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A SOCIO-TECHNO-ECONOMIC FRAMEWORK TO SUPPORT INFORMATION SYSTEM-BUILDING FIT FOR THE ENVIRONMENTAL POLICY TRAJECTORY

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Abstract

This paper advocates a holistic socio-techno-economic approach to IT system-building for Life Cycle Asset Information Management (LCAIM) in the built environment, challenging the current technology-focused research trajectory. Drawing precedence from paradigm transitions in other related sectors, a Design Science Research (DSR) methodology is used to propose and prototype a framework as a software UI, evaluating it using expert focus groups. The paper contributes a framework that aligns IT system design with the environmental policy landscape, emphasising considerations beyond technical aspects, such as *trust* and *scalability*. The results demonstrate the frameworks effectiveness in addressing the broader requirements of future LCAIM systems.

Introduction

The urgent need to reduce environmental impacts from anthropogenic activities obliges countries and corporations to account for their resource use through non-financial information disclosures; the European Union (EU), for example, recently legislating for the *Corporate Sustainability Reporting Directive* (European Commission, 2023). But transitioning from voluntary (market-driven) to mandatory (governance-driven) sustainability reporting represents a fundamental shift in Information Management (IM) capabilities. This transition is particularly challenging in the built environment which, as a result of its complexity, has been slow to embrace digitalisation (Manyika et al., 2015).

To tackle emissions within the built environment specifically, the EU has recently introduced a number of targeted measures. These include the *Energy Performance of Buildings Directive (EU) 2024/1275* which will require governments to calculate Global Warming Potential across the entire lifecycle for all new buildings from 2030; the *Construction Products Regulation (EU) 2024/3110* which aims to incorporate sustainability reporting into product standards; and the *Ecodesign for Sustainable Products Regulation (EU) 2024/1781*, a framework establishing ecological design requirements for products classified as *sustainable*.

This emerging policy landscape is underpinned by an ability for organisations to conduct, manage and report multi-criteria Life Cycle Analysis (LCA). Such insight can provide a comprehensive view of an asset's resource consumption over its entire life. This enables evidence-based decision making supported by long-term value (Kehily and Underwood, 2017) rather than solely focusing on short-term, or initial investment costs which has typically been the default (Ashworth, 2021).

However, despite significant focus from both the research community and industry to address the technical challenges around LCAIM, due to the inherent complexity of both the sector and the methodology itself, widely-agreed solutions remain aspirational. A further challenge, and the point of departure for this paper, is that the majority of research to-date has focused primarily on the technical aspects, while broader socio-economic considerations have been largely ignored.

This paper hypothesises that by considering the socio-technical (political) and techno-economic (practical) aspects holistically, in addition to the technical perspective, IT system providers might better support environmental policy in the built environment. This research aims to design and evaluate a decision-support system prototype which reflects these holistic requirements, and by doing so, assess the suitability of the proposed policy-aligned requirements framework.

The remainder of this paper is structured as follows. First, we reflect on the state-of-the-art in LCAIM research, establishing a research gap. Next we outline a potential solution in the form of a socio-techno-economic requirements framework. A focus group evaluation design is described, and we conclude by discussing the findings and remark on future work.

Background

Information management in sustainability reporting

To satisfy the aforementioned environmental policy requirements, organisations in the built environment require structured information about facilities and infrastructure with which to conduct and report LCA. This information, however, is frequently unavailable or incomplete due to the inadequacy of current IM practices in the sector, including the lack of standardisation as well as data scarcity, variability and quality issues (Soust-Verdaguer et al., 2017; Gao and Pishdad-Bozorgi, 2019; Noorbakhsh et al., 2020; Lu et al., 2021). Additionally, the software required to perform data integration and analytics is often unsuitable. Existing LCSA applications tend to be too costly for wide adoption, lack the flexibility to meet specific stakeholder needs (lacking case specific configurability), or simply be unavailable altogether. As a result, the vast majority of practitioners rely on laborious, error-prone, ad-hoc analyses to support their decisions and reporting. Consequently, the potential benefits of LCAIM are not being widely realised.

