ADAPTIVE LIFE CYCLE ASSESSMENT AS AN EVOLVING ENVIRONMENTAL KNOWLEDGE STATE FOR DIGITAL BUILDING LOGBOOKS

Kilian Speiser and Jochen Teizer
Technical University of Denmark, Denmark

Abstract

This paper introduces Adaptive Life Cycle Assessment (ALCA) as a time-resolved framework for continuously evaluating building environmental impacts over the lifecycle. Using a conceptual design science approach, the study develops a multidimensional framework integrating prospective and retrospective data and situates it within the Digital Building Logbook (DBL). An illustrative additive manufacturing case demonstrates data flows and feasibility. The results show that ALCA enables continuous updating of accumulated impacts, improves traceability, and supports PDCA-based environmental control. The framework addresses limitations of static and dynamic LCA and provides a governance-oriented approach for lifecycle impact monitoring and regulatory alignment.

Introduction

The building industry is a major contributor to environmental impacts and therefore plays a key role in the transition required to maintain climate stability and planetary habitability (Global Alliance for Buildings and Construction, 2022). Life Cycle Assessments (LCAs) quantify the environmental impacts of buildings and support informed decision-making. This approach helps avoid the unintentional transfer of burdens to other environmental impact categories (Hauschild et al., 2017). In addition, quantification supports the definition of environmental targets, which can guide actions to improve the environmental performance of buildings (International Energy Agency, 2023). Such targets have also translated into quantified thresholds on national levels, where construction projects must hit specific targets, like in Denmark, where only 6.8-8.0 kg CO2 eq are permitted per used m2 and year of a building (Social- og Boligstyrelsen, 2018).

LCA is primarily performed prospectively (ex-ante) but can also be performed retrospectively (ex-post), also referred to as historical LCA (Bruhn et al., 2024; Kristensen et al., 2015). In the remainder of this work, we adopt the terminology for prospective and retrospective LCA proposed by Arvidsson et al. (2024). Aside from the timing of the assessment relative to the product life cycle, time is typically not explicitly resolved in either prospective or retrospective LCAs. Both approaches are generally time-integrated to a reference point (Arvidsson et al., 2024).

LCA is currently performed in the early stages or upon completion and is always time-integrated to a certain point in time (Forth, 2025). A building has a long lifetime with changes through renovations and shifting boundary conditions, meaning that assessments produced early in the project fail to quantify the building's impact once those changes occur. This time-dependency motivates investigation of different LCA approaches.

Dynamic LCA (DLCA) is an approach to LCA that recognizes the changing nature of parameters and processes within assessed systems and incorporates their temporal evolution into the LCA framework. It is therefore time-resolved within the modeling framework, where certain parts can be retrospective and others can consider future events, products, and processes (Arvidsson et al., 2024). In DLCA, temporal evolutions are defined as variations in parameters. Although DLCA explicitly represents time, temporal trajectories are predefined, meaning that the final results are static after LCA completion. Changes in parameters or processes during the product's lifetime are not considered once the LCA is completed. Figure 1 illustrates this limitation: even when time is represented, module contributions remain static once the assessment is produced. In contrast, continuous updating revises module estimates when new evidence becomes available.

Figure 1 suggests that DLCA offers greater opportunities to accommodate time-dependent aspects relevant to the long lifetimes of buildings, but it fails to respond to actual changes over time. The actual impacts after construction, during operation, and renovation are not considered and are based on early predictions, which often significantly deviate from measured energy consumption during operations (De Wilde, 2014). Similar issues occur during the construction phase: as-built LCAs rely on information collected from drawings or Building Information Models (BIM), but significant deviations in the materials used go unnoticed and are hidden from the LCA. This leads to incorrect expectations about environmental impacts.

Ongoing regulatory developments in Europe may provide a framework to address this issue. The Digital Building Logbook (DBL) is defined as a tool to record and assess data, information, and documents that include "maintenance, refurbishment, [...] traceability and characteristics of construction materials, performance data such as operational energy use [...] and lifecycle emissions" over all phases of a building (Volt et al., 2020). Once such logbooks are available, reported renovation and measured operational energy performance can be used to update prospective LCAs with observed data. In addition, the mandated Digital Product Passport (DPP) can further improve accuracy by enabling instance-specific tracking of building components, so that emissions are linked to a specific installed element rather than to generic impact declarations (European Commission, 2024).

