

PROTOTYPING A CONSTRUCTION-STAGE PLATFORM FOR AS-BUILT SUSTAINABILITY DATA MANAGEMENT

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ABSTRACT

New regulations and voluntary green certification schemes mandate the disclosure of as-built life-cycle global warming potential (GWP). Current construction-phase data management is a bottleneck because contractors and subcontractors manage data using fragmented digital workflows. This study utilizes an Action Design Research (ADR) approach to develop and pilot a low-code/no-code (LCNC) digital platform designed to integrate BREEAM reporting and automated A1 to A5 carbon calculations into routine site operations. This preliminary study was implemented over a two-month pilot on a commercial project in Tallinn, Estonia, involving five subcontractors. The System Usability Scale (SUS) method yielded an average score of 89.5, indicating good usability and successful workflow integration. Pilot demonstration and expert feedback confirmed that domain-specific, structured data capture significantly improves reporting quality, auditability, and calculation readiness. The findings demonstrate that digitizing the reporting responsibility enables lean-aligned carbon performance feedback, providing a solution for meeting emerging "as-built" environmental disclosure requirements.

KEYWORDS

Construction-phase LCA, as-built carbon reporting, Low-code/no-code (LCNC), data management standardization, lean construction.

INTRODUCTION

The construction sector must decarbonize. European regulations (Commission 2025; European Commission 2024) and voluntary building certification frameworks, such as LEED and BREEAM (Tsirovasilis et al. 2025), accelerate the shift by requiring the disclosure of the life-cycle global warming potential (GWP) for the as-built stage. This implies the need to move from the existing methods, tools and practices focused on the design-stage approaches and assumptions to capture construction-phase data in a reliable manner. This is challenging as construction phase impacts are project-specific (Joseph and Mustaffa 2021): while upstream assessments (A1 to A3) are supported by products' environmental performance documentation, modules A4 (transport) and A5 (construction) depend on reliable on-site data management.

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Despite established expectations and requirements, construction-phase data management remains fragmented, dependent on spreadsheets and email exchanges (Bolpagni et al. 2022; Martinez and Pfister 2023): methods that are not standardized, traceable, and auditable. Poor construction-phase data quality is wasteful, causing rework and delays, and preventing effective feedback loops. While improving construction information flow is a typical Lean research objective (Al Hattab and Hamzeh 2018; Dave et al. 2014), current workflows lack the digital integration necessary to extend data actionability beyond traditional time, cost, and quality metrics to encompass environmental performance (Pikas et al. 2024). To address this gap, the study develops a LCNC-enabled prototype to intervene in the construction-phase data management process using an Action Design Research approach (Peffer et al. 2018; Sein et al. 2011). This paper reports the first preliminary results for digitizing the on-site data management.

RESEARCH METHOD

This study applies the Action Design Research (ADR) approach (Sein et al. 2011), a genre of Design Science Research (Peffer et al. 2018), to identify a problem, develop a digital artifact, and intervene in construction-site workflows. The study was initiated by co-author who worked as a BREEAM consultant on a construction site in Tallinn, Estonia. His observation was that BREEAM and carbon related environmental reporting relied on fragmented methods and tools. This work followed four ADR stages:

1. **Problem Formulation:** Combined a literature review and industry experience to establish the need for standardized, workflow integrated data management. Regulatory developments, lean construction research, and the literature on domain engineering and LCNC informed the elicitation of the artefact objectives and requirements.
2. **Building and Intervention:** The focus was on artefact development and intervention implementation. The LCNC approach was chosen to facilitate rapid prototyping. Development progressed through two cycles: iteration 1 established the digital solution for monthly BREEAM data capture and management; and iteration 2 integrated calculation logic for LCA modules A1 to A5.
3. **Evaluation and Learning:** User feedback from the pilot and expert interviews with a BREEAM assessor and a carbon specialist/researcher were used to evaluate and refine the artefact. Improvements focused on both functionality and usability.
4. **Formalization of Learning:** The fourth ADR stage focused on generalizing learnings: making the project's situated insights transferable to a broader class of construction specific problems. Building on the problem class defined in stage 1, main lessons learned in the form of artefact and process design principles were articulated.

PILOT, DATA COLLECTION AND INTERVIEWS

This paper documents the first phase of a platform development, piloted over two months on a commercial construction project (the foundation and structural works phase). All five subcontractors, who were already obligated to submit monthly BREEAM-related data (e.g., material deliveries, transport information, and waste quantities), were involved. The intervention replaced the existing Excel spreadsheet and email-based reporting routine with data entry on the cloud platform. During the pilot, the responsible researcher on site provided user support, monitored system use, and documented issues as well as user learnings.

