projects revealed several reasons behind how LCA currently practiced in the construction sector. While the discourse around LCA often frames results as absolute facts, the interview findings reveal that practitioners themselves generally understand LCA results as potential impacts rather than definitive facts. This highlights a gap between the communicated messages and practitioners' deeper awareness of the uncertainties and assumptions underlying LCA outputs. The interviewees revealed that, in the Danish context, they primarily conduct LCAs to comply with regulations or certifications. Several practitioners viewed this as sufficient justification for not communicating certain modelling assumptions. Communicating modelling considerations is considered challenging, as it may confuse the audience or reduce their interest in the results. Seven out of eight interviewees reported that they conduct LCAs to comply with legislation or certifications, rather than for optimising and improving environmental performance. Although practitioners see this as a strength, it highlights a significant gap in how LCA is currently used, suggesting its full potential is underutilised, when solely used for compliance. Additionally, it was found, that the use of LCA is heavily influenced by the ambitions of the building developer, who determines when the LCA process begins and what the study's goals should be.

Addressing the overall research question: *To what extent do LCA case studies and professionals' perceptions align and shape the role of LCA in the construction sector's transition to sustainability?* the study finds a misalignment between the information presented in case studies and professionals' perceptions. The gap between the knowledge presented in cases and the knowledge held by practitioners risks positioning LCA as a positivist and unambiguous source, despite its inherent limitations. As a result, the LCA process often focuses more on meeting GWP limit values than critically assessing the broader environmental impact of building design. Building on this with the use of Choice Awareness Theory, we find the "illusion of confidence" risks leading to misguided communication of results and decisions based on them. Oversimplification or lack of critical discussion could lead to misuse or overconfidence in the results, reducing trust in the assessment method. As such, it is recommended that future research investigates different communication strategies to move from oversimplified and compliance-driven LCA to improving environmental performance in the building sector.

CRediT authorship contribution statement

Emily Greve Somerset: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kíra Lancz:** Writing – review & editing, Visualization, Supervision. **Henrikke Baumann:** Writing – review & editing, Supervision. **Thomas Elliot:** Writing – review & editing, Writing – original draft, Visualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank all the interview participants who kindly took the time to discuss their perceptions of LCA, and feedback from Timen Mattheüs Boeve on an earlier version of the research.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.buildenv.2025.113439.

Data availability

Everything is shared in the supplementary information.

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