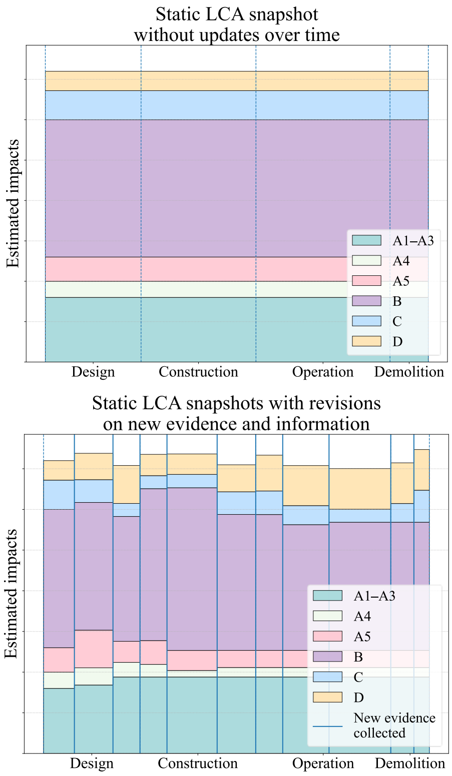

Figure 1: Conceptual comparison of static estimates of LCA and continuous updating based on new evidence. The figure does not show accumulated impacts but the estimates at a given time.

For regulatory environmental impact targets, such as those in Denmark, prospective LCAs are insufficient because they fail to accurately reflect the environmental impacts of buildings as they are actually constructed and operated. The evidence for this gap is well established: as-built deviations systematically alter embodied impacts (Forth, 2025), and the performance gap between predicted and measured operational energy use is widely documented (De Wilde, 2014; IEA, 2023). There is, however, a gap in the conceptual description of how a retrospective LCA can be incrementally developed for buildings over their full lifetime. This would enable more accurate estimates and require stakeholders to act when targets are not met. With the development of DBLs, such updating of impacts could become mandated, but a technical and conceptual description of the information flows and governance structure remains absent.

This work presents the concept of Adaptive LCA (ALCA). It is a time-resolved framework in which LCAs are continuously updated throughout the building's lifetime. Information is updated based on new inputs from either planned changes or retrospective measurements. Previous versions are timestamped and stored, and can become part of the DBL. The paper presents the information dimensions and definitions that align with ALCA and situates it within the information governance context of the Digital Twin Construction (DTC) (Sacks et al., 2020). Additive manufacturing (AM) in construction provides an illustrative context for framework development, as it enables higher traceability of information through sensors and continuous measurements of material use and energy consumption. ALCA is intended as a general framework for buildings; AM is used here as an enabling context that makes information flows more tractable, not as a limiting scope condition.

The paper addresses two research questions:

- RQ1: How can a building LCA be conceptualized as a continuously evolving environmental knowledge state that integrates accumulated ex-post impacts and projected ex-ante impacts over the lifecycle?
- RQ2: How can ALCA be integrated into a DBL to support traceability, regulatory use, and decision-making?

The paper makes four contributions. First, it introduces ALCA as an evolving environmental knowledge state that integrates accumulated and projected impacts over the building lifecycle. Second, it proposes a multidimensional conceptual framework that formalizes the temporal and epistemic information structure of products and processes within ALCA. Third, it clarifies how ALCA can be integrated into a DBL ecosystem while preserving institutional roles and governance boundaries. Fourth, it uses AM as an illustrative context to show how high-resolution process data, together with DPPs, can reduce uncertainty and improve the instance-specific accuracy of environmental impact declarations.

Research methodology

This paper adopts a conceptual design science research approach (Hevner et al., 2004) to develop the ALCA framework. The framework is derived through three steps. First, limitations in existing LCA approaches, specifically the inability to incorporate observed changes during the building's lifetime, are identified through analysis of established LCA literature and standards (ISO 14040; ISO 14044). Second, the ALCA concept is constructed by synthesizing LCA theory with emerging digital building governance frameworks, including the DBL definition (Volt et al., 2020) and DTC concepts (Sacks et al., 2020). Key framework dimensions (temporal, epistemic, and product-process) are grounded in established LCA terminology and standard practice. Third, the framework is instantiated illustratively in an AM construction context to demonstrate feasibility and to identify key information flows. Evaluation at this stage is argumentative and conceptual: the framework is assessed for internal consistency and alignment with established standards rather than through empirical testing. Empirical validation in pilot settings is identified as the primary direction for future research.

Conceptual framework for ALCA

ALCA builds on the recognition that retrospective environmental information is increasingly available throughout the building lifecycle. Measurements derived from sensors, construction documentation, operational monitoring systems, and project reports during construction, operation, renovation, and demolition enable systematic observation of realized environmental impacts (Volt et al., 2020; IEA, 2023). Advances in digitization, Internet of Things (IoT) integration, expanded Environmental Product Declaration (EPD) databases, and emerging forms of robotized and AM processes have significantly increased the availability, resolution, and traceability of such data (European Commission, 2024; Schlenger et al., 2025). This development enables the establishment of a closed-loop environmental control logic.

