Mind the gap: Facilitating early design stage building Life Cycle Assessment through a co-production approach

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This is an Authors' Accepted Manuscript version of the following paper: Şeyma Atik, Teresa Domenech Aparisi, and Rokia Raslan, 'Mind the gap: Facilitating early design stage building Life Cycle Assessment through a co-production approach', published in Issue 464 (2024) of the Journal of Cleaner Production, under the guidance of the handling editor, Mattias Lindahl.

The final authenticated version is available online at: https://doi.org/10.1016/j.jclepro.2024.142803

Abstract: Despite the transition towards a circular economy (CE) being a significant element in achieving the decarbonisation of the built environment, a clear and common pathway to applying CE principles to building design is still lacking in both industry practice and academia. The integration of Building Information Modelling (BIM) and Life Cycle Assessment (LCA) has the potential to enable the identification of feasible pathways to increase circularity. This study aims to investigate its practical use to facilitate the application of circular economy principles at the early stage of building design via using LCA-based BIM plugins. Within this aim, the paper centres on a co-production approach and presents a gap analysis by identifying gaps in knowledge and implementation as well as addressing the pressing needs of the current practice in the UK. A series of semi-structured interviews with expert practitioners in the field were conducted for data collection, contributing to the following phases of the co-production by allowing for an in-depth investigation and reflection of the practice. The findings have revealed that: (a) there is still an insufficient level of contextual awareness and readiness in the implementation of CE principles in the built environment and LCA understanding and (b) the adoption of BIM at the early stages of building design is still limited in the current practice; BIM models with sufficient level of data details and quality to enable circularity assessment are rarely produced. Thus, the paper highlights the need for enabling mechanisms, including the introduction of legislative instruments, the involvement and commitment of the industry and key stakeholders, the support for training and skills improvement, and the establishment of effective communication and implementation process management frameworks. Future research agenda points to the need of formulation of a BIM protocol to enable integration of BIM and LCA to promote CE principles in the building design process.

Keywords: Building Information Modelling, embodied carbon, circular economy, integrated design process, building design practice, industry interviews

1. Introduction

The architecture, engineering, and construction (AEC) sector consumes significant amounts of energy and materials; accounting for approximately 30% of global energy use and around 37% of total direct and indirect energy related CO_2 emissions [1][2]. Due to its high energy demand and significant consumption of raw materials, the AEC sector holds a pivotal role in achieving decarbonisation targets. Previous efforts have focused on enhancing energy efficiency in buildings and, indeed, have achieved a considerable reduction in operational carbon impacts. However, these efforts leave aside embodied carbon impacts stemming from resource-intensive building construction materials and substantial waste generated during building construction and demolition phases. Previous studies revealed that the AEC sector urgently needs to take meaningful actions to address the growing concerns about material efficiency and resource consumption [3] by developing and implementing novel strategies, such as adopting principles of the circular economy (CE) [4][5][6], which is accepted as a potent contributor to achieving zero-carbon prosperity across all sectors [4][7]. Despite the potential of the transitioning to a CE in achieving decarbonisation in the built environment, a clear pathway for applying CE principles to building design is still lacking in both industry practice and academia [8].

Life Cycle Assessment (LCA) methodology has been widely adopted in practice to evaluate the environmental impacts of a building throughout its lifecycle. As a robust and data-driven tool providing a quantification of environmental impacts of buildings, LCA provides necessary insights to inform actions aimed at reducing the impact of buildings. Thus, it is becoming an important requirement in emerging regulations to assess sustainability measures [9]. Notably, some European countries, such as the Netherlands, France, and Denmark, have national regulations mandating the measurement and limitation of life cycle emissions for certain building types [10], though this is not yet the case in the UK. Despite the potential benefits of LCA as a tool and CE as an approach towards building sustainability, challenges exist in their implementation. Due to the nature of buildings, which involve a wide spectrum of construction materials having long lifespan as well as relying on intricate networks embedded in each lifecycle stage, the implementation of LCA and CE principles into the building design and operation is a more challenging practice than their implementation in a product-based manufacturing process [11][12].

As Building Information Modelling (BIM) provides efficient resource and data management and enhance collaboration and communication, the integration of BIM and LCA has the potential to enable the identification of feasible pathways for decarbonisation of the built environment. Numerous studies are focussing on the integration of BIM and LCA [13][14] and the benefits embedded in using this integrated approach; however, few studies have evaluated how it is used in the industry through practitioners' perspective [15]. Centred on the opportunities and challenges of using an integrated BIM and LCA approach, a previous study undertaken by the authors [16] revealed that there is a need for effective management relating to both time and work, along with clear guidance for BIM modelling and the use of LCA plug-ins. It also highlights that the research problem requires more involvement of the industry practitioners and other key industry stakeholders to enhance the impact of the research outcomes and the usability of the knowledge produced.

Given the growing interest in circular thinking, there is a need for a considerable work on how CE principles can be applied in the design practice [17]. This is the first of a set of papers investigating how the LCA-based BIM plugins can be used to facilitate the application of CE principles at the early stages of building design. Within the aim, the overall research centres on a co-production approach to present a practice of engagement between academia and the industry practitioners in the field and generate solutions for enhancing the usability of the plugins in the industry. Therefore, this paper aims to investigate the practical use of the LCA-based BIM plugins by scrutinising gaps in the current practice and identifying requirements to facilitate the application of circular economy principles at the early stage of building design. The paper presents a gap analysis by: (a) portraying the current practice of undertaking a building LCA and applying CE principles into the building design in the UK's AEC sector, (b) identifying gaps in knowledge and implementation of the LCA-based BIM plugins at early stages of building design to facilitate the application of CE principles, and finally (c) reflecting the pressing needs of the practitioners in the current practice and outlining a set of requirements for the desired process.

2. Methodology: engaging with the industry through the co-production approach

As a recent promising approach, co-production is defined as a framework for a joint production of knowledge or innovation between interdisciplinary or transdisciplinary participants to address a problem or a set of problems and deploy effective solutions for them [18][19]. In recent decades, co-production has emerged in a wide spectrum of fields under three main disciplines: public administration, science and technology studies, and sustainability research [20][21][22]. Regarding specific concerns and agendas in each field, it has been used in a variety of ways, and scholars have proposed models which are context-specific and quintessentially diverse. However, the underlying core principles, which are specified as being: context-based, pluralistic, goal oriented, and interactive, have remained overlapping in each model within the sustainability research [23].

