Life cycle cost analysis at scale: a reference architecture-based approach

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Abstract

Purpose – This research demonstrates the theoretical merit of a reference architecture-based approach to life cycle cost (LCC) analysis system provision in the built environment. LCC insight is considered fundamental to sustainable decision making by asset managers; however, the current capabilities in practice do not align with the political ambition and the scale of competencies required to realise sectoral emissions-reduction targets.

Design/methodology/approach – In pursuing practical outcomes, the study employs a custom design science research-inspired methodology. Domain requirements are gathered via literature research as an initial top-down software reference architecture which is refined, bottom-up, through testing and implementation in a representative case study. A prototype IT system and reference architecture artefact are developed and used to evaluate the concept qualitatively through broad practitioner focus groups.

Findings – Sentiment analysis of the expert opinions is broadly positive and helps to substantiate the proposal’s theoretical suitability in addressing the scalability challenge. Additionally, constructive feedback provides guidance towards this trajectory, highlighting the importance of aligning with existing communities and standards, broadening future research scope to consider further scenarios and prioritisation of efforts to build trust around contracts and data quality.
1. Introduction

The built environment accounts for a significant proportion of global resource use, around 40% (UN Environment and IEA, 2017) and is thus a major contributor to climate change. Within the built environment, the operational phase of the building life cycle comprises the majority resource use, around 70% (Geekiyanage and Ramachandra, 2018). Reducing the burden of this lifecycle stage is therefore a priority for research to align with policy objectives, in Europe, for example, around sustainable transition finance (European Commission, 2023b) and recent regulation for organisations to report their Environmental, social and governance (ESG) performance (European Commission, 2023a). Asset managers (AMs) create value for organisations during this operational lifecycle phase by effectively maintaining and operating facilities on their behalf (Salvado et al., 2018). A fundamental knowledge category for strategic decision making by AMs is insight into the life cycle cost (LCC) of a component which accounts for expenses beyond the initial investment and can facilitate value-based decision making (Kehily and Underwood, 2017). For this reason, policymakers consider LCC analysis a key mechanism to ensure value for public expenditure (European Parliament, 2014).

LCC is a well-established science used in many industries; however, in the built environment, several challenges limit widespread adoption, including the inherent difficulty in predicting future events, the organisation-specific nature of value creation and the data-intensive and non-standardised nature of inputs to support analytics within IT systems (Santos et al., 2019). All of this means that implementations in practice tend to be case-specific and difficult to reuse in other scenarios, and despite widespread recognition of the generalisation problem, the research and commercial trajectory remains comprehensive and monolithic product-focused. Reference architectures, in contrast, provide high-level blueprints to support IT system building by software developers by describing generalisable design patterns (Gamma et al., 1994). But despite being well-established as a scalable strategy in other sectors, they have yet to be proposed as a means to address LCC system deployment.

Given the case-specific nature of LCC analytics in practice, as well as the ambition for large-scale adoption, an extensible reference architecture-based approach seems a reasonable proposition; Hence, the main aim of this research is to evaluate the suitability of a reference architecture-based approach to LCC analysis system provision. Research objectives towards this aim are to

1. **investigate** how LCC research to date has addressed scalability, identify the research gaps and pose a hypothesis;

2. **propose** a methodology, which includes the development of a LCC reference architecture, to test the research hypothesis;

3. **evaluate** the theoretical merit of a reference architecture-based approach to LCC system availability and identify the wider considerations to support this trajectory.
A methodology based on design science research (DSR) is developed in order to evaluate the theoretical merit of the concept. Domain requirements are gathered to form an initial LCC reference architecture concept. The solution is then refined through implementation at a representative AM case study, and subsequently, both the solution artefact and the theoretical concept are evaluated qualitatively with a wide expert group. In doing so, theoretical merit is established and future work outlined. The ambition of this approach is not a comprehensive description of all possible LCC scenarios, but to provide a foundation that can be extended for individual use cases. The novelty and contribution of this work is the provision of a reusable development and evaluation methodology for LCC reference architectures. These results can guide both policy and research efforts towards pragmatic solutions that solve the real domain challenge of aligning analytics and reporting capabilities with political sustainability ambition.

The remainder of this paper is structured as follows. Section 2 investigates the research gaps relating to scalability of LCC systems which motivates the study and justifies the methodological choice. Section 3 describes a custom methodology to test the research hypothesis. Section 4 details the steps to develop, demonstrate and evaluate a LCC reference architecture. Section 5 presents the results, and finally, Section 6 discusses the findings, including the potential wider implications and recommendations for future research.