Lu et al. (2021) collate much of the scientific work in LCA research up to that year in their domain review. The body of work illustrates that significant research effort has been expended in addressing LCAIM challenges, but until now, the focus has mainly addressed technical issues, broadly ignoring the more systemic socio-economic ones. But in Operations Research fields, such as built environment asset management, such factors can be equally, if not more important in solving challenges in practice.

Existing requirements frameworks

A number of existing frameworks are available to support LCAIM objectives. In terms of software, both Bari et al. (2022) and Dervishaj and Gudmundsson (2024) propose LCSA tools requirements frameworks which illustrate future software needs and outline directions and priorities for technical research. Their recommendation is for software tools to become standardised, yet more adaptable to the range of cases encountered in practice, and to improve prediction capabilities through machine-learning and other emerging analytics techniques. Similar recommendations are derived in the related work of Shaw et al. (2025) who provide harmonised practice-governance LCAIM software requirements. Though technically-focused, the ambition is towards a broader set of considerations, aiming to support practical implementation of policy.

Though analytical capabilities are clearly a fundamental component of LCAIM, a criticism of current practice is that tools have prioritised reporting functions and have not improved design and operational decision making by practitioners where the greatest impacts can be made (Rock et al., 2018). For this reason, recent work by Feng et al. (2022) aims to integrate IM capabilities into asset design and operations processes. Their Strategic Asset Management (SAM) information flow framework maps *"overly general portfolio-level IM data standards"* to a practical facility/operational-level, and focuses particularly on making construction-stage data useful downstream, post-handover. Conversely, Röck et al. (2024) scale up LCAIM capabilities, their SLiCE data model providing a Space-Time-Indicator (STI) framework built specifically for stock-level LCA. Though the SLiCE datamodel provides an indication of broader impact categories, still it remains technically focused and incorporates few socio-economic aspects.

It is clear that efforts to-date within built environment research have focused predominantly on technical aspects of LCAIM and are lacking the wider socio-technical and techno-economic considerations needed to align our IT systems with the environmental policy trajectory. As such, our IT system requirements frameworks are limited in their ability to fully describe the context needed to support paradigm change, a stated aim of the EU's sustainability transition (European Environment Agency, 2024) However, precedence from other sectors which share the objective of environmental transformation may be useful for considering a suitable approach.

In their work, which integrates a techno-economic and socio-technical perspective on energy transitions, Cherp et al. (2018) explain that such theoretical integration is *"widely recognised as necessary for a comprehensive understanding of transitions"*. In other words, practically enabling a fundamental transformation in the energy sector requires a broad view beyond the technical considerations, similar to the fundamental shift in IM capabilities imposed by the policy trajectory we have outlined.

Synthesis and gap

As we have seen, existing research in the domain has been primarily focused on technical and analytical considerations in IT system development, but a broader view is needed in the field to support transition ambitions. Despite the lack of a comprehensive approach to describe policy-aligned LCAIM systems, a socio-techno-economic framework from the related energy sector can provide precedence for our objectives of policy-aligned requirements specifications.

To address this research gap, the following section describes a conceptual socio-techno-economic LCAIM system requirements framework.

Framework concept and evaluation method

Design of the conceptual framework draws on the body of work in LCAIM as discussed in the previous section. In particular, we draw on the harmonised practice-governance LCAIM software requirements from Shaw et al. (2025). Furthermore, the concept benefits from domain expert input, undergoing a number of iterations, presented to and discussed with LCAIM system end-users and other researchers in the field.

Figure 1 describes an initial conceptualisation, illustrating criteria which extend beyond the overly limited, often technocratic view of available frameworks, and includes important socio-economic considerations.

This broad view represents a pragmatic approach within a practice-focused Operations Research field, but to assess the scientific value of the concept, an evaluation method is required, preferably drawing on domain expert knowledge. Conceptual frameworks can be difficult to meaningfully evaluate with domain experts due to their abstract nature, however, Design Science Research (DSR) may provide a suitable approach.