This research adopts a co-production approach (Figure 1), involving three main phases: the formulation of gaps and needs, the generation of a solution, and the validation cycles of the solution. It is important to note that co-production is a dynamic process; therefore, it is unrealistic to have a 'one size fits all' approach for application in various investigations. Within the objectives, resources, and interests of the research, the co-production models can be tailored to meet the specific needs and dynamics of the investigation [22]. Evidence from the existing studies in other fields reveals that the incorporation of co-production into research introduces several advantages; such as contributing to generating innovation by drawing upon the diverse expertise and valuable insights of the contributors and then enhancing the applicability of research and chances of successful uptake [24]. The framework presented in this research is concerned with the enhancement of the existing practice with the application of research insights. Within the aim of this research, the adoption of the co-production approach will foster a better understanding of the research phenomenon and lead the investigation results to facilitate better alignment with the complex needs of the industry.

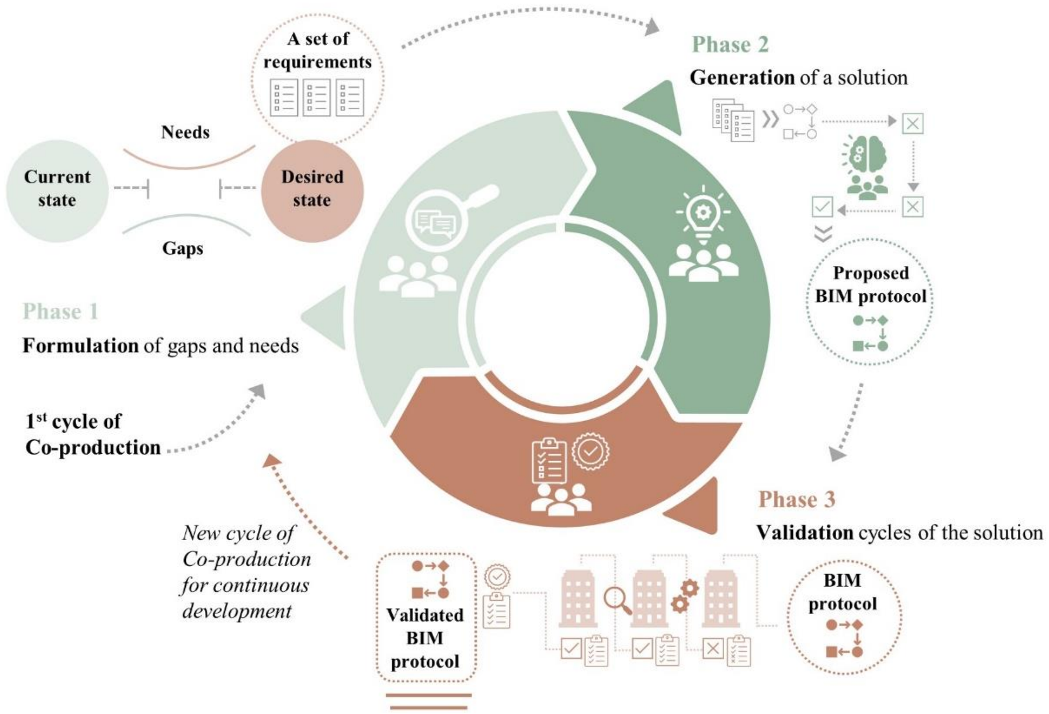

Figure 1: *An application of the conceptual co-production framework (Source: authors)*

This paper focusses on Phase 1: Formulation of gaps and needs. It presents a gap analysis by identifying gaps in knowledge and implementation as well as addressing pressing needs of the current practice, which was limited to, and reflective of the UK context. Enabling researchers to capture diverse perspectives and potentially better understand complex phenomena [25], interviews were considered a suitable method for this initial phase by the authors, as they feed into the following phases by allowing for an in-depth investigation, reflecting the real practice, and framing the gaps and needs. The paper, therefore, adopts a phenomenological research methodology by conducting an industry-based study involving in-depth semi-structured interviews with expert practitioners in the field as the means of data collection.

Given the importance of software tools and their practical implementation in design practice, recent studies have adopted qualitative methodologies to investigate the research phenomenon from an industry perspective. For instance, Zimmermann et al. in 2021 [15] conducted 8 in-depth interviews with LCA practitioners in the Danish AEC sector to understand the dynamics of the practice; Sartori et al. in 2022 [26] interviewed 9 participants working as LCA tool developers to investigate how whole building LCA is integrated into different project phases of buildings. Hollberg et al in 2022 [27] conducted 13 interviews with stakeholders in Sweden to define requirements for the development of an LCA tool. Regarding the implementation of CE principles in the building sector, Kanters in 2020 [5] undertook 11 semi-structured interviews to investigate the perspectives of architects and consultants; Giorgi et al in 2022 [28] conducted 38 semi-structured interviews with building stakeholders across European countries to delve into the current practice by examining drivers and barriers. Concerning the use of BIM to facilitate the adoption of CE principles, Charef and Emmitt in 2021 [29] interviewed 20 experts to discuss its potential and identify barriers to its implementation.

2.1 Sampling strategy, recruitment, and procedure

A non-random purposive sampling strategy was employed to ensure participants possess expertise in BIM, LCA practices, and CE approach, along with exposure to state-of-the-art tools. Regarding the sample size in studies focussing on 'expert voices', a study conducted by Baker and Edwards in 2012 [30] emphasises the importance of the quality of the analysis and the dignity, care, and time taken to analyse interviews, rather than the quantity of interviews. Given the early stage of implementing CE principles in building design and the limited availability of LCA experts skilled in BIM in the AEC sector, it is challenging to find practitioners possessing all the skills. While the investigation of practitioners aimed to find informants experienced in all areas, it was necessarily divided into two main pools where sampling comes from: (a) experts in building LCA and implementation of CE and (b) experts in BIM with an exposure to building LCA processes. The investigation was conducted throughout the UK. Practitioners were identified based on their organisational and business profiles and contacted via email. A total of 7 interviews were conducted in this study. This sample size is consistent with recent studies in this field [15][26].

Adhering to data protection and ethical requirements, the participants in this study were provided with detailed information, and their consent was obtained for recording and using data before the interviews. They were requested to provide background information on their skills and experiences as well as choose a specific project, in which they had been involved, to discuss during the interview. This narrative approach [31] was utilised to tailor questions to explore the actual experiences of the practitioners through their anecdotes and allowed them to articulate their aspirations regarding the practice. Due to the Covid-19 pandemic closure and restrictions, all interviews were held on GDPR compliant online platforms, lasting approximately one hour, and audio-recorded. Following transcription by the authors, transcripts were checked and validated by the interviewees.