2. Background and motivation

2.1 Life cycle costing in the built environment

Decision-making within the built environment tends to be shortsighted and based primarily on upfront costs (Grzył et al., 2017; Ashworth, 2021). In contrast, providing value-based insight through LCC analysis is recognised as promoting long-term, holistic decision making (Nisar, 2013; Wang et al., 2014), supporting sustainable development. Perhaps the most tangible pillar within a wider Life Cycle Sustainability Assessment (LCSA) framework (Dong and Ng, 2016), LCC methods underpin sustainability mechanisms such as ESG reporting, the EU Taxonomy and the EU’s ambitious building certification framework, Level(s), where LCC (indicator 6.1) is a key metric (Dodd et al., 2021). Salvado et al. (2018) discuss the regulatory and non-regulatory environment of LCC in detail, and in the context of the domain trend towards performance-based contracting over the lifecycle of assets, their work aims to “trigger more frequent application of LCC”. They identify a key Directive (2014/24/EU) that calls for “cost-effective LCC approaches” (European Parliament, 2014); in other words, it appeals for broad accessibility of LCC competencies. This represents an acknowledgement of the practical challenge of requiring complex reporting within the built environment, a sector comprising ~85% micro to small-medium enterprises (Eurostat, 2020), where complex reporting requirements can pose a barrier to entry. A further indication of political ambition is a recent UNEP (2023) report which identifies the funding of “methodological developments for whole lifecycle assessments” as a key objective for policymakers. But despite the potential benefits, political appetite and impending requirement for use, LCC analysis remains underutilised in practice (Goh and Sun, 2016). Gao and Pishdad-Bozorgi (2019) explain that, currently, LCC is used mainly for comparative purposes in estimating costs at design tender stage; however, the possibility of supporting progressive performance-based contracting during the in-use phase means that the full potential is not being realised.

Domain challenges which limit the wider application of LCC methods have been discussed extensively, and include the lack of standardisation, data scarcity/variability/quality issues, and the inherent complexity in attempting to predict future events (Gao et al., 2020; Noorbakhsh et al., 2020; Lu et al., 2021). The imperative for addressing these challenges is demonstrated by the research community’s great efforts, detailed by Lu et al. (2021) in their seminal domain review. Although advances have been made in several key areas,
a generalisation problem remains due to the case-based nature of LCC analysis (Santos et al., 2019), making it challenging to reuse processes in other contexts. Thus, none have yet been widely adopted. Moreover, it appears that the trend in both research and industry is towards comprehensive, monolithic IT system provision, evidenced by research contributions which suggest generality through, perhaps, a small number of case studies. Common methodologies are nonetheless a valid research aim. Standardisation within any field can facilitate reproducability through verifiable, top-down processes, and indeed, LCC calculation formulae and other domain knowledge are already formalised as international standards (such as ISO 15686, ISO 21930, EN 15978 and the new ICMS 3), which specify analysis techniques. Carrying out LCC analysis in practice, however, can be tedious, time-consuming and error-prone (Meynerts et al., 2017). Recent research efforts address the significant data-processing challenge by formalising domain knowledge as machine-readable ontologies (Gao et al., 2020; Sobhkhiz et al., 2021; Wilde et al., 2022; Ghose et al., 2022), providing reusable data models and are a path towards standardisation; however, a general consensus has yet to be reached. Furthermore, despite the existence of standards detailing LCC methods and formulae, an agreed set of technically mature analytical IT functions that cater to a broad set of stakeholders is missing.

2.2 Reference architectures as a path to scalable life cycle cost analytics

In relation to IT systems, the term scalability refers to the capacity of a product or service to be deployed in multiple contexts with minimal adaptation or cost (McGlinn et al., 2017). The Digital Impact Alliance (2023), in partnership with the UN Development Program, specify ‘Principals for Digital Development’ that describe designing for scalability as “thinking beyond the pilot and making choices that will enable widespread adoption later, as well as determining what will be affordable and usable.” Research in the related field of building analytics, such as Lin et al. (2022) and Mavrokapnidis et al. (2023), provides examples of pragmatic, practice-focused studies which address application scalability. There is, however, no standard evaluation metric for scalability, a consequence of the broad interpretations and abstract nature of the concept. The above works are evaluated quantitatively, based on the number of lines of code requiring modification for new contexts, while others, such as McGlinn et al. (2017), use qualitative metrics.

Characteristics indicating scalability in IT systems are relatively well agreed upon, and include being implementation language agnostic, high-level, extensible, reasonably affordable/accessible, widely applicable and capable of capturing domain knowledge (Gamma et al., 1994). Reference architectures, which “model the abstract architectural elements in the domain of interest independent of the technologies, protocols and products that are used to implement a specific solution” (European Innovation Partnership on Smart Cities and Communities, 2017), embody these characteristics and are, thus, considered a scalable approach to IT system deployment in computer science theory. Evidence of reference architectures supporting scalability in other domains include ISO 23247 (ISO, 2021) which provides a blueprint for automation system interaction for advanced manufacturing, while the European (energy) data exchange reference architecture 3.0, or BRIDGE (European Commission, 2023), plays a similar role for stakeholders in the energy sector. Both examples ensure interoperability of the inevitable case-specific solutions and set out system design patterns and relationships. Such extensible blueprints provide technical design guidance for software developers, reduce requirements-gathering effort (a significant exercise in IT system building), support scalability and ensure alignment with domain standards and regulatory requirements.