DSR is well suited to addressing such practice-oriented research challenges, *"bridging the theory-practice divide*

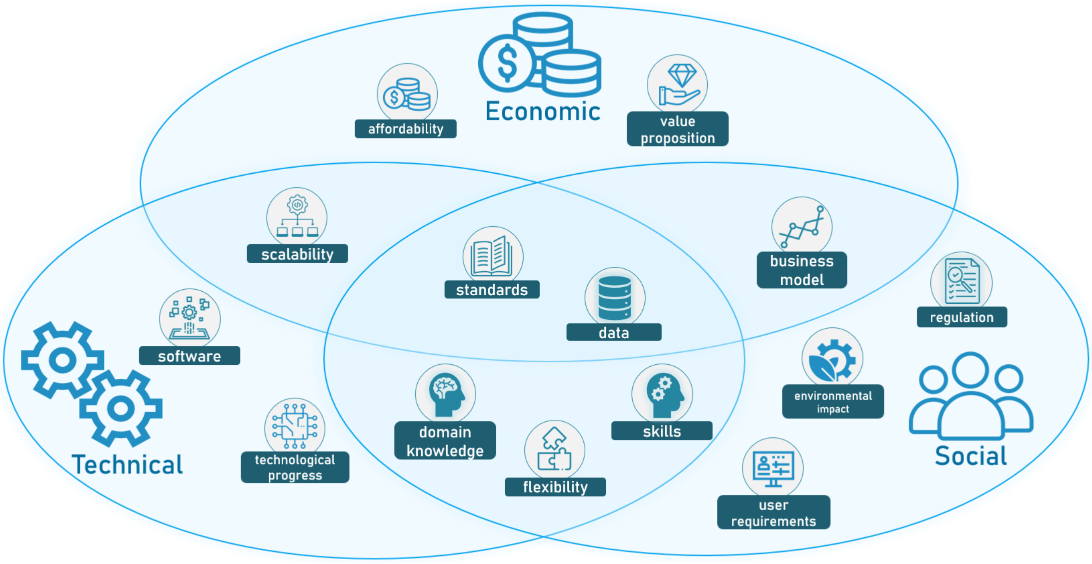

Figure 1: Conceptual requirements framework for developing environmental policy-aligned information systems.

[..] typically resulting in practical results" (Holmström et al., 2009). DSR involves the *"development of artifacts and testing their effects in practice"* (Kehily and Underwood, 2017). By representing aspects of the framework as a prototype IT system, a form familiar to domain experts, they may provide more meaningful feedback as to the value of the system. By doing so, we may reasonably infer an assessment of the framework itself, by proxy.
Structured around the stages of DSR, figure 2 illustrates the research methodology of this study. The following section outlines the methods and presents initial results from the evaluation stage.

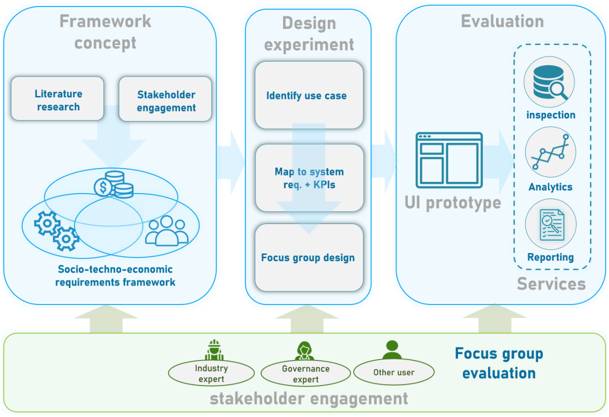

Figure 2: Methodology for developing and evaluating a policy-aligned IT system requirements framework

Evaluation via DSR

Through phases of *incubation*, *refinement* and *evaluation*, a concept is developed and tested using DSR, typically with end users. The following subsections outline the steps for designing an experiment to evaluate the socio-techno-economic requirements framework proposed in the previous section.