2.2 Thematic analysis

The data were analysed using 'thematic analysis' as a fundamental method for qualitative analysis [32]. In line with the principles of this method [33][34], key information from semi-structured interviews was identified and encoded; then subthemes and main themes were derived and interpreted. The analysis adhered to a systematic guideline, involving six main steps, proposed by Braun and Clarke [32][35]. Based on this guideline, the coding aimed to capture all unique patterns to provide a comprehensive thematic description of the entire dataset [32]. Theme generation was based on inductive and data-driven approach. NVivo 13 was used for a more rapid and rigorous process of data analysis, and a participant coding system was employed to enable cross-referencing (e.g., P1 denoting Participant 1).

3. Results

3.1 The gaps in knowledge and implementation

The research focuses on the integration of different methods, approaches, and platforms, all of which have specific features and require individual inquiry. Although the interview questions addressed the holistic integration of these components, the responses centred on the practitioners' experiences with each, reflecting limited use of the integration in the current practice of undertaking a building LCA and implementing CE principles.

Through the thematic analysis, three main themes were derived: (a) building LCA strategy and its delivery via the use of LCA-based BIM plugins, (b) implementation of CE principles in building design, and (c) implementation of BIM to undertake LCA in the industry. The gaps identified within each context-specific theme were categorised into four perspective levels as follows:

- Policy level gaps are related to the shortcomings of normative regulatory instruments and limited actions taken by the government.
- Organisational level gaps are linked to how the industry perceives the inquiry and what is lacking in the industry.
- All the gaps impeding the information flow through the process and the obstacles arising from technological limitations of the tools are grouped under process and platform level gaps.
- Individual level gaps refer to the individual behaviours and approaches to the inquiry.

3.1.1 Building LCA strategy and its delivery:

The findings show that the current practice of undertaking LCA to measure, report, and mitigate carbon emissions within the UK AEC sector is still on a voluntary basis, with exceptions in certain local authorities' planning requirements. Therefore, the practice was indicated as depending on the motivation of the project developers and clients either to acquire green building certifications, such as BREEAM and LEED. Strongly associated with the developers' motivation, the results revealed that the current practice has been dealing with a limited budget allocated to the design team to develop models which are just enough to meet their contractual requirements and insufficient to use in the LCA practice. Considering the limited budget, the interviewees alluded to the fact that it was not a surprising outcome in the current practice to be given limited attention by the design team to model development for LCA practice, which require extra time and work. All interviewees stated the time and resource-intensive nature of the current practice, referring to several reasons covered at each level of gaps below.

As future aspirations, the practitioners emphasised the necessity for national regulation as a crucial step toward achieving decarbonisation goals. In line with this overarching objective, they emphasised the importance of receiving adequate support and increasing attention from the industry and design team to benefit from the outcomes of the LCA practice. All interviewees pointed out that undertaking LCA practice required organisational enhancements to foster collaborative teamwork and technological improvements to facilitate the practice across the different platforms, which are covered in Section 4.

At the policy level, the gaps within this theme were given under two categories:

- **Lack of legally binding requirements to undertake LCA in the national and local planning policy:** All interviewees agreed on the lack of regulatory enforcement at the national level, coupled with its impact on local planning policies, as the main barrier limiting the practice from being widespread, described as "*roadblocks (P2)*".
- **Lack of benchmarks:** The practitioners noted that the limited availability of well-prepared benchmarks prevented them from making informed decisions by comparing the assessment results with these benchmarks and then identifying the next steps to reduce overall impacts of building design.

Regarding the organisational level, the following gap was identified:

- **Lack of motivation from developers and clients to prioritise LCA:** Given the lack of national policy and the inadequate number of local policies, the practice was notably associated with the motivation of the developers, which particularly influences the design objectives and budget allocation for these objectives, quoted by the interviewees as "*a client-driven exercise (P1)*" and "*sustainability wasn't really at the top of their agenda (P3)*". Furthermore, the "*more costly (P3)*" feature of environmentally friendly building materials compared with traditional alternatives was linked to the low motivation levels of clients in this context.

Focussing on the process of undertaking LCA and using the LCA-based BIM plugins revealed four main gaps at the process and platform level:

- **Lack of a detailed design brief:** Rooted in the developers' motivation and narrow agenda, the practice in most cases was stated as undertaken with unclear objectives at early design stages, with examples of phrases such as "*a very limited Design Brief and fee (P5)*" and "*...because it wasn't in the Project Brief (P7)*".
- **Lack of clear programme and standardised process:** All interviewees agreed that there was a lack of standardised process and programme, which is still the case. A variety of perspectives was

expressed by them involving unclear schedule of completion, a scarcity of concise information delivery programme as well as a lack of standardised information exchange process. A few of the many examples given include "*…coordination with the design team…takes a long time to ask for the quality level of information we want…(P1)*" and "*…the format of information…they have it in* [*sic*] *doesn't comply with the RFI* [request for information]*…what they end up doing is sending us stuff like the CAD files and the cost plan and we have to manually sift through it…do our best with it…(P3)*". The lack of standardisation in the process was indicated to hamper the practice to achieve the desired outcomes by limiting the collaboration between the different disciplines as well. One interviewee mentioned the inefficiency of the practice where a lack of collaboration was the case, by expressing *"…coming up with a design and then passing it to you. So, you almost doing it backwards…(P7)*".

- **Lack of a common database and methodology:** Regarding the LCA-based BIM plugins, some interviewees clearly stated that the presence of diverse tools with various databases and methodologies created conflicts between the results, making the practice more challenging. An example given includes: "*…our values* [from eTool] *for equivalent buildings were coming in a lot higher than the companies using One Click…(P3)*". Moreover, the databases of the plugins were criticised for being limited due to a lack of templates and materials in line with the design specifications.
- **Limited graphical user interface:** eToolLCD and One Click LCA, predominantly used plugins in the UK practice, were considered as beneficial for informing early design decisions. However, some interviewees noted practical limitations regarding the graphical user interface of these plugins, which incorporates visualisation features to enable users to understand outputs easily and compare design options more insightfully. The current interface and design of the plugins was found to be suitable for specialist use. In contrast, alternative plugins such as Tally and CarboLifeCalc were considered to offer more practical and user-friendly interfaces.

At the individual level, the following gap was identified within this theme:

- **Lack of motivation from the design team to be involved in the process:** Some interviewees experienced that, in most cases, the design team, especially the architects, did not have the motivation to participate in the practice of undertaking LCA, attributing this reluctance to their limited knowledge about the process. Given that, the practice was described as necessitating guidance for the design team, expressed as "*spoon-feed the design team (P1)*". The lack of motivation was also associated with the limited time and budget allocated to the design team for the architectural model development.