2.3 Synthesis and research gap

Current LCC analysis capabilities in industry do not align with the sector’s environmental policy objectives, and aside from efforts to formalise LCC concepts as reusable ontologies,
existing research contributions remain case-specific and difficult to reuse. Furthermore, both research and commercial efforts have focused on comprehensive IT solution development, yet such an approach faces obstacles related to case-specificity (requiring flexibility) and the sector’s organisational makeup (requiring affordability), hindering the provision of LCC competencies at scale. This prompts the exploration of alternatives to comprehensive, product-based LCC solutions. Considering the success of high-level, extensible reference architectures in achieving scalability of IT solutions in other domains, we hypothesise that

**H1. A reference architecture-based approach may be a suitable path towards scalability of LCC capabilities within the built environment.**

Such extensible design patterns, which could be tailored for specific cases, can potentially deliver the necessary analytics at scale, in line with the sector’s deployment goals. The next section describes a methodology to evaluate the merit of this proposition.

### 3. Research methodology

Given the nature of the research gap and stated aim, this study requires a methodology that can both demonstrate a concept’s theoretical merit and bridge the theory-practice divide to support practical outcomes. Compared to traditional scientific methodologies, which tend to be more theoretical and linear, DSR is exploratory and iterative by nature, and can lead to the discovery of novel practice-oriented contributions through the exploration of parallel disciplinary domains.

We adapt the framework proposed by Holmström et al. (2009) which sets out incubation, refinement, substantive and formal theory phases. The authors explain that work in an applied operations management field, such as AM, typically makes use of the first three, with formal theory building as a potential follow-up step. The third phase “contributes to the generalisability of the results […] not in the statistical sense, but rather in the theoretical sense” (Holmström et al., 2009). In other words, it establishes theoretical merit of an idea. In this way, DSR differs from traditional theory building in that it develops or improves technologies, evaluating them in practical settings which accounts for the complexities of reality versus theoretical testing alone.

Kehily and Underwood (2017) explain that to contribute new knowledge using DSR, an artefact must be “developed and evaluated through an articulated formulated process to determine its effect on the environment to which it will be introduced”. Their DSR-based study employs expert focus groups to evaluate usability of a LCC solution. Such expert opinions offer nuanced viewpoints and insight, as demonstrated by Ashworth (2021), who uses focus groups to validate a research hypothesis. In both cases, an artefact is required in order to conduct effective focus groups; Thus, this research includes the development of LCC reference architecture artefacts to evaluate a solution in practice. Although no reference architecture development methodology exists specifically for LCC, several were investigated and inspired the research design. Schäffer et al. (2021) employ a user-centric approach, using Agile-type refinement iterations, and Rogers et al. (2023) provide extensive advice on requirements gathering and evaluation techniques. A list of development steps which guide our approach include

- background research;
- define scope/business cases;
- requirements gathering;
- assess available resources for reuse/alignment;
- select representation method;
solution design;
- testing/implementation/refinement; and
- documentation/deployment.

Figure 1 outlines the research methodology for this study. In the incubation phase, we identify the research gap, propose and justify a possible solution and devise a research design. The refinement phase constitutes the main contribution to knowledge, a novel methodology for reference architecture development in the LCC domain. With the intention to address scalability, we first capture the domain requirements (top-down) from background literature research as a concept design. This initial artefact is subsequently tested through implementation at a representative case study and refined (bottom-up) in an iterative software development process. Finally, the prototype and overall concept are evaluated qualitatively based on project-specific criteria through sentiment analysis of domain expert focus groups. The outcome of the evaluation stage brings us to the third phase of the DSR framework, substantive theory, where we aim to establish the theoretical merit of the proposed concept. The following section describes the research methods involved in the refinement phase.

4. Developing a reference architecture for life cycle costing IT systems
This section describes the research activities for the refinement phase of the DSR methodology in detail, addressing research objective two, and constitutes the main contribution of this study. The results of this section are used to substantiate the research hypothesis.

4.1 Domain requirements for life cycle costing systems
In this initial step we develop a reference architecture concept design by establishing the wider AM domain requirements for LCC IT systems. Various sources are considered including academic and non-academic literature, international standards, previous ethnographic work with AM practitioners (Shaw et al., 2023) and other supplementary interviews. We also draw on the background research from section 2.

Source(s): Adapted from Holmström et al. (2009)
An important first activity in reference architecture development is establishing a clear scope and boundary. The LCC domain review by Lu et al. (2021) highlights “a lack of studies that encompass multiple lifecycle stages” with limited application beyond the tender stage. To address this gap, the scope of this research centres on the AM as a pivotal stakeholder across the building lifecycle, especially in the use stage where the real potential for LCC can be realised (Gao and Pishdad-Bozorgi, 2019). In terms of business functions, AMs typically need to understand the life cycle value of their portfolio, assess the impact of decisions, and report performance in terms of cost to their employer organisation. A list of broad functional and non-functional domain requirements which guide the initial solution include:

- flexibility/adaptability for case-specific implementation (i.e. user is not over-constrain);
- visualisation of analysis/reporting;
- perform life cycle cost calculations;
- data aggregation per various categories;
- access/integrate asset/cost data;
- provide decision-support/recommendations;
- align to domain standards, as required;
- intuitiveness/ease of use; and
- cost-effectiveness/accessibility.