ALCA conceptualizes a building LCA as an incrementally evolving environmental knowledge state. It extends DLCA by not only resolving time within the modelling framework but by updating the assessment incrementally when new information becomes available. ALCA structures the assessment into discrete LCA states. Each state integrates accumulated retrospective (ex-post) impacts and projected prospective (ex-ante) impacts over the remaining lifecycle. At any point in time, one state represents the best available environmental knowledge of the building. When new measured data or planned changes occur, ALCA generates a new timestamped state while preserving the previous version.

ALCA structures environmental knowledge along three explicit dimensions. The temporal dimension distinguishes between retrospective (ex-post) and prospective (ex-ante) impacts across lifecycle phases. The epistemic dimension differentiates primary (measured) data from secondary (estimated or modelled) data. In addition, ALCA separates product-related and process-related impacts to ensure traceability of materials, components, and activities. These dimensions define the information structure required for integration into a DBL, where each LCA state can be timestamped, stored, and audited.

Regarding lifecycle phase characteristics, ALCA's adaptive updating does not apply uniformly across all phases. Module A (product and construction stage) covers activities from raw material extraction through construction completion. Once construction is finished, modules A1-A5 become fully retrospective: no further updating of construction-stage impacts is possible, though their accuracy can be refined with as-built data. By contrast, modules B (use stage) and C (end-of-life) remain partially or fully prospective throughout most of the building's life. The most significant adaptive value of ALCA therefore lies in operational monitoring (module B), renovation cycles (module B4), and end-of-life planning (module C), where continuous updating against realized performance can detect deviations from targets and trigger corrective action. This distinction is important for scoping the practical application and governance responsibilities of ALCA.

LCA methodology steps

According to ISO 14040 and ISO 14044, LCA consists of four phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. Information emerges and evolves across all four phases. The goal and scope define the functional unit, system boundaries, assumptions, and impact categories. The LCI quantifies input and output flows across all lifecycle phases of the built asset. In construction projects, these flows correspond to building products and processes. The LCIA translates quantified flows into environmental impacts using selected impact assessment methods and indicators. The interpretation phase evaluates results in relation to regulatory thresholds, project location, and environmental targets.

Although information occurs throughout all phases, the inventory plays a central role. The LCI contains the quantified units and parameters that determine environmental impacts. Changes in quantities, material specifications, process data, or service life assumptions directly affect impact results. Because ALCA incrementally updates environmental knowledge, revisions typically begin at the inventory level and propagate through LCIA and interpretation. The inventory therefore forms the structural backbone of the evolving LCA state.

EPDs provide product-specific LCIA results together with metadata such as reference service life and transport assumptions. However, EPDs cover products only. A building LCA must additionally quantify and assess construction and operational processes, including products that are partially or fully consumed.

Within this methodological structure, data correspond to quantified flows and parameters in the LCI. Information emerges when these flows are characterized through LCIA methods. Knowledge results from interpreting impacts in relation to regulatory requirements and environmental targets. In ALCA, new evidence may require updating inventory data, recalculating impacts, and revising the interpreted knowledge. Each incremental update produces a new LCA state that reflects the best available environmental knowledge at a given time.

Temporal dimension

Prospective and retrospective information both address LCI and LCIA throughout all phases of the building. Prospective information is based on assumptions (design and processes), scenarios (future site conditions), and declared environmental impact data from EPDs. EPD assumptions refer to the declared values and boundary conditions embedded within an EPD dataset, including assumed reference service life, transport distances, and upstream production conditions. As the building progresses through its lifecycle stages, parts of the LCI or LCIA can become historical, meaning that prospective information can be progressively replaced or refined with retrospective information, such as measured, reported, or verified data, thereby reducing uncertainty.

Retrospective information can address more specific knowledge about units or quantities in the LCI, or more accurate information on impacts in the LCIA (instance-specific EPDs, measured emissions). Additionally, the lifetime of certain elements can be revised based on retrospective evidence.

When updating the LCA using new retrospective information, previous versions are preserved as earlier states. These past projections remain valid representations of former knowledge, enabling learning and retrospective analysis.

Table 1 presents four knowledge states derived from the intersection of two binary dimensions: the temporal dimension (prospective vs. retrospective) and the epistemic dimension (primary vs. secondary). These four states represent analytically distinct combinations relevant to building LCA practice, each characterized by a different uncertainty profile. They are not mutually exclusive within a single ALCA state: a given module may simultaneously draw on both primary and secondary data or combine retrospective and prospective contributions. The four-state structure reflects a minimum necessary set of categories to capture the full range of data quality configurations encountered across the building lifecycle.