3.1.2 Implementation of circular economy principles in building design:

The results revealed that CE was perceived as a relatively new topic for the UK AEC sector, and there was a limited understanding of the overall CE concept. The interviewees summarised the implementation of CE principles into the building design practice as being not currently mandated except for large-scale developments in London, which are subject to the requirements of the Greater London Authority (GLA). It was stated that its implementation is surrounded by certain barriers and faces many challenges; therefore, it was highlighted that its implementation is still in its initial phases.

The interviewees desired to work in an environment where the implementation of CE is mandatorily required at the national level and both a sufficient level of awareness about the circularity across the sector and a clear and mutual understanding about its implementation exist.

The results identified several gaps at the policy level, categorised under two main and interrelated discourses:

- **Lack of regulations:** As indicated in Section 3.1, the absence of regulations was identified as a key barrier to expediting the implementation of CE principles into the current practice. The interviewees implied that the lack of regulations and support from the government resulted in a range of issues, such as leading up to a natural disregard for its implementation from the industry and stakeholders and a variety of inconsistencies between approaches proposed for the implementation, which are detailed in subsequent sections.
- **Lack of clear methodology and standardised approaches:** Given the gaps in knowledge of the CE concept, it was indicated that there was a lack of an agreed approach for its application in the current practice, described as "*a very grey area (P2)*". The interviewees noted that due to the lack of a clear methodology on how to assess the circularity of buildings, the practice was dominated by merely generating ideas and preparing statements based on written practice, which hindered it from achieving a correct application and getting efficient outcomes. As linked to this, the absence of quantifiable circularity metrics and lack of benchmarks were also stated as gaps creating challenges in its application.

At organisational level, the following gaps derived from the analysis:

- **Inadequate industry support:** Linked with the lack of regulations, insufficient demand from the industry to proceed the practice, described as "*they show no interest (P3)*" and "*lack of ambition (P6)*", was highlighted as one of the key barriers to accelerating its implementation. The practitioners shared their observations about the attitudes of some clients where they tended to neglect the end-of-life practices of the buildings, as they had already received the profits from the buildings before the buildings reached their end-of-life. This attitude was expressed by one interviewee as "*a lack of sense of ownership (P3)*". Without sufficient interest and commitment as well as an adequate budget allowance from clients, the interviewees indicated that the overall practice, in some cases, became a practitioner-driven exercise in which the practitioners were imposed responsibilities to convince clients to proceed, stated as, "*we try to tell clients or educate clients of the benefits of it (P2)*". Even with these efforts, the practitioners indicated, in some cases, that the client was reluctant to adopt the CE due to its "*knock-on effect (P6)*" on cost and coordination, despite the design team eagerness.

- **Lack of mechanisms for secondary resource management:** This gap pertains to the paucity of well-established database, the lack of market and insufficient market demand for reclaimed building materials. The interviewees stated that these lacking mechanisms hindered the practice, stressed as "*the biggest barrier (P5)*".
- **Insufficient involvement of manufacturers:** The interviewees described the involvement of manufacturers as inadequate. They associated this with the lack of transparency and standardisation in the data provided by manufacturers regarding the procurement procedures and systems, which are about the rate of recycled content, the percentage of recyclability, and the geographical scope of the products. One interviewee captured this gap by stating, "*Manufacturers usually love to give you brilliant figures, but then they were not accurate (P5)*".

The following gaps were grouped at process and platform level:

- **Paucity of well-defined targets at the beginning and lack of work plan:** The interviewees shared their experiences dealing with poorly defined and "*not numerical (P4)*" targets lacking sufficient details. They attributed numerous challenges to the absence of an organised and clear work plan that precisely specifies the information format and the content and schedules its delivery.
- **Unclear models and details:** Consistent with the previous theme, the insufficient level of detail and lack of clarity in the models were highlighted as obstacles hindering the process. This limitation prevented the practitioners from conducting in-depth analyses regarding circularity scenarios and carbon reduction measures. Instead, they noted how they had to allocate considerable amounts of time to manually extracting the details, such as material quantities and specifications, from limited and often inadequate sources provided to them.
- **Lack of full compatibility of the tools to implement CE:** Given the paucity of platforms and databases indicating available resources to reuse and the lack of transparency in circularity metrics, the interviewees highlighted that these limitations hampered the capability of the plugins to facilitate the implementation of CE, as an example of statement "*…all the tools available in the market right now that they are not able to prepare this kind of particular assessments…(P1)*". Furthermore, it was noted that the absence of a link between the plugins and the limited databases or platforms providing information about the reclaimed materials in the market hindered decision-making and assessment processes. Consequently, the overall practice was indicated as partially

reliant on the tools and still requiring "*a lot of (P5)*" specialist work to be done manually outside of these tools, leading to difficulties in the practice.

Given the insufficient emphasis on CE at both the policy and organisational levels, the analysis identified three main gaps associated with the individual level:

- **Limited number of experts in the sector:** Many interviewees noted a scarcity of CE specialists with sufficient expertise to implement CE and analyse assessment outcomes. Moreover, the interviewees stated they struggled with keeping track of changes, described as "*…constant…and…large…(P2)*" and absorbing all latest information even though they had sufficient foundation of knowledge. One interviewee defined the overall process as "*steep learning curve (P3)*".
- **Limited consideration of the long-term thinking:** The interviewees highlighted a narrow focus on scenario modelling concerning the end-of-life stages and circularity of the building materials. They attributed this to a challenging process of time and resource management required for adequately considering and evaluating the long-term impacts of the materials.
- **Reluctance of the design team:** Similarly mentioned in the previous theme, the practitioners noted that there was a tendency of the design team to be reluctant to implement CE principles. They linked this reluctance with the insufficient understanding of the CE concept and its implementation in the building design practice. They pointed out that one of the main reasons the design team engaged in the process was solely to meet the requirements of planning applications or certification schemes, where its drawback described as "*plagues the entire sustainability field (P5)*". On the other hand, practitioners noted that, even if the design team is aware of the CE concept and its basic implementation, providing detailed information for the practice should be considered a challenging task for the design team.

3.1.3 Implementation of BIM to undertake LCA in the industry:

As derived from the analysis, although the use of BIM to undertake LCA was believed to offer many opportunities, the current practice was indicated as lacking to benefit from its all potential, which is still the case. The interviewees stressed that its use was primarily for visual purposes, with its geometric features dominating the industry. As a result of receding its semantic features, the BIM models were indicated as immature to undertake the assessments at the early design stage. Therefore, regarding the current practice, the interviewees pointed out that BIM models were rarely used, and the assessments were carried out based on cost plans, which are lists of the materials.