Reference architectures can be represented in various forms. The Unified Modelling Language (UML) is widely accepted as an effective means of communicating software/system design. Simple and visual, UML diagrams are useful for communicating with both technical and non-technical stakeholders (Maul, 2000). Additionally, because UML is language-agnostic, design patterns can be implemented downstream in any programming language, reflecting its scalability. Other communication tools, such as process maps and textual descriptions, can also represent aspects of reference architectures (Muller, 1999), and so a variety are employed, as required. A conceptual framework (Figure 2) is developed using the Business Process Modelling Notation (BPMN) method to describe a generalisable scenario where an AM utilises a decision-support system that provides LCC analysis insight based on the above domain requirements. The framework represents abstract information flows and interactions between stakeholders and forms part of the initial reference architecture design, which is refined throughout the following steps.

4.2 Refining the reference architecture through implementation and testing in a case study

Implementation and testing in reference architecture development ensure that the high-level concepts are usable in practice and can refine solutions through problem-solving in specific business contexts. A suitable implementation case is representative of wider phenomena, so for our purposes, the case should feature AM where LCC analysis is required.

A major European infrastructure facility was selected as the case study; the tier-1 AM contractor is responsible for operating and maintaining ~5,000,000 m² of transport infrastructure comprising ~30 mixed-use buildings, all owned by a single client. The case study is of particular interest due to the progressive contract stipulation between AM and owner of the need to reduce total-cost-of-ownership (TCO) by 10% over the 10-year contract period through effective asset management. This business goal is, of course, only one of potentially numerous. For example, in public-private partnerships the AM strategy is
Figure 2. BPMN diagram representing continuous AM enhanced with a LCC decision-support system which constitutes the initial reference architecture.
typically to run at a minimum cost and ramp up investment at the end of the contract period to hand over at the agreed condition. In any case, the objective of AM is to “realise value from assets in the achievement of organisational objectives”, with the interpretation of value being defined by the organisation (ISO, 2016). The takeaway here is that reusable analytical functions which support various AM goals exist. These functions, relationships and concepts can be formalised as elements of a LCC reference architecture. TCO reduction is increasingly a driver in the built environment and will be a Key Performance Indicator (KPI) of sustainability reporting mechanisms such as the Level(s) framework in future. Thus, this case study is deemed suitably representative.

This implementation and testing step follows a typical iterative software development cycle involving requirements gathering, IT system prototyping and validation with users. To support these activities the main researcher conducted ~60 hours of semi-structured interviews with diverse stakeholders from both the AM and client organisation. In fulfilling their contractual obligations, the AMs at the case study routinely carry out LCC exercises but rely on a cumbersome spreadsheet-based system. While previous research endorses a spreadsheet-based approach for its adaptability to the case-based nature of LCC (Kehily and Underwood, 2017), this practice currently limits the AMs from adjusting the study period in their model dynamically, the client having negotiated a change in analysis terms from over contract life (~10 years) to over whole asset life (~80–100 years). This necessitates a programmatic approach as a fundamental requirement. Based on the AM goal in this case, the prototype should:

1. calculate total aggregated life cycle costs (i.e. TCO);
2. simulate decision scenarios and make recommendations; and
3. measure and report performance over time (regarding TCO reduction/variance).

These case study user requirements reflect closely the wider domain requirements established in the previous step and feature reusable patterns. Based on this specification, a prototype LCC IT system was developed using Python 3 with the Pandas and Matplotlib packages (Supplementary_Materials_Appendix_1 describes the three developed functions). The strategy comparison module (Figure 3) allows users to simulate decision alternatives. By considering operation costs over the asset life, an evidence-based, long-term value decision can be made. The prototype underwent several iterations, incorporating and validating various capabilities, such as calculation, aggregation and visual representation components. The prototype was tested using economic assumptions from the AM’s current LCC model and information from the facility asset register, which comprises ~4000 assets and includes data typically available per asset, such as historical acquisition, energy, and maintenance costs, as well as predicted costs and their frequencies.

The reference architecture was refined based on insights gathered throughout this implementation phase. For instance, it was found that the initially proposed data model over-constrained practitioners in the case study, which resulted in further abstracting the reference architecture design. In another example, UML sequence diagrams, a key representation technique used by software developers (Muller, 1999), were found to be useful in describing both data transformations and exchanges between parts of the IT system while remaining programming language-agnostic (see Figure 4), and were thus utilised, further refining the reference architecture artefact.

Overall, this refinement step indicates that the requirements of the case study broadly align with those of the initial reference architecture design which were based on wider domain requirements. The resulting IT system prototype can be used to evaluate the research hypothesis with practitioners in the next step. Furthermore, through the learnings from this...
activity the reference architecture is simultaneously refined, providing an enhanced blueprint for system developers while also abstracting the concepts for wider applicability.

4.3 Evaluating the reference architecture using expert focus groups

Addressing research objective three, the LCC reference architecture concept is evaluated qualitatively by analysing the sentiments of a carefully selected cohort of AM stakeholders based on two overarching questions: “Does the reference architecture support the provision of useful insight?” and “Does the concept offer a suitable approach to address the availability of LCC systems?”. KPIs can be used to evaluate software solutions and frameworks, as demonstrated by Ashworth (2021), and a similar approach is employed in this study. The following criteria were refined throughout the research to fit the specific objectives, and encompass both the scalability indicators (section 2.2) and the domain requirements (section 4.1). They are:

- usefulness and insight;
- flexibility and ease of use; and
- representativeness and scalability.