Table 1: Temporal-epistemic knowledge states in ALCA

	Secondary (estimated/ modeled)	Primary (measured/ verified)
Prospective	Projected impacts from assumptions • Design-based quantities • Type-level EPDs • Modeled or simulated future scenarios	Empirically grounded projections • Measured baselines • Supplier-specific data • Measured process rates
Retrospective	Reconstructed past impacts • As-built model • Back-calculated activities (fuel/time/waste) • Gap-filled inventories w/o evidence	Observed and measured impacts • Verified quantities (delivery notes, monitored) • Metered process data (energy, telemetry) • Time-stamped records

Epistemic dimension

Information can be measured or estimated. In the context of LCA, these are described as primary (measured) and secondary (estimated). In ALCA, there is no fixed correlation between these and prospective or retrospective information. Instead, primary information reduces uncertainty compared to secondary information. Estimated information refers to assumptions, calculations, simulations, or predictions. Measured information includes raw sensor readings, machine telemetry, verified quantities, and reported data.

Concrete examples of sensor-derived data relevant to ALCA include: electricity consumption of AM robots or construction equipment, directly informing process energy in the LCI; material flow data from weigh cells or volume sensors on concrete pumps, informing material quantities; air quality or particulate sensors on construction sites, informing process emissions; and Building Management System (BMS) data on heating, cooling, and ventilation during operation, replacing assumed operational energy with metered values. Manual data extraction from delivery notes, invoices, and project reports complements sensor data where automated collection is not possible.

The retrospective dimension will still include a significant amount of estimation. For instance, precise on-site fuel consumption tracking does not necessarily linearly translate into specific environmental impact indicators such as NOx. Accurate quantity information in the LCI does not therefore automatically produce accurate impact results; estimation through characterization factors remains necessary. The level of uncertainty, however, should decrease when moving from prospective to retrospective. Yet, uncertainty cannot be eliminated.

Primary and secondary data directly affect the LCI, while LCIA remains largely model-based even when inventory data are measured. LCA interpretation integrates both prospective and retrospective results for decision-making.

Process-product dimension

In addition to temporal and epistemic structuring, ALCA distinguishes between product-related and process-related impacts within the LCI. In standard building LCA practice, although all environmental impacts ultimately originate from physical and chemical processes, they are attributed either to physical building elements (products, with their embodied impacts) or to lifecycle activities such as construction, operation, and demolition. This distinction follows standard LCA practice and enables structured accounting within the inventory.

Product-related impacts refer to impacts embodied in materials, components, and assemblies. These are typically represented through product datasets such as EPDs and quantified as element quantities linked to upstream production processes. Process-related impacts arise from activities such as construction, operation, maintenance, and demolition, and are quantified through activity data, including energy use, transport, equipment operation, and waste handling.

From an ontological perspective, product datasets summarize process-based information into standardized units. While this aggregation enables comparability and practical application, it may obscure instance-specific variations, such as deviations in transport distances, execution conditions, or site-specific energy mixes. Direct process information can therefore reduce uncertainty when available, particularly in adaptive contexts where execution data are progressively observed. Product impacts are generally object-based and may stabilize once elements are installed, whereas process impacts are activity-based, time-dependent, and execution-sensitive. Within ALCA, both categories coexist in each environmental knowledge state, and updates may affect product quantities, process activities, or both. The distinction serves as a structuring principle within the inventory, enabling clearer allocation, updating, and traceability of impacts across phases.

Conceptual ALCA state

At any given point in the lifetime of a construction project, ALCA is represented by a discrete, timestamped environmental knowledge state. This state reflects the most accurate available environmental knowledge of the building at that moment. It integrates accumulated retrospective impacts and projected prospective impacts across relevant lifecycle modules, preserving traceability of the data and assumptions on which they are based.

Figure 2 represents this multidimensional structure. The three dimensions define the axes of the ALCA knowledge space. The stacked cube representation is scientifically motivated: it visualizes that each lifecycle phase module simultaneously occupies a position along all three dimensions. A given module may involve both prospective and retrospective contributions, draw on both primary and secondary data, and combine product and process impacts. The stacking therefore reflects that no single cell exclusively characterizes a given module; an ALCA state is a composite of multiple co-existing knowledge configurations. When new evidence becomes available, a subsequent ALCA state is generated, preserving prior states for comparison, learning, and regulatory auditability.