On the other hand, all interviewees expressed a desire for a seamless integration between the platforms—BIM and the plugins—as a key component for efficiently undertaking a comprehensive building LCA in terms of time and effort. It was also indicated that, when properly implemented, BIM could support the implementation of CE by storing all the information about the materials and their conditions during the asset lifecycle. This enables communication and data exchange across different disciplines, as well as specifying and managing end-of-life scenarios for the materials.

In line with these, only one gap at policy level was derived from the analysis, which is:

- **Lack of a national BIM protocol:** Concerning the process of undertaking LCA and the adoption of CE principles, it was pointed out by all the interviewees that there was a lack of a national BIM protocol tailored to guide this process involving specifications about modelling and information exchange.

The following gaps were grouped at organisational level:

- **Lack of an organisational BIM guideline:** The absence of national standardisation and organisational guidelines for the process were emphasised as leading to various challenges, such as insufficient communication across the disciplines to create a coordinated model and incompatible model design for use in LCA purposes, which are detailed in the subsequent section.
- **Insufficient demand from the industry:** Similar to the previous themes, the interviewees highlighted a constraint: the insufficient demand from the client to develop a BIM model in the current practice, which was expressed as "*…not every contractor would be willing to provide Revit model…(P3)*".

In line with the gaps at the process and platform level defined in the first theme, the following gaps derived from the analysis:

- **Lack of model granularity at the early design stages:** While the immature BIM models were accepted as inherent to the practice, the practitioners stressed that these models significantly hindered achieving a successful practice. One interviewee expressed the inadequacy of a model that just geometrically represents the building design without sufficient details about materials and design specifications. Therefore, it was emphasised that the model necessitates additional inquiries regarding the material specifications by the practitioners. The inquiry process was stressed as resulting in loads of irrelevant information for the assessments, described with the phrase "*absolutely no relevance (P5)*". Moreover, the lack of proper use of BIM led the practitioners to search for other types of resources storing information about the materials, such as operation and maintenance manuals. To highlight the difficulty and the inefficiency of this task, one interviewee used an expression "*cumbersome (P5)*".
- **Incompatible models:** The current practice was stated as being based on a multidisciplinary collaborative approach where the involvement of each discipline was important and required. Due to the lack of standardisation and guidelines, the interviewees, however, stressed a lack of coordinated models across different disciplines, noted as "*primary constraints (P7)*" and associated

with insufficient communication across the disciplines. The practitioners reported that, in some cases, the lack of agreement across disciplines, stemming from differing viewpoints on material and design specifications as well as cost considerations, heightened the challenges and intensified the time and resource demands of the practice.

- **Lack of robust integration across the tools:** The interviewees pointed out a prevalent "*manual process (P5)*" involving material mapping across the tools in the current practice. This manual process was attributed to the lack of robust integration between the BIM and LCA plugins. Consequently, it required more time and effort, as exemplified by one interviewee: "*...most of the work for the LCA happens outside of BIM software...the link is pretty much,* [*sic*] *just nothing but a conduit between the two…LCA plugins…kind of failed to map those properly…tend to combine them, grouped them incorrectly (P5)*". This was linked with the lack of a naming convention across the platforms. Similarly, the plugins were criticised for lacking a systematic structure to categorise the building elements according to the required classification system for reporting, such as RICS building element categories. The interviewees highlighted the nature of the building modelling process, which is prone to human errors leading to inaccuracy in modelling and assessment results.
- **Lack of naming convention across the tools:** Given the desired practice expressed by the practitioners, the current integration between BIM and LCA-based BIM plugins was implied as inferior to its actual potential. This limited integration was explicated by the lack of a naming convention between the platforms. One interviewee noted how laborious the process of matching non-systematically modelled building elements with available materials in the plugins was: "*…they had just done the big model, so we took it in order to do the quantities take-off and do the assessment…there were so many elements with different names that I had to link with the materials in One Click, that took so many hours...(P4)*".
- **Limited use for the purpose of data management:** It was noted that in terms of data management, current practice does not take advantage of BIM's potential to serve as a materials bank that stores all detailed information about materials. One interviewee mentioned this limitation preventing "*…to track and easily extract information…(P5)*" while the building was operating and when it reached its end-of-life phase; then noted how proper use of BIM in terms of data management could lead to implementing a successful circularity approach.

Two gaps were identified at the individual level:

- **Insufficient expertise or experience in BIM:** The interviewees admitted that they rarely encountered assessments proceeding through BIM models, as mentioned earlier as a tendency in the current practice. Given that, many of them expressed their knowledge in BIM process as "*limited (P2)*".
- **Human errors in BIM models:** Regarding the design model developed by architects, one interviewee pointed out that "*…There is a significant room for error…(P5)*" by stressing the

tendency of architects to use BIM models widely for visual purposes, where it was described as "*…-more like a 3D SketchUp model, rather than a BIM model the way it is designed to be able to actually store information…(P5)*". Due to the lack of consideration regarding the accuracy of BIM models even geometrically, the interviewees stated that these mistakes, such as modelling double or triple elements for a single element and mismatching building elements, caused inaccurate assessment results. These errors in modelling were also interrelated to the reluctance of the design team, expressed as "*seldom happy (P6)*" to provide a BIM model with sufficient details at the early design stages. While a majority highlighted the reluctance of the design team to provide a BIM model, a minority mentioned the resistance of the design team to proceed with accurate modelling where low levels of profits are concerned.

3.2 The emerging needs and requirements

The needs and requirements that enable the process to be facilitated and disseminated are also categorised under the four levels explained in Section 3. This categorisation not only provides the ability to prioritise requirements but also presents them in a structured way, allowing for the navigation of adequate attention and resources to enable corrective actions. Figure 2 shows an entity-relationship diagram illustrating the connections between the identified gaps in each field and the framed needs to address challenges.

3.2.1 Policy level: Required actions by policy makers

Since the current policy was perceived by the interviewees as impeding the practice, several requirements centred on the importance and influence of regulatory enforcement to undertake the practice and monitor the process to ensure consistency and accuracy in the reported results. The most highlighted enablers for both accelerating the transition to a circular built environment and undertaking a building LCA were the availability of national and local policies regulating the consideration and implementation of the practices. In the context of circularity, the necessity for clear and well-conceived standards and frameworks was underscored to guide the practice and ensure its proper execution. Furthermore, the need for clear benchmarks was noted to provide an indication of the predicted performance and prioritising aspects for more detailed consideration and analysis. To enable consistency in measurements and reports, there was a need for well-defined and "*more quantifiable (P2)*" circularity metrics. All these were stated as key enablers of establishing a common methodology for successfully implementing CE principles in building design. Considering that many interviewees revealed limited experience in carrying out building LCA through BIM models in current practices and underscored the BIM use for implementation of CE principles being still in infancy, they emphasised the potential role of a national BIM protocol in guiding stakeholders and promoting the effective implementation of these practices.