Participants were selected for their specific expertise and represent the broad subject areas involved in this study, including AM, LCC, software development and public procurement (Table 1). Participants were provided with background information (including supplementary material in Supplementary_Materials_Appendix_1 and Supplementary_Materials_Appendix_2) ahead of a 1.5-hour online meeting. Each session was tailored to suit that specific cohort’s contribution to the study. For example, the software developers scrutinised the reference architecture diagrams in detail, whereas AM practitioners received an overview of this content, instead focusing on the IT system prototype. In all sessions, the researcher introduced the prototype, which participants could test/adjust by adjusting the
Figure 4. UML sequence diagram describing the information transactions between different parts of a potential LCC IT system.

- **Aggregate TCO (Function 1)**
- **Simulate options (Function 2)**
- **Baseline comparison (Function 3)**

**Source(s):** Figure by authors
### Table 1.

Focus group participant demographics reflect the interdisciplinary nature of the study.

<table>
<thead>
<tr>
<th>Focus group</th>
<th>Cohort type</th>
<th>Participant code</th>
<th>Role</th>
<th>Organisation type</th>
<th>Expertise/Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AEC software developers</td>
<td>1.1</td>
<td>Lead software engineer</td>
<td>AEC software developer</td>
<td>Developing software solutions for the AEC sector utilising BIM and GIS technologies</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.2</td>
<td>Researcher, Architect</td>
<td>AEC research institute</td>
<td>Researcher in energy-related European project consortia, past involvement in LCC IT application prototyping</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.3</td>
<td>Head of energy efficiency, Software architect</td>
<td>AEC research institute</td>
<td>Head of energy efficiency department, leads European project consortia, software development background</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.4</td>
<td>Technical project manager, Computer scientist</td>
<td>Multinational tech. corporation</td>
<td>IT project manager, PhD in ontology engineering, co-founder of major AM data standard</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>Enterprise architect</td>
<td>Multinational contractor</td>
<td>IT solutions architect in data integration for major assets through all life cycle phases</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.6</td>
<td>Data engineer</td>
<td>Infrastructure owner</td>
<td>Specifying data alignment of contractors from owner-side for major infrastructural hub</td>
</tr>
<tr>
<td>2</td>
<td>AM practitioners</td>
<td>2.1</td>
<td>Lifecycle manager</td>
<td>Multinational contractor</td>
<td>Involved in public-private partnerships across asset life cycle</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.2</td>
<td>Lean consultant</td>
<td>Asset management consultant</td>
<td>Consulting on process optimisation and asset management for healthcare, manufacturing and state energy department</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.3</td>
<td>University lecturer, consultant</td>
<td>University, consulting</td>
<td>PhD in life cycle costing, background in quantity surveying and consulting to real estate investment trusts (REITs)</td>
</tr>
<tr>
<td>3</td>
<td>AM practitioners</td>
<td>3.1</td>
<td>Asset manager</td>
<td>Multinational contractor</td>
<td>Involved throughout life cycle of civil infrastructure assets</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.2</td>
<td>Director of international operations, Facilities department</td>
<td>Multinational developer/owner, build-to-rent sector</td>
<td>Background in procuring hospitals, schools and other public-private partnerships</td>
</tr>
<tr>
<td>4</td>
<td>Public sector</td>
<td>4.1</td>
<td>Senior quantity surveyor, technical advisor</td>
<td>Office of government procurement</td>
<td>Overseeing development of public works contracts and legislation to support central government real estate procurement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.2</td>
<td>Data analyst, Policy advisor</td>
<td>Office of government procurement</td>
<td>Advisory to development of standards and legislation for public procurement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.3</td>
<td>Systems integrator</td>
<td>Smart building solutions provider</td>
<td>Extracting and integrating distributed HVAC systems data, supporting predictive and prescriptive maintenance and fault detection and diagnostics</td>
</tr>
</tbody>
</table>

Source(s): Table by authors
inputs within the coding environment. The researcher then facilitated a semi-structured discussion, asking open-ended questions and encouraging participants to engage in discussion. The cohort was highly motivated to contribute, and the researcher managed time by moving the discussion forward when topics became overly debated.

The focus groups were audio recorded and the transcripts analysed based on the evaluation criteria using a thematic synthesis methodology, described in detail by Shaw et al. (2023). Responding to the third research objective, this step includes further encoding of domain insight and recommendations to both refine later iterations of the reference architecture, and to generate recommendations for wider considerations and future work. Encoding was carried out using Nvivo V1.6 software and the results discussed by two researchers until consensus was reached on the sentiment of participant contributions.

5. Results
Interpreting sentiments and synthesising meaning across an interview cohort is a key activity for researchers in qualitative studies. Table 2 summarises the focus group evaluation and facilitates substantive theory building per DSR phase three. Verbatim quotation examples are provided in Supplementary_Material_Appendix_3 as supporting evidence.