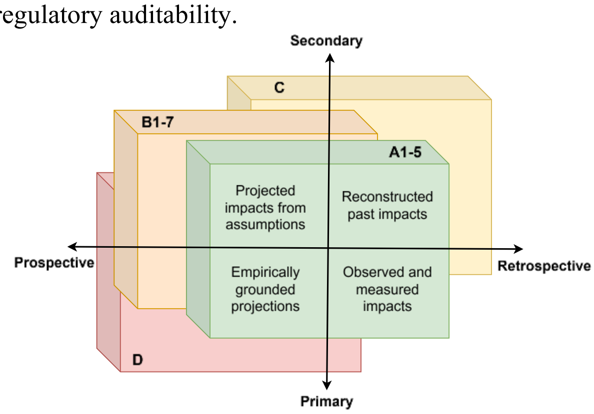

Figure 2: A conceptual ALCA state combining temporal, epistemic dimensions for all building phases.

Continuous PDCA-based control logic

ALCA operationalizes a Plan-Do-Check-Act (PDCA) control logic for environmental performance throughout the building lifecycle. In the planning phase (Plan), prospective LCA defines expected impacts based on design assumptions and scenarios. During execution (Do), construction and operational activities generate retrospective information in the form of measured or reported data, which incrementally replaces earlier assumptions within the ALCA state. Each update produces a revised, timestamped environmental knowledge state, which can be checked.

The checking phase (Check) evaluates the updated ALCA state against environmental targets or regulatory thresholds. If deviations occur, the acting phase (Act) involves mitigation measures such as design adjustments, modified construction methods, or operational interventions. In this way, ALCA transforms LCA from a static reporting instrument into a control mechanism, linking prospective planning with retrospective evidence through structured state transitions.

Regarding operational implementation, several clarifications are relevant. Updates to the ALCA state are triggered by three types of events: phase completion (e.g., end of the fabrication stage), delivery of new monitoring data (e.g., annual metered energy from the BMS), and significant deviations from regulatory thresholds, with specific deviation magnitudes to be defined by regulatory frameworks. Primary responsibility for maintaining the ALCA state lies with the building owner or operator, analogous to existing building maintenance and reporting obligations. Construction teams supply phase-specific process data during active construction stages. Automated data flows from IoT sensors can reduce manual effort significantly, particularly for operational energy monitoring, though manual reporting from delivery notes or invoices remains relevant where automation is unavailable. From a computational standpoint, ALCA does not require substantially new infrastructure: standard LCA calculation engines apply at each state, and the primary technical challenge is data integration and interoperability rather than computational intensity. Building owners and regulatory compliance bodies stand to benefit most from ALCA, as it enables accountable and verifiable impact tracking aligned with regulatory obligations. Design and construction teams also benefit from early deviation detection, which enables timely corrective action before lifecycle thresholds are exceeded.

Additive manufacturing as an enabler for continuous LCA

AM provides a particularly suitable context for illustrating ALCA due to the digital controllability and data richness of AM processes, which directly improve the epistemic quality of LCA inputs. AM processes are typically computer-controlled with integrated logging and are electricity-driven, resulting in accessible and high-resolution energy records. Sensors can additionally track material streams. As a result, material quantities and energy consumption can be recorded at high temporal resolution at the machine level.

Table 2 summarizes generic data characteristics of AM compared to conventional construction. While AM does not eliminate uncertainty it significantly improves the reliability of accumulated impacts during early lifecycle phases. This improvement stabilizes projections of remaining lifecycle impacts and strengthens the basis for continuous evaluation against regulatory thresholds.

Table 2: Generic comparison of data characteristics relevant to Adaptive LCA.

Aspect	Conventional Construction	Additive Manufacturing
Process control	Distributed, manual	Centralized, digital
Quantity tracking	Indirect	Direct or machine-derived
Energy monitoring	Limited	High-resolution, electricity-based
Temporal resolution	Low-medium	High

Impact on LCA uncertainty	High	Reduced (not eliminated)

During the design phase, all information is secondary and prospective. Designers derive quantities and impacts from models and assumptions, covering all lifecycle phases. Some primary historical data from comparable projects may inform baselines, but all future impacts are estimated. Once fabrication starts, modules A1-A3 are progressively updated from estimated to tracked and measured information (see Figure 3). Project teams can integrate instance-specific EPDs for products and measured data for processes. In AM, machine-logged electricity consumption and material flow sensor data can replace estimates directly.

During transport and construction (modules A4-A5), IoT-based measurements replace predicted construction process impacts. Updated as-built BIM models and tracked material quantities progressively substitute simulated impacts. Exact delivery routes or reported fuel use from transport vehicles improve transport accuracy. In AM, robot sensor data provide comparable information for material use and process energy.

During the operational phase (module B), two primary information types become relevant. First, metered energy from BMS progressively replaces estimated consumption for heating, cooling, and ventilation. Continuous prospective projections remain necessary to detect deviations before targets are exceeded. Second, renovation activities must be incorporated with their specific materials, processes, and impacts.