Framework reflected in a prototype system

The proposed framework describes a relatively abstract set of categories, so, in order to develop a representative system with which to evaluate the framework via stakeholder focus groups categories are mapped to specific system requirements. For example, the framework concept of *software* is mapped to specific system requirements relating to *modularity*, *extensibility* and *analytical and reporting functions*. These more tangible and actionable requirements may then be incorporated into the prototype system design. The prototype system requirements generated in this way include;

- integration and aggregation of heterogeneous information sources;
- open data principles and standardised vocabularies (or *ontologies*);
- domain logic-encoded knowledge graph;
- extensibility for case-specific data management and flexibility in visualisation;
- harmonised governance-practice analytics and reporting functions;
- scalability across organisational types and portfolio sizes; and
- modular, flexible services accessible over the web.

To depict a system in use which would be familiar to domain experts, three fundamental Use Cases are established which reflect future harmonised governance-practice needs for LCAIM systems as defined by Shaw et al. (2025). These include a;

1. data ingestion / inspection module;
2. performance contract monitoring module; and
3. multi-criteria reporting module.

User Interface (UI) dashboards are developed to simulate a 'performance contract' scenario between an Asset Manager and client, whereby a series of unforeseen events change the scope throughout a conveyance period. Multi-

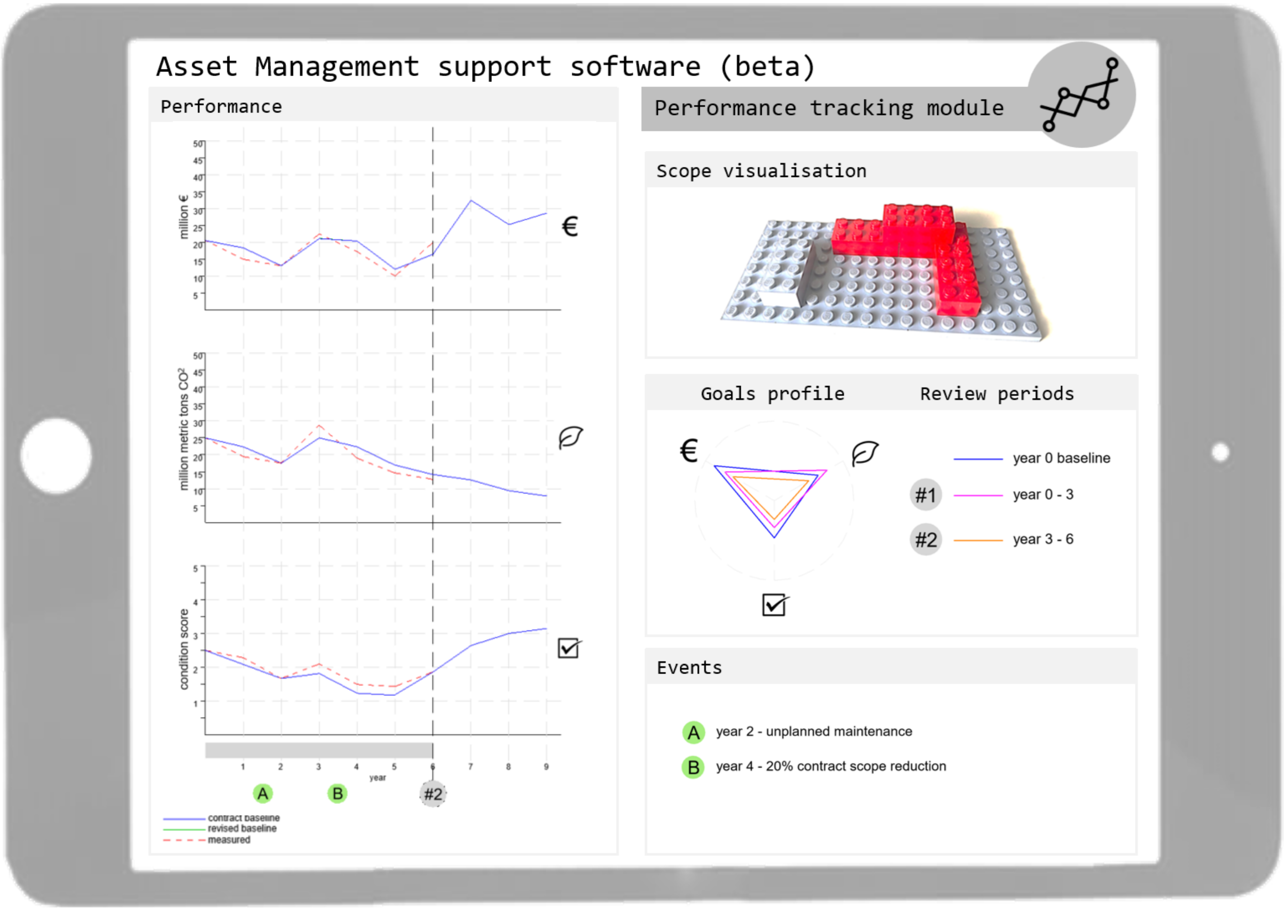

Figure 3: UI dashboard for the prototype decision-support system which is evaluated by domain experts during interdisciplinary focus groups. Use case 2 monitors multi-criteria asset status during a contracting period.

criteria LCA projections based on data from a real Asset Management case study, as presented in Shaw et al. (2024), are used in describing the scenario. The case comprises a major European transport hub where an extensive asset register for ∼4000 assets was available for conducting life cycle cost and energy analysis. The scenario also includes hypothetical data and simulations, specifically in order to provide projections on *asset condition* for which data was unavailable in the case study.