There was resounding positivity from the participants regarding the reference architecture-based approach to system provision, as well as the prototype solution. “Adjust parameters and see the results immediately. Really useful for simulating [alternatives]” (Participant 3.1). One participant discussed how the functionality advances the current state of practice. “I’ve been doing it [LCC analysis] in spreadsheets for years […] It’s typical just to accept inaccuracy because of that complexity […] I can maybe do some of the stuff you’re outputting but it’s tedious and time-consuming […] So it’s brilliant” (Participant 2.3). Participants also report that the approach retains the flexibility needed to be compatible in various contexts. “I think what you’ve done is very flexible and with small adjustments can be widely useful” (Participant 3.2). Domains that were mentioned as potential beneficiaries for such capabilities included public-private partnerships including infrastructure (government procurement), real estate investment (portfolio-level), facilities management (building-level), and quantity surveying (estimating and design). This portrays the artefact as being reusable and widely applicable. Having said this, constructive criticism highlights the need to expand the organisational goals encapsulated within the reference architecture from TCO reduction alone, to other investment scenarios, while acknowledging that the analytical functions presented can support these goals. This is evidence of the suitability of describing generalisable AM business processes as high-level design patterns within such a reference architecture.

The positive response to the concept by this diverse cohort helps to substantiate the research hypothesis of a reference architecture-based approach as a suitable proposition to address the LCC scalability challenge. Furthermore, recommendations and insight, gathered during evaluation, can be incorporated into subsequent iterations of the reference architecture and guide future research. These outcomes are discussed in the following section.

6. Discussion
Environmental sustainability is driving an urgent need to reduce resource consumption in all sectors of the global economy, including the built environment, with a widely agreed target of net zero by 2050 (IEA, 2021). Indeed, our research results reflect this shift in priorities, with one government procurement participant reporting that the climate driver “has removed barriers that were previously there” (Participant 4.1). Impending regulatory requirements such
<table>
<thead>
<tr>
<th>Evaluation criteria</th>
<th>Overall Synthesis of cohort</th>
<th>Group 1 (AEC software developers)</th>
<th>Group 2 (AM practitioners)</th>
<th>Focus group</th>
<th>Group 3 (AM practitioners)</th>
<th>Group 4 (public sector)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usefulness and Insight</td>
<td>Demonstrates a challenging but necessary analysis to support direction of sector in line with climate targets. Further use cases, asset management goals and data-related functionality should be considered as next steps.</td>
<td>Helpful for describing high-level design to developers. A list of typical requirements to be gathered will be helpful to guide implementations.</td>
<td>Responds to a challenging gap in commercial software, providing insight and evidence-based visual reporting needed by practitioners. Needs to allow for case specific flexibility and not over-constrain user.</td>
<td>A suitable demonstration case which fits some needs without much alteration, but further development should consider broader asset management goals and investment strategies.</td>
<td>Insight and blueprint very useful for direction of sector to align with strategic climate targets. Communicates life cycle reporting in transparent way. Constrained by the quality of input data. Data ingestion a useful next step.</td>
<td></td>
</tr>
<tr>
<td>Flexibility and Ease of Use</td>
<td>Programmatic approach provides the required domain flexibility in a simple-to-use way, but further asset management goals and use cases should be supported. Core data model selection a key decision requiring consensus. Extending functionality to re-program analysis scope, and providing in an accessible platform, would support innovative performance-based contracts, which is the trajectory of industry, in line with current climate goals.</td>
<td>Agnostic approach maintains flexibility, but selection of data model is a choice which will dictate ease of implementation. UML is a somewhat dated approach but still easy to understand by wide group of stakeholders. Provided material will be helpful for software developers.</td>
<td>Simple inputs and programmatic approach improves on what is currently available and used in practice, particularly the flexibility to extend the study period. Formalises practitioner knowledge and is immediately useable. Ensure that users can flexibly input cost categories and frequencies to adapt to broad domain scopes.</td>
<td>Aims of the project align with broad stakeholder needs for case-specific inputs, but consider further case studies with varying asset management goals. Flexibility is needed in reprogramming the baseline, as well as development of contractual arrangements to support this nuanced approach.</td>
<td>Simple inputs provide insight needed to support public procurement in line with climate goals. A web-based platform with link to cost databases would facilitate accessibility and engagement.</td>
<td></td>
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<table>
<thead>
<tr>
<th>Evaluation criteria</th>
<th>Overall Synthesis of cohort</th>
<th>Group 1 (AEC software developers)</th>
<th>Group 2 (AM practitioners)</th>
<th>Group 3 (AM practitioners)</th>
<th>Group 4 (public sector)</th>
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<tbody>
<tr>
<td>Representativeness</td>
<td>Insight provided by the prototype is required to support direction of domain towards life cycle-concentrate approach. Implementation guidance for developing such systems could comprise the presented reference architecture. Focus on guiding principles over rigid structures. Promote scalability by aligning with existing communities and standards and demonstrate with strategic partners in exemplary cases to build trust.</td>
<td>Not unusual to provide high-level, very general reference architectures. Concentrate on reusable components and guiding principles. Ensure flexibility of asset selection and grouping. Align with industry-agreed data model (rather than recreating) and communities for scalability. Demonstrate in exemplary cases for validation and potential for roll out.</td>
<td>Aligns with direction of key standards (ISO/ICMS) but allows for case-specific flexibility. Cost model can be a reusable component but ensure the system can be ‘sanity-checked’ by users to build trust in the analysis.</td>
<td>Supports the need to communicate life cycle insight with stakeholders who are interested in different levels of granularity. Demonstrate in further case studies, considering varying asset management and investment strategies, to build trust.</td>
<td>Supports the broad domain needs and shift of focus towards sustainability and life cycle thinking. Insight provided by the work is required to support the direction of public works contracts away from lowest-bid towards performance-based tenders. An implementation guide, such as the presented reference architecture, could support government aims to assist suppliers with impending reporting requirements in a transparent, top-down way.</td>
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Source(s): Table by authors
as the EU’s Corporate Sustainability Reporting Directive (CSRD) (European Commission, 2023) using Level(s) and ESG reporting frameworks, and the resulting signal to investment markets through financial mechanisms like the EU taxonomy, indicate that the financial pillar, within a wider sustainable development agenda, clearly underpins the political trajectory. It is within this context that we discuss the study results.