The demolition phase (module C) determines the realized building lifetime, the key parameter assumed at the outset. Only at demolition can final accumulated impacts be determined with certainty. Although corrective action is no longer possible at that stage, stakeholders can transfer results to subsequent projects or apply financial adjustments if targets were exceeded.

DBL integration

In this work, the DBL provides the institutional and technical context for operationalizing ALCA. It functions as an authoritative repository for realized building information, including as-built products and as-performed construction processes, rather than as an analytical or predictive system. This aligns the DBL with the ex-post dimensions of ALCA: measured or reported information provides an auditable baseline of accumulated impacts, while projected future impacts are generated by external analytical services, such as digital twin tools, using DBL data as their factual basis.

The role of DPPs within this architecture is significant. DPPs, mandated under the EU Ecodesign for Sustainable Products Regulation (European Commission, 2024), enable instance-specific documentation of individual building products and components, including material composition, declared environmental impact data, and service life information. Within ALCA, DPPs serve as the link between generic EPD datasets and instance-specific LCA inputs. Where a standard building LCA uses a type-level EPD covering a class of products, DPPs enable attribution of verified environmental data to a specific installed component, e.g., a particular concrete batch used on a specific date, with documented transport distance and energy consumption. This instance-specific traceability directly improves the accuracy of product-related impacts .

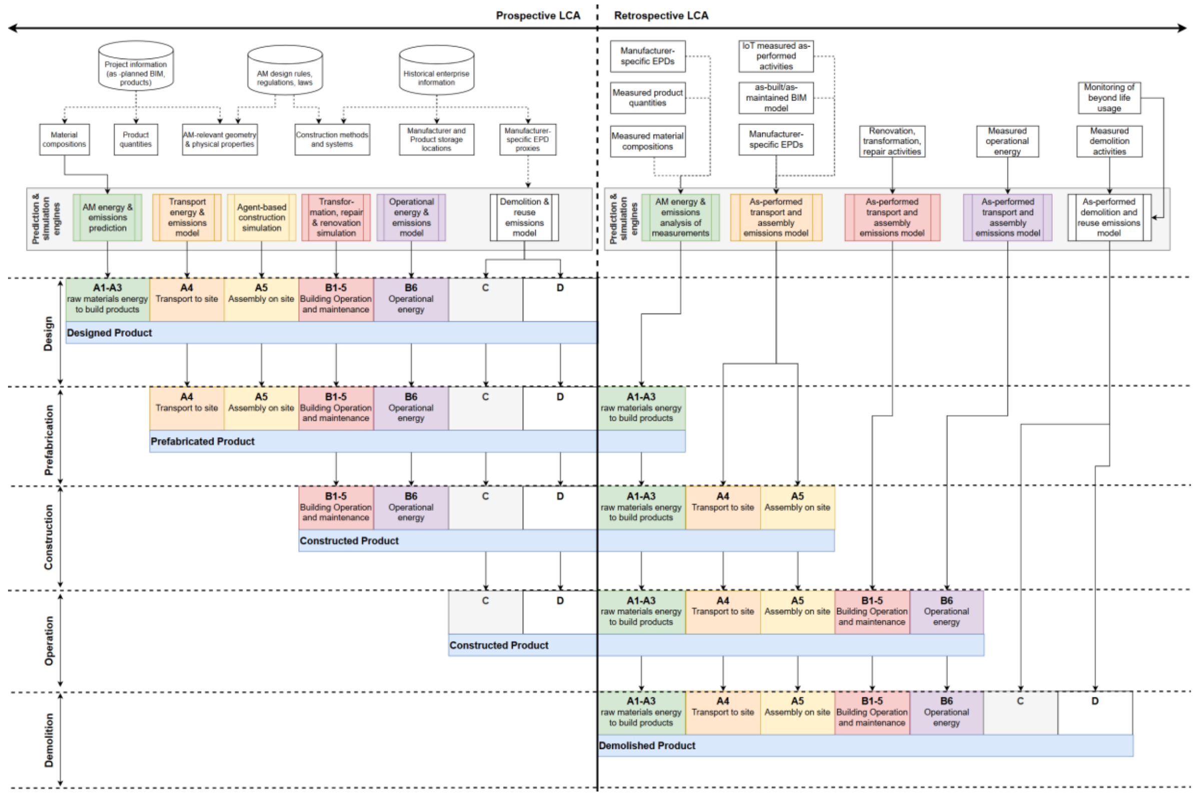

Figure 3: Instantiation of ALCA in an AM construction site.

in the LCI and reduces the uncertainty associated with generic EPD assumptions. As DPP adoption expands under EU regulation, the epistemic quality of ALCA inputs is expected to improve correspondingly, progressively replacing secondary estimates with primary, product-specific data. This connection represents the core mechanism through which the fourth contribution of this paper is realized in practice. The evolution of EPD content within DPP frameworks, particularly the shift from generic type-level declarations to instance-specific performance records, is therefore a key development that ALCA is designed to leverage.