Figure 3 depicts the UI dashboard for Use Case 2, and this, along with the other two use cases, are used for stakeholder evaluation in the following step.

Focus group study

Given the broad nature of the research objectives and subject matter, a mixed-discipline focus group design is employed. Experts from governance and practice, from various European countries, and who are representative of a range of asset categories and scales, are sourced and arranged into three focus groups per Table 1.

Participants are provided with background information and consent forms ahead of a 1.5-hour online meeting. During the focus group, the lead researcher introduces the study and the UI dashboards are presented via the aforementioned performance contract scenario, simulating a

Table 1: Focus group participants categorised by organisation and discipline, ensuring an interdisciplinary study.

Focus Group	Discipline	Sector	Public / Private	Region
1	Asset owner	Multi-sector	Private	Britain and Ireland
	Asset manager	Infrastructure	Public	Benelux
	Information manager	Infrastructure	Public	Benelux
	Policymaker	Infrastructure	Both	Germanic
2	Policymaker	Residential	Public	Britain and Ireland
	Asset manager	Infrastructure	Public	Britain and Ireland
	Information manager	Multi-sector	Public	Benelux
3	Asset manager	Infrastructure	Both	Germanic
	Information manager	Infrastructure	Public	Scandanavian
	Information manager	Infrastructure	Public	Scandanavian

user experience of the prototype decision-support system. The researcher then moderates a semi-structured discussion, posing open-ended questions and encouraging participants to engage in debate. The focus groups are audio recorded and the transcripts analysed in the following step.

Thematic analysis

Evaluation criteria, or Key Performance Indicators (KPIs), are developed to reflect the study aims, and to assess the broad framework concepts. Figure 4 maps the conceptual framework categories to representative system requirements, and subsequently to evaluation KPIs.

A thematic analysis, similar to the methods described in

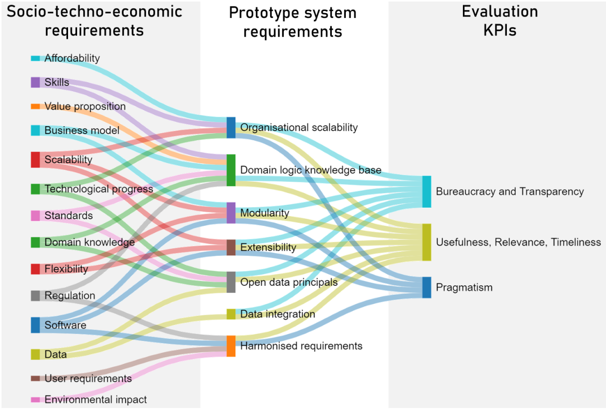

Figure 4: Conceptual mapping from the proposed framework to system requirements, and subsequently to evaluation KPIs.

detail in Shaw et al. (2023), is employed to analyse the focus group transcripts and derive sentiments relating to the evaluation criteria. Encoding is carried out using Nvivo V14 software and the results are discussed by two researchers until consensus is reached on the *meaning* of participant contributions.