This research aims to establish a theoretical basis for a step change in delivering LCC analytics capabilities, from comprehensive product-based, to one based on a high-level, extensible reference architecture to align practice with the political ambition for availability. To guide the study, three research objectives are established at the outset and considered in this discussion. The first objective is addressed by investigating how research to date has tackled scalability in the LCC domain and by identifying shortcomings. We illustrate misalignment between LCC analytics capabilities and political ambition for use. A generalisation problem is identified in the body of work, and reflection on how scalability is addressed in other related domains leads to hypothesising a reference architecture-based approach for LCC deployment as a suitable alternative. The second objective is addressed by proposing a novel methodology to test this hypothesis based on DSR and constitutes the main contribution of this study. An initial top-down reference architecture is refined through bottom-up prototyping in a case study and evaluated positively through expert focus groups. We find that the case study needs broadly align with the wider domain requirements for LCC systems (between Sections 4.1 and 4.2), and where practitioners became over-constrained, it led to further abstraction in the reference architecture, demonstrating the refinement capabilities of the methodology. The third objective involves synthesising the evaluation results in relation to background research and the wider context. Positive feedback during evaluation substantiates the research hypothesis as having theoretical merit, while constructive responses and domain insight help to generate future research directions.

This study builds on previous work in several ways. First, initiatives within the existing body of work which may contribute to a general reference architecture for the LCC domain have focused on the significant challenge of data management, mainly through the development of ontologies. Our work expands the formalisation of domain knowledge towards generalisable analytical functions and system architectures. Second, the background research identified that the number of studies addressing multiple lifecycle stages is very limited. Due to the scope of this study, which spans the AM role, the full range of life cycle stages are incorporated into the reference architecture concept. Finally, no work to date has demonstrated a theoretical justification for addressing scalability in the domain, and we do so by adapting the DSR methodology and analysing the valuable opinions of domain experts regarding the concept.

With a view to the bigger picture, we now discuss how the results of this work can impact practice, policy and future research. The results of this study can affect practice by making LCC methods more widely available, potentially at lower cost and better suited to their specific context than what has been achieved through monolithic software development. Practitioners report that commercial approaches to date have been inflexible and over-constraining, causing them to revert to tried and tested, albeit tedious, methods. “I went back to my spreadsheets, at least then I know what’s going in there” (Participant 2.3). Given the domain characteristics and organisational demographics outlined, a customisable approach based on extensible high-level patterns may be preferable. With regulatory requirements for LCC reporting imminent, and sustainable finance mechanisms beginning to drive investment, practitioners have received little guidance on assembling the requisite information, technically. In relation to making sense of available LCC standards, one participant summarised the difficulty for practitioners well. “I did a PhD in life cycle costing and have trouble navigating them. For a non-domain expert, good luck” (Participant 2.3). A reference architecture, such as the one developed in
this study, could take the form of implementation guidance to complement existing international standards such as ISO 19650-3 (ISO, 2020), similar to provisions within ISO 23247 and BRIDGE standards, discussed earlier. This proposal is supported by the opinion of one government procurement participant who said “I can see this being directly useful for the things we want to do in government. Having a software architecture written out for [relevant LCC standard], we would love to be at that stage” (Participant 4.2). Furthermore, the presented methodology, specifically because of the top-down/bottom-up integration, as demonstrated in the refinement stage, may offer possibilities for harmonisation between such regulatory and practitioner requirements.

This study endeavours to illustrate the political context of LCC. Regulatory requirements and ambition for LCC availability drove the concept, but the proposal’s theoretical substantiation can, likewise, drive policy. It suggests a need for a paradigm shift in LCC software application deployment, and we find evidence from other domains of comparable calls-to-action. A recent study, which implores fundamentally rethinking research and development within the health-tech sector, highlights the predicament of “pilotitis”, or the phenomenon of “an inability to bring solutions past the pilot stage of development to market”. The research recommends a “fundamental mindset shift” in software provision away from product-based, to a focus on data structuring and accessibility, encouraging smaller, distributed and specialised service development on an as-needed basis, with interoperability at its core (Egermark et al., 2022). This mirrors the objectives of the linked open building data community (W3C 2022) as well as researchers within the LCC space, around describing and formalising consensus domain knowledge, with Sobhkhiz et al. (2021) concluding that linked open data, semantically structured on the web “is the only logical choice of technology” to solve the data management challenge in LCC. The data availability/quality issue is, of course, central to the LCC debate, and the focus group participants, specifically the software developer cohort (Group 1), recommended both data ingestion as well as alignment/reuse of domain data models as important next steps for developing the concept towards broad adoption.