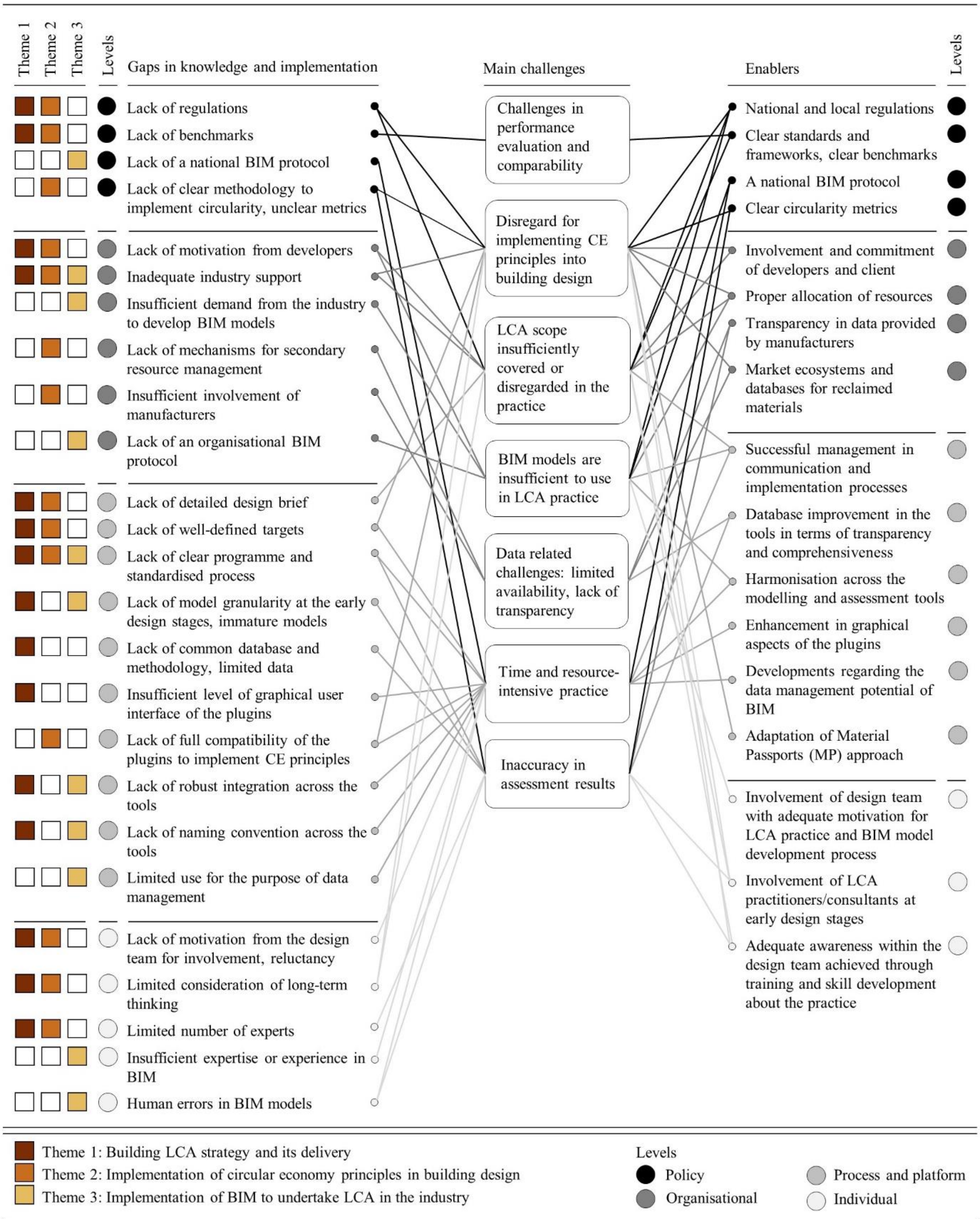

Figure 2: *An entity-relationship diagram for mapping gaps, challenges, and enablers (Source: authors)*

3.2.2 Organisational level: Involvement of organisations and developments in the sector

The interviewees stated the importance of the involvement of developers and clients who are motivated to undertake the practices and even have the ambition to achieve decarbonisation and promote the transition to a circular built environment. Similarly, there was a need for adequate demand from these stakeholders to undertake these practices through BIM platforms. Associated with their commitments, the need for a proper allocation of resources, especially in terms of finance, time, and staff, was expressed to foster the overall practice. Moreover, the interviewees noted the need for transparency regarding the environmental performance of the buildings to support benchmarking as well as the provision of clear and open information about the materials by the manufacturers.

In the context of circularity, the availability of market ecosystems and databases for reclaimed materials, along with the need for access to these databases through plugin platforms, were indicated as enabling stakeholders to make data-driven decisions at any project stage, particularly at early stages.

3.2.3 Process and platform level: Enablers in communication and implementation process management

All interviewees agreed on the need for having successful management in both the communication process between the stakeholders and the implementation process of the principles and the tools in the current practice. As a starting point of the management, it was required to have a detailed project brief prepared within the consideration of undertaking a building LCA practice and implementing CE principles into the building design. This brief should clearly outline the aims, specific objectives, and expectations of the developers and clients. The practitioners perceived its advantages as preventing them from dealing with "*written down in vague glorified briefs (P2)*" and providing clear understanding of the required actions.

The interviewees expressed the importance of well-defined project information requirements at the beginning of the project to frame and manage project tasks. The availability of these requirements could aid in fostering clear and structured communication between stakeholders. This could eliminate immediate information requests at unexpected stages and contribute to fulfilling the project aims and objectives by drawing upon the knowledge and experience of each member of the team. In addition, a standardised information exchange process was highlighted as crucial for enhancing the collaboration between the disciplines and improving the quality of information shared for completing the related tasks as well. The interviewees also noted the importance of a clear schedule of completion for efficient time and resource management during the practice.

Regarding the use of LCA-based BIM plugins, the requirements for the desired practice defined by the interviewees particularly focused on two plugins, eTool and One Click LCA. Concerning the coverage and regional representativeness of the databases, one interviewee (P2) implied the requirement for an improvement in the database of eTool. Criticising the variety of plugins and tools with differing databases and methodologies, the interviewees suggested having a common platform to undertake all assessments to streamline the practice and aid in benchmarking. Moreover, considering the availability of different plugins in the current practice, the interviewees highlighted the need for developments on these plugins to improve their integration with BIM platforms. The main enabler for achieving seamlessly integrated modelling and assessment platforms was indicated as having a naming convention between the plugins and BIM platforms, which saves time and resources during the assessment by reducing the manual material mapping process, expressed by the desires of: "*...If you have a standardisation of name…so that the names you have in the Revit model are automatically recognised from the tool and automatically translated to emissions, then it's absolutely fantastic!…(P4)*".