Results

Table 2 provides a summary of participant contributions per evaluation KPI. In terms of ***Usefulness, Relevance and Timeliness***, a sentiment that reflects the collective response was proffered by an information manager who said *"The approach of this software is what we really need. It's the right tool at the right time."* (Group 2). This sentiment was echoed by an asset manager of public infrastructure, who said *"Coincidentally, I'm now being asked to explain the variation from our predictions. It's exactly this question we're facing. I would like to have this functionality right now"* (Group 1). Overall, the cohort found the prototype to be timely and relevant in the context of shifting policy and legal contexts, particularly in Europe, providing the imminently needed functionality by their respective organisations.

Then in terms of ***Bureaucracy and Transparency***, a sentiment that reflects the collective response was provided by an asset manager for one local authority who offered the opinion that *"assets have become more complex and we need these kind of systems to make it easier for us to [...] communicate effectively with our stakeholders, convey complex information in a simple way, which this system does well."* (Group 3). Another example which speaks to the transparency of the prototype came from an information manager who assessed the prototype as being *"very clear, very simple [...] Don't need to study IT to understand values. Really good idea, really intuitive."* (Group 1). In all, the prototype system is commended for effective communication with verifiable data inputs, and for enhancing transparency in imperfect information contexts, with the suggested potential for improving verification and validation processes highlighted, in support of the policy trajectory.

Finally, in terms of ***Pragmatism***, the cohort view is that the prototype effectively balances idealistic strategic goals with practical operational needs, with particular value in the operational phase. A sentiment that illustrates this collective view is offered by one information manager, saying that *"Data capture, management and expert knowledge in the field is imperfect and we need to operate within that. It works if you understand what you know and what you don't know. This tool helps enormously in clarifying that."* (Group 1).

Overall this feedback provides evidence that the prototype, and by proxy the framework, are representative of current and future needs of LCAIM systems. There are, however, a number of areas for improvement reported in the analysis. Constructive criticism highlights the need to: further develop the performance contract concept, incorporate advanced prediction / recommendation capabilities, expand the goal-setting abilities for flexibility in stakeholders' motivations, and consider user experience and ergonomics of the prototype system. Gathering and reflecting on these and other shortcomings, provides a clear strategy for both future prototype iterations and our future work.

Discussion

As reflected in the summaries and quotation examples in the previous section, the feedback generally illustrates the prototype, and by proxy the framework, as suitable to convey future governance-practice needs. This serves as evidence that the proposed socio-techno-economic requirements framework comprises the broad considerations required in practically specifying and developing future-oriented and policy-aligned decision support systems in the built environment.

Reflecting on the mapping process (see Figure 4), it is clear that many concepts in the framework map simultaneously to various system requirements. It is perhaps an indication that the framework categories remain excessively abstract to be useful. For example, the *Environmental Impact* category may be interpreted as *technical LCA calculations*, but was intended to be considered as *environment* in the context of *collective public commons*. For this reason, a further improvement to the framework would be to be more specific in categorisation.

Intuitively, it is rather likely that during product development, solutions providers already consider many, if not all, of the criteria identified in the conceptual framework. However, since the sum results in an unsuitable IT landscape to enable LCAIM at scale, as discussed at the outset, justification for such a renewed focus and guidance seems reasonable. Furthermore, the framework can support not only solutions providers, but also policymakers in a collective effort towards a reformed sector in terms of information and environmental performance. A potential follow-up activity to make the outcomes of this work more useful to support policymakers could be to map categories of the framework to specific policies / articles of policies, in future work. This could also be used to highlight poli-