Additional insights from the focus group analysis provide a roadmap to support the envisioned trajectory. While there is evidence of progress in the built environment away from lowest-bid contracts towards performance-based procurement paradigms, which place a value on the lifecycle impact of decisions, for example, the Capital Works Management Framework for Irish public procurement (OGP, 2023), a nuanced approach was recognised by focus group participants as being necessary if such reforms are to have the desired effect. Given the inherent difficulty in accurately predicting the future, a concern is that contractors may be assuming disproportionate risk, and it was suggested by the participants on both sides of the debate that contracts, as well as the decision-support systems, aim to reduce this performance gap (between prediction and reality) by facilitating reprogramming of the measurement baseline to accommodate scope changes. “You’re looking at a long time here. A lot is going to change outside of your control, so for [performance-based contracts] to work you need to be able to adjust that baseline, set checkpoints to see where you’re going with your prediction, otherwise you can’t compare, and the contracts need to facilitate this” (Participant 3.2). Such capabilities could contribute to reestablishing public confidence in public-private partnerships as a procurement model, essential in reforming the sector towards the challenging emissions-reduction targets. This intersection of engineering and legal sectors instigates a need for multidisciplinary research, and a DSR strategy has been demonstrated herein as potentially helpful in this regard.

By adapting the DSR framework, this research establishes a theoretical basis for the suitability of a reference architecture-based approach to practically address domain needs. In terms of formal theory building (DSR phase 4), further implementations and empirical testing
will be needed, a limitation of this work. Several additional limitations should be highlighted for clarity. First, the study does not advance cost prediction by any statistical means, and thus, the analysis is constrained by case study data quality. Future iterations of the concept would benefit from exploring data integration and improved prediction methods, such as in the works of Gao et al. (2020) and Asghari et al. (2021). Next, testing, as part of the refinement stage, was limited to a single case study and, hence, one AM goal/investment strategy. In building a general reference architecture for the domain, the selection of further test cases should diversify the investment context, investigate the types of business insights required in those environments, and expand/abstract the LCC reference architecture scope to encompass this (though the authors anticipate many common design patterns/functions). Finally, this study has been limited to analysing financial metrics, and thus omits important greenhouse gas, social and other ESG criteria involved in a comprehensive Life Cycle Sustainability Assessment. Subsequent iterations of this work should consider how the methods fit within the context of such a holistic framework, again highlighting the importance of harmonisation between the requirements of policy and practice, as well as the relevance of multidisciplinary research.

Our future work will enhance the LCC reference architecture based on the insight and recommendations from the focus groups, and will pursue empirical testing of the solution to enable progression from stage three to stage four of the DSR framework, towards formal theory-building. In addition, the significant challenge exists to advance IT systems and contracts to support dynamic baselines in performance contracting, which will also be explored in future work. The final, and perhaps most pressing, issue is the harmonisation required between practitioners and policymakers in terms of enabling consistent reporting to envisaged future frameworks such as Level(s) and regulations such as the CSRD, and it is intended that our concept and future work support such consensus-building efforts.

7. Conclusions

The availability of LCC systems in the built environment does not currently align with the political ambition for reforming the sector in line with sustainability targets. A main reason for this is the unique specificity of each LCC case, and hence the need for flexible methodologies. However, the trajectory in both the research community, and in industry, remains comprehensive product focused. We identify precedence from other sectors which supports the concept of a paradigm shift towards more abstracted and extensible answers to scalability in LCC IT system deployment. A methodology is developed based on pragmatic DSR to investigate the theoretical merit of this proposition. It incorporates both a top-down and bottom-up reference architecture development method, which refines a LCC reference architecture artefact through a process including domain requirements gathering, implementation/testing at an AM case study and evaluation in wide practitioner focus groups. This methodology constitutes our main contribution to knowledge.

We find that the focus group cohort, which includes software developers, AMs and government procurement participants, sees significant potential in the proposal, and sentiment analysis helps to substantiate theoretical merit. Given the imminent regulatory requirements (such as the EU’s CSRD) for reporting LCC as part of holistic sustainability frameworks like ESG and Level(s), such a high-level reference architecture could provide technical implementation guidance to augment existing text-based standards. Furthermore, insight and recommendations from the analysis articulate the wider considerations to support such a trajectory, including the need for developing suitable contractual mechanisms, prioritising harmonisation efforts between practitioner and regulatory information requirements, and exploring further investment scenarios and data ingestion methods to advance analytical capabilities. Overall, the study highlights the
importance of multidisciplinary research in addressing real-world challenges, and the
provided methodology demonstrates the potential for discovering novel pathways by
exploring what are often siloed domains, in parallel; in this case, that of built environment
engineering and computer science. Though the work stops short of incorporating other
important environmental and social metrics, it can be regarded as a key pillar within a
wider Life Cycle Sustainability Assessment framework. Our future work will aim to further
develop the reference architecture, expand/abstract to broaden the scope, empirically test
the impact on practitioners, and investigate alignment with existing data models and
communities as a means to scalability and consensus building.

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Supplementary material
The supplementary material for this article can be found online.

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