Operationalizing ALCA through the DBL requires interoperable data structures and robust versioning. The DBL should act as an integration layer connecting DPPs, material passports, permit documentation, and LCA state records, rather than duplicating all data. Each update must include timestamps, source links, assumptions, and provenance metadata so that accumulated impacts remain auditable and suitable for regulatory compliance.

This separation clarifies the distinction between the DBL and a DTC. Although the DBL can serve as an information container within a DTC ecosystem, it does not perform reasoning, prediction, or optimization. The DBL stores and exposes information, while external tools provide analytical capabilities. Maintaining this separation preserves institutional clarity and avoids mixing authoritative records with interpretive or predictive models.

Discussion

DBLs and related passport systems should be understood as governance instruments, not merely technical data containers. They formalize documentation obligations, responsibilities, and verification mechanisms across the building lifecycle, giving ALCA the institutional continuity required for regulatory use.

An explicit comparison with DLCA clarifies ALCA's contribution. DLCA resolves time within the LCA model by defining parameter variations as predefined functions, enabling time-specific characterization of emissions and impacts (Arvidsson et al., 2024). However, once the DLCA model is constructed and executed, its results are fixed: the model does not update when actual conditions deviate from modeled trajectories. ALCA differs fundamentally in this respect. Rather than predefined trajectories, ALCA responds to actually observed data, generating new timestamped states as evidence accumulates. ALCA therefore does not replace DLCA; instead, it introduces an adaptive dimension that DLCA lacks. In practice, DLCA methods could be deployed within each prospective ALCA state, while the adaptive state-transition logic of ALCA incorporates retrospective evidence as it emerges. The two approaches are therefore complementary rather than competing.

Regarding standardization, LCA is an ISO-standardized methodology (ISO 14040; ISO 14044), and ALCA does not propose an alternative impact assessment method. Impact categories, characterization factors, and system boundary conventions remain unchanged. What ALCA introduces is a governance framework for managing the updating process: defining when a new state is generated, how prior states are preserved, and how accumulated and projected impacts are combined at any point in time. Developing normative standards for these aspects, including trigger thresholds, state management protocols, and interoperability requirements between DBL systems and LCA calculation engines, represents a necessary step toward regulatory adoption. Engagement with standards bodies such as ISO TC 207 and CEN TC 350, alongside regulatory alignment at the national and EU level, is an important direction for future work.

The conceptual relationship between ALCA and DTC reveals strong theoretical overlap. Both rely on structured information dimensions, iterative updating, and PDCA-based control logic. However, their scopes differ: DTC focuses primarily on construction process monitoring and optimization, whereas ALCA addresses lifecycle environmental impact accounting across all phases. ALCA can therefore be understood as a specialized environmental subsystem within a broader DTC ecosystem, accessing shared semantic information while specifying environmental data requirements that other subsystems must provide. Ontology-based semantic frameworks developed in DTC research (Schlenger et al., 2025; Speiser et al., 2025) offer a promising direction for future integration, particularly to enable consistent cross-system interpretation of environmental data. Extending such frameworks toward environmental impact accounting is acknowledged as future research rather than a current contribution of this paper, as it presupposes empirical validation of the ALCA framework itself. Generative and agentic AI can support experts in including relevant knowledge into such systems (Speiser et al., 2026).

The separation between DBLs as authoritative repositories and digital twin services as analytical engines has important governance implications. Verified ex-post information becomes part of the regulatory record within the DBL. Predictive simulations and scenario analyses remain external and do not automatically acquire authoritative status. This preserves institutional clarity and prevents conflation of observed performance with modeled projections. Regulators can assess compliance based on accumulated and verifiable impacts, while project teams use predictive tools to anticipate deviations and implement mitigation measures within a PDCA logic.

The framework remains conceptual and has undergone argumentative rather than empirical validation. While AM illustrates the feasibility of high-resolution monitoring, application in conventional construction, operational phases, renovation cycles, and end-of-life processes requires further investigation. Long building lifetimes limit full lifecycle validation, but prefabrication facilities and AM environments may serve as short-term testbeds. Standardization of semantic structures, interoperability requirements, and regulatory alignment remain open research challenges. Moreover, although ALCA progressively reduces epistemic uncertainty, it cannot eliminate inherent predictive limits in future lifecycle modules.