There was a common evaluation of the functionality of the plugins in adopting CE principles and assessing the circularity of the design, which was indicated as limited. As enablers, the interviewees suggested some features needing to be developed for the plugins. These improvements were about addressing specific details regarding reused and recycled content in materials to make informed decisions and providing options in the end-of-life scenario modelling process to reflect circularity in the design.

The interviewees expressed the further potentials of BIM, provided that some developments and enhancements regarding data management exist. One of the potentials was about using BIM as material banks, expressed by "*a container of information (P1)*", where all the geometric and semantic data of the materials used in the building, such as their specifications, quantities, and performance, were involved. Concerning facilitating the implementation of CE principles, the interviewees pointed out how effectively this use could assist in specifying end-of-life scenarios for the materials and insightfully leading design decisions by more accurately quantifying the materials and providing information regarding their conditions. Considering the capability of BIM to digitally record data regarding the materials and provide transparency in them, they specified multiple benefits of the BIM-integrated MP approach in assisting and supporting the transition to a circular built environment, explained as "*...by developing the Material Passports, we will be able to have more transparency and feel more safe* [sic] *about making any decisions of reusing materials…(P4)*". Linked to the Digital Twin technologies, one interviewee mentioned the potential of this approach to overcome data management: "*...a twin building…that exists virtually where you are able to track and easily be able to extract that information…(P5)*". One interviewee noted the need for more integrated platforms, or even standalone platforms, reducing the need for third-party tools to execute the associated practices. Similarly, another expressed the importance of introducing environmental impact data in the material library used in BIM platforms. It was linked to the capacity of BIM to be a "*central hub (P7)*" where all data is stored and required assessments are undertaken.

3.2.4 Individual level: Awareness and involvement of the design team

The involvement of each project team member was implied as an important requirement to make adequate progress during the practice of both undertaking a building LCA and adopting CE principles into the building design. To enable the practices to proceed through BIM platforms, adequate motivation from the design team, especially from the architects, was required to develop and provide BIM models at early design stages. Since the interviewees attributed the lack of motivation of the design team to the knowledge level of the team; they highlighted the importance of the "*educational process (P1)*", referring to having a good understanding of the LCA and CE concept as well as their implementation, to break the unwillingness of the design team within this context and contribute to undertaking a successful practice. Furthermore, the early engagement of the specialists, such as LCA consultants and CE experts, in building design was stated as an enabler to emphasise the importance of considering circularity at the first stage and to make "*substantial impacts (P7)*" in terms of reducing the impacts of the proposed design. Constantly engaging with industry and being up to date with the latest policies were additional requirements mentioned by interviewees.

4. Discussion

Despite the growing attention regarding the LCA and CE concept in the built environment, the results portray the general practice as not reflecting this enthusiasm and lacking adequate consideration of circularity and LCA implementation in the building design process. Hence, **a lack of clear structure and consensus** on how to implement those remain gaps which make the practice still limited. **Legislation** and **policies** play a crucial role in achieving the decarbonisation of the built environment by regulating the practice, offering a standardised approach for the practice, and encouraging all stakeholders to consider environmental performance and circularity of buildings within their agenda. Many studies in the pertinent literature stress the influence of policies [16][36][37]. In the absence of regulations in the practice, the pursuit of undertaking the assessments is dominated by a focus on green building certification purposes and requirements of planning applications. However, both considerations overlook potential benefits of the practice during the decision-making process. As in previous studies [16][38], the results show that **limited awareness** and **inadequate knowledge** of implementing these assessments are the primary constraints in cultivating the enthusiasm for the uptake of these concepts in the building design process. Considering the findings, it seems difficult to pursue a successful sustainability practice without fostering mechanisms, especially **regulatory requirements**, and continuous, effective **training** to upskill the workforce, which are indicated in several studies [28][29][36] as well.

Current practice suffers from a lack of data standardisation for circularity and limited resources for managing circularity data. The **availability of clear circularity metrics** enables the assessment and measurement of the circularity performance of the building; the importance of these metrics is also highlighted by Charef and Emmitt [29]. Regarding the management of circularity data, MPs have considerable potentials as digital resources providing access to insightful information regarding materials, as well as monitoring lifetime interventions and maintenance activities in the building with the help of the Digital Twin integration. Despite the popularity of the concept of MPs and a growing number of technologies in this field [39], the interviewees have not shared their experiences in using them in the practice, aside from expressing their opinions about the potential of adopting MPs into the design process. This is because these technologies are still in their infancy and rarely adopted in the current practice. Associated with this, Giorgi et al [28] stressed the pressing need for new professionals with specialised skills, particularly in areas related to BIM, MPs, and LCA, as well as the requirement of trainings to enable utilising these technologies. There are other emerging technologies in developing digital marketplaces for reclaimed building materials. For example, Madaster [40] and Globechain [41] are digital platforms developed to increase the value of these materials and provide transparent access to them. The availability of these marketplace platforms could aid the transition to a circular built environment by prolonging material life, eliminating waste, and reducing carbon emissions [42].

In addressing the implementation of LCA and CE principles, the results obtained herein demonstrate a significant challenge: the lack of systematic structure and coordination in executing these practices leads to diverse approaches, impeding the accuracy of assessment results. The analysis revealed that the practitioners see considerable potential in using LCA-based BIM plugins. However, their primary concern about the efficient building design process lies in the **lack of a structured workflow and robust integration** between the modelling and assessment tools. Similar constraints regarding the process and practice have also explored by Zimmerman et al. [15]. Hence, **the availability of mechanisms for communication and process management** can play a significant role in delivering successful practices by deepening engagement among stakeholders, standardising the information exchange process in a time and resource-efficient manner. To facilitate robust integration between the tools, two factors become fundamental. The first is **the availability of a standardised structure** for organising and grouping building elements and components. The second is **the need for harmonisation** among the classification system used in modelling, the data structures adapted in the LCA-based BIM plugins, and the categorisation structure of building elements followed in reporting in the current practice, such as RICS building element categories for the UK. While the former is vital for providing transparency and accuracy of building data [43], the latter supports interoperability and automation by enabling recognition of materials for an accurate mapping in the plugins [16].