Table 2: Focus group summaries based on evaluation criteria

Evaluation Criteria	Focus Group 1	Focus Group 2	Focus Group 3
Timeliness, Relevance and Usefulness	Timely and useful to support current decarbonisation needs. Enhancements include flexibility in goal setting and providing decarbonisation risk analysis. Data quality is emphasised as key.	Recommended improvements include adding risk factors and flexibility in goal setting. Governments are increasingly recognising open data as key to built environment reform.	The initiatives reflect challenges the industry is struggling to address for compliance with increasing environmental regulations. Enhancements suggested include prioritising investments, maintenance recommendations, and scenario modelling aligned with IPCC projections.
Bureaucracy and Transparency	Balances communication with useful, verifiable data inputs. Low-code graph exploration is intriguing. Some continued need for data integration expertise.	Transparency provides necessary insight into imperfect information realities. Group criticised certification schemes, with the tool seen as an effective validation mechanism.	Tool supports transparency needed for downstream AM. Group highlighted criticism of subjective and unverifiable certification schemes and recognised the tool's potential for improving verification and validation.
Pragmatism (Idealism vs Practicality)	Harmonises idealistic C-suite and realistic operational AM insights. Open-source ambitions are becoming mainstream.	Regarded as most useful in the operational phase due to limited early-stage data. Baseline reprogramming is ideal but raises concerns about macroeconomic disruptions.	System regarded as ideal for communicating long-term asset management goals. Participants noted challenges in achieving harmonisation across domains but were optimistic about its role in the transition.

cies which are lacking consideration of a certain category and facilitate targeted reform.

The limited availability of appropriate tools on the market to support future environmental requirements was discussed at the outset of this paper. It implies a renewed focus on developing an appropriate software landscape, including tools, if policy ambitions are to be realised. The implications of the findings in this paper for practice are that, both, currently available and upcoming analytics tools providers should consider the broader set of issues presented in order to remain relevant and useful in the changing policy and business environment. For this, the provided framework can serve as guidance.

It was also discussed at the outset that LCA and related analytics underpin the majority of environmental policies. As a result, the implications of these findings for policymakers are that those concerned with governance and policy implementation may, in our opinion, view their envisioned mechanisms (declarations, auditing etc.) as feasible endeavors where underpinned by an appropriate software landscape, with a focus on practical implementation and availability. This may, in turn, guide prioritisation of efforts and investment in policy implementation.

This paper adds to the body of work in the field which is already standardising and defining in a structured way, the processes relating to LCAIM, which is crucial for consistency across the sector and wider global economy.

Our future work will aim to incorporate the valuable feedback from the focus group studies into the prototype system. In particular, we will focus on defining the role of advanced analytics functions within LCAIM processes, and expand to a wider set of use cases or *goals*. For this, expanding the focus group study could be valuable. We will also focus on adapting the framework to be more directly useful to end users, perhaps expanding the included categories, presenting them in greater detail or directly aligning them with functional and non-functional system requirements for use by tools developers, or with specific policy articles and regulations for use by policymakers.

Conclusions

The findings presented in this paper underscore the importance of adopting a socio-techno-economic perspective in designing IT systems for Life Cycle Asset Information Management (LCAIM) in the built environment. While technological advancements have received significant focus to-date, broader socio-economic considerations remain under-explored. This paper demonstrates the value of integrating these dimensions through a prototype decision-support system aligned with a novel requirements framework. Feedback from industry and governance stakeholders attests to the framework's ability to capture often ignored considerations such as scalability, trust, and practical implementation.

The implications for practice suggest that current and emerging analytics tools providers must address a wider range of issues, including policy alignment, scalability, and affordability, to remain relevant in a rapidly evolving regulatory landscape. While optimistically, policymakers are encouraged to view standardisation and auditing mechanisms as feasible given an appropriate software landscape, guiding priorities in policy implementation.

This work contributes to the field by offering a structured approach to LCAIM and advancing sector-wide consistency. Future efforts will refine the prototype and framework based on stakeholder input, and our own reflections on practicality, considering greater specificity and the potential value pf mapping to specific policies. We will also aim to expand the prototype functionality, and explore further user goals and scenarios. These developments aim to strengthen the bridge between governance requirements and practical solutions, towards a digitally enabled, sustainable built environment.

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