Conclusions

This paper introduced ALCA as a time-resolved framework for treating building LCA as a continuously evolving environmental knowledge state. ALCA combines accumulated ex-post impacts with projected ex-ante impacts across lifecycle phases and structures this information through temporal, epistemic, and product-process dimensions. By generating discrete, timestamped states as verified data become available, ALCA reframes building LCA from a static reporting exercise into an ongoing process of environmental knowledge revision.

The paper further showed how ALCA can be anchored within a DBL ecosystem. The DBL provides an authoritative repository for verified ex-post information, while DPPs improve the instance-specific accuracy of product-level LCA inputs and external digital twin services support projection and decision-making. This separation preserves governance clarity while enabling continuous monitoring and PDCA-based intervention.

The framework remains conceptual and requires empirical validation in pilot settings. Future work should develop interoperable semantic structures, test ALCA across construction and operational contexts, and define normative requirements for adaptive LCA updating.

Declaration of AI in the writing process

During the preparation of this work, the authors used generative AI to proofread text and improve clarity. After using this service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Acknowledgments

The research presented in this paper was funded by the European Union Horizon 2020 research and innovation program under agreement no. 101162318 (AM2PM).

References

Arvidsson, R., Svanström, M., Sandén, B.A., Thonemann, N., Steubing, B. and Cucurachi, S. (2024). Terminology for future-oriented life cycle assessment: review and recommendations, International Journal of Life Cycle Assessment, 10.1007/s11367-023-02265-8.

Bruhn, S., Gislason, S., Røgild, T., Andreasen, M., Ditlevsen, F., Larsen, J., Sønderholm, N., et al. (2024). Pioneering historical LCA - A perspective on the development of personal carbon footprint 1860–2020 in Denmark, Sustainable Production and Consumption, Vol. 46, 10.1016/j.spc.2024.03.014.

European Commission. (2024). Ecodesign for Sustainable Products Regulation, Official Journal of the European Union.

Forth, K. (2025). BIM-Based Semantic Enrichment for Environmental Analyses Using Large Language Models.

Global Alliance for Buildings and Construction. (2022). 2022 Globall Status Report for Buildings and Construction.

Hauschild, M.Z., Rosenbaum, R.K. and Olsen, S.I. (2017). Life Cycle Assessment: Theory and Practice, Life Cycle Assessment: Theory and Practice, 10.1007/978-3-319-56475-3.

International Energy Agency. (2023). Benchmarking and Target-Setting for the Life Cycle-Based Environmental Performance of Buildings.

Kristensen, T., Aaes, O. and Weisbjerg, M.R. (2015). Production and environmental impact of dairy cattle production in Denmark 1900-2010, Livestock Science, Vol. 178, 10.1016/j.livsci.2015.06.012.

Sacks, R., Brilakis, I., Pikas, E., Xie, H.S. and Girolami, M. (2020). Construction with digital twin information systems, Data-Centric Engineering, Vol. 1 No. 6, 10.1017/dce.2020.16.

Schlenger, J., Pluta, K., Mathew, A., Yeung, T., Sacks, R. and Borrmann, A. (2025). Reference architecture and ontology framework for digital twin construction, Automation in Construction, Vol. 174, p. 106111, 10.1016/j.autcon.2025.106111.

Social- og Boligstyrelsen. (2018). BR18, Bygningsreglementet.Dk.

Speiser, K., Seiß, S., Boukamp, F., Melzner, J. and Teizer, J. (2025). From fragmented data to unified construction safety knowledge: A process-based ontology framework for safer work, Automation in Construction, Vol. 176, p. 106293, 10.1016/j.autcon.2025.106293.

Speiser, K. and Teizer, J. (2023). An Ontology-Based Data Model to Create Virtual Training Environments for Construction Safety Using BIM and Digital Twins, 30th European Group for Intelligent Computing in Engineering Conference (EG-ICE), London, UK.

Speiser, K., Maciocci G., Boukamp F., Teizer J. (2026). “Agentic system for construction safety risk assessments using large language models and knowledge graphs”, Advanced Engineering Informatics, Special issue: AI for the Built World, https://doi.org/10.1016/j.aei.2026.104681

Volt, J., Toth, Z., Glicker, J., De Grotte, M., Borragán, G., De Regel, S., Dourles-Quaranta, S., et al. (2020). Definition of the digital building logbook - Report 1 of the Study on the Development of a European Union Framework for Buildings’ Digital Logbook, 10.2826/480977.

De Wilde, P. (2014). The gap between predicted and measured energy performance of buildings: A framework for investigation, Automation in Construction, Vol. 41, 10.1016/j.autcon.2014.02.