Regarding the use of BIM, the current practice is still dominated by conventional workflows, and it seems not yet ready to harness the full potential of BIM. This study revealed multifaceted challenges and barriers impeding the proper and wider implementation of it. They are **the limited availability of skilled professionals**, **the lack of consistency and coordination in the modelling process**, and **the constraints on time, resources, and budget** allocated to the design team. These factors contribute to **the immaturity in the models**, both in geometric and semantic terms, which is a challenge also implied by Schumacher et al. [36]. Regarding the barriers, literature [44][45] also states the limited financial capacity of companies, especially small and medium-sized enterprises (SMEs), in using BIM platforms during the building design process. However, it is not observed in this study. This might be related to the limited sample size of the study and the sample pool inherently involving practitioners from larger companies.

5. Conclusion

As the first step of implementing a co-production approach to developing a BIM protocol for the use of the LCA-based BIM plugins to support the implementation of CE principles into early-stage building design, this study provides a comprehensive overview of the current state of the industry in undertaking the LCA practice and implementing CE principles into the building design process and insights into the improvement of these practices. Through enhanced engagement of the practitioners, the findings of this study shed light on what gaps exist in the knowledge and implementation in the current practice and how they impede the process. In addition, this study delineates the needs and requirements to achieve the desired process. Therefore, this study, as an action that scholars can take to improve the current practices, enriches the existing grey literature by presenting empirically validated findings.

This study demonstrates that the adoption of the co-production approach is a promising method for investigating the research phenomenon concerning both the issues in the current practice and the evolving needs of the industry. Similarly, Giorgi et al. [28] emphasise the importance of collaborated efforts and co-creating process to develop strategies facilitating the application of circular economy strategies in the construction sector. The novel outcomes of the study discussed in this paper can enhance the workflow in the practice and promote wider applicability of the tools and principles with increased contextual awareness and readiness to apply them among the stakeholders.

Aligned with the discussion of the findings, the key messages can be concluded as follows:

- The current practice requires the introduction of enabling mechanisms, particularly **legislative instruments**, to regulate and lead the application of LCA and CE principles.
- As an inherent repercussion of inadequate legislation and policies, a notable constraint is observed in the awareness and motivation levels among the stakeholders concerning active involvement in and commitment to the associated practices. Therefore, it becomes fundamental to provide **training programs** to enhance the skill set of the workforce, ensuring proficiency in the practice.
- Given the insufficient use and limited adoption of BIM in the current practice, there is a need to develop **a structured workflow** for the execution of LCA and CE principles in the early-stage building design.

5.1 Limitations of the study

It must be kept in mind that the generalisability of the research outcomes is subject to certain limitations. One limitation of this research was the small number of interviews. This was mainly because of the focus of the research on eliciting insights from expert voices. While the purposive sampling strategy aligns with the study objectives, certain issues emerge with this selection. The access to state-of-the-art and advanced tools requires considerable licensing costs, and proper training is imperative for their effective use [46]. Consequently, participants in studies focusing on expert voices are more likely to be affiliated with prominent organisations rather than SMEs. In line with this, the sample selection in this research reflects this dynamic, where the participants are expected to be part of specific and larger organisations that have the resources to dedicate to the associated practices. It inevitably introduces a degree of selection bias. While the inclusion of SMEs in the sampling pool would have potentially allowed for the inclusion of a diverse range of perspectives, it could be argued that the absence of SMEs within the sample pool is reflective of the case in wider practice, where SMEs often lack resources that could be dedicated to the implementation of LCA within the organisation. Therefore, the sampling in this study may reflect an industry pattern rather than an actual limitation. Furthermore, this study provides a snapshot of the current practice in the UK; therefore, the findings may not necessarily reflect long-term trends and changes in the UK practice and may not be applicable to practices in other countries.

During the Covid-19 closure and restrictions, social distancing measures limited face-to-face interactions and full engagement with the industry practitioners. Despite challenges, the Covid-19 pandemic introduced new opportunities, prompting the development of more efficient modes of digital engagement and data collection approaches [22]. This research benefitted from the utilisation of digital platforms to connect with the participants across various locations in the UK.

5.2 Future research

Thanks to the novel insights derived from the evaluation of the findings, this study elevates the importance of strategic guidelines, actions, and coordinated communication and process management. Through the joint framing of these elements, this study serves as a starting point for a co-production cycle concerning the development of a structured framework to manage and enhance the communication and information exchange process during the building design and the execution of the LCA and CE principles. Therefore, the next step of this research is to formulate a structured BIM protocol tailored for organising and streamlining the modelling and implementation processes, especially in the early design stages. It will serve as a useful instrument for the design team by clearly defining information requirements, delineating roles and responsibilities, and providing a structured information exchange process during the practice. The authors believe that this initiative can create momentum that may, over time, result in changes in the practice and industry, such as increasing the motivation and commitment levels and the number of experts involved with the associated practices.

This study elucidates the gaps in the current state of digital tools. Given the variety of tools and a lack of compatibility between them, further developments should be pursued for harmonisation across the modelling and assessment tools with the help of standardised data structures. In addition, further research could investigate the practical implementation of MPs by outlining information requirements for creating MPs and exploring the potential of introducing Artificial Intelligence (AI) technologies into MPs to enhance data accuracy regarding the condition assessments of the materials.

CRediT authorship contribution statement

S. Atik: Conceptualisation, Methodology, Investigation, Data curation, Formal analysis, Software, Visualisation, Writing – original draft, Writing – review & editing. **R. Raslan:** Conceptualisation, Methodology, Supervision, Validation, Writing – review & editing. **T. Domenech Aparisi:** Conceptualisation, Supervision, Writing – review & editing.

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.

Compliance with ethical standards

This study was undertaken as a part of an ongoing PhD research: Investigating the effectiveness of implementing LCA-based BIM plugins in early-stage building envelope design. This study is registered with UCL Data Protection (Z6364106/2020/05/148) and has been approved by the UCL BSEER IEDE Research Ethics Committee (20200506_IEDE_PGR_ETH).

Acknowledgement

The PhD research has been funded by the Republic of Turkey Ministry of National Education. The authors would like to acknowledge the interview participants for generously giving their time and providing the most valuable information that was of vast benefit to the data collection.

Disclosure statement

During the preparation of this work, the authors used ChatGPT 3.5 to identify and correct grammatical errors in the paper. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Appendix A. Supplementary data

Supplementary data to this article can be found online at [*link*]

The Authors' Accepted Manuscript

This is an Authors' Accepted Manuscript version of the following paper: Şeyma Atik, Teresa Domenech Aparisi, and Rokia Raslan, 'Mind the gap: Facilitating early design stage building Life Cycle Assessment through a co-production approach', published in Issue 464 (2024) of the Journal of Cleaner Production, under the guidance of the handling editor, Mattias Lindahl.

The final authenticated version is available online at: https://doi.org/10.1016/j.jclepro.2024.142803

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