The System Usability Scale (SUS) (Lewis 2018) was used for assessing the usability of the established platform. In SUS, scores above 70 typically indicate good usability, while scores above 90 indicate excellent user experience. Participants completed the SUS at the end of the first iteration. Additionally, users rated the platform against the previous Excel and email

workflow in terms of ease and speed of data submission. An open-ended question (“What would you change or improve?”) captured qualitative improvement suggestions.

Additionally, two semi-structured expert interviews were conducted in the second iteration with a BREEAM practitioner and a LCA researcher. A demonstration-focused format was used to examine the artefact’s alignment with industry needs and to identify opportunities and barriers for wider adoption.

PROBLEM FORMULATION

CONTEXT AND PROBLEM BACKGROUND

The construction sector contributes ca 34% to the global CO₂ emissions (United Nations Environment Programme 2025), making its decarbonization a central priority (European Commission 2020). The recast of Energy Performance of Buildings Directive (EPBD) strengthens the regulation by requiring disclosure of life-cycle greenhouse gas (GHG) emissions together with the building energy performance certificates (European Commission 2024). The EPBD shifts the attention to whole-life carbon, requiring the life-cycle GWP to “[...] reflect the as-built stage” (Commission 2025). This implies that methods, currently focused on embodied and operational carbon estimates prepared in the design stage, need to be adapted to capture as-built emissions (Joseph and Mustaffa 2021).

However, the requirement for as-built LCA is not new. Voluntary certification schemes (e.g., BREEAM and LEED) require LCA implementation in the design and construction stages by systematic monitoring of materials, logistics, site energy use, and waste streams (Cole and Jose Valdebenito 2013; Tsirovasilis et al. 2025). For example, BREEAM requires monthly reporting of construction stage inputs (Ferreira et al. 2023). That is, LCA has become a well-established methodology for quantifying environmental impacts in voluntary certification projects.

In the design stage, LCA calculations often rely on averaged assumptions. However, construction-phase emissions are shaped by project-specific variables, including manufacturer specific products, supplier locations, transport modes and distances, equipment selection, temporary site energy demand, and actual waste generation (see **Error! Reference source not found.**). Furthermore, also use-stage is influenced by as-built outcomes: material substitutions, installation choices, and construction quality impact embodied and operational carbon. Despite the well-established frameworks, BREEAM and carbon data management during construction remains problematic, particularly for A4 (transport) and A5 (construction) modules (Pikas et al. 2024). In the absence of integrated construction-phase data management, site personnel often depend on fragmented spreadsheets and email-based reporting (Bolpagni et al. 2022).

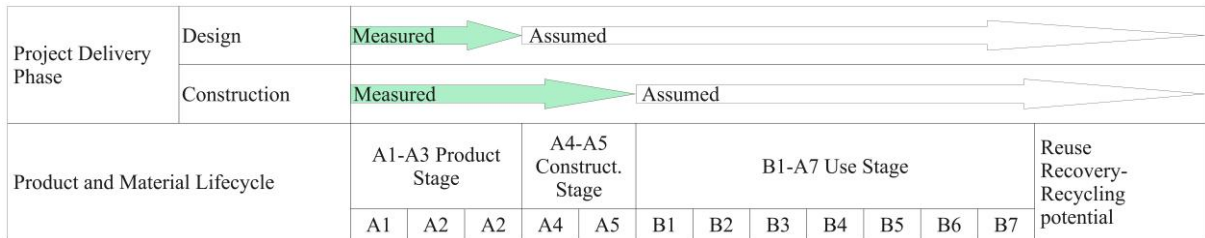


Figure 1: Construction project delivery phases aligned to LCA stages and data type (measured or assumed) used (adapted from (CEN 2011, 2012)).

DATA NEEDS AND REQUIREMENTS FOR LCA CALCULATIONS

Error! Reference source not found. summarizes data categories and information needs to calculate embodied carbon for modules A1 to A5 and to determine use-stage operational assumptions for modules B1 to B7. If available, upstream impact assessments A1 to A3 are

typically calculated using Environmental Product Declarations (EPDs) (Del Borghi 2013) or national databases and selected B-stage inputs are grounded in product documentation issued under the Construction Products Regulation (Commission 2022). Modules A4 and A5 depend on project-specific site data, covering logistics and transport, temporary works and materials, electricity and fuel consumption, and waste generation and treatment, where current data management practices remain the least standardized and fragmented (CEN 2011, 2012; Pikas et al. 2024; Pügi 2025).

Table 1: Typical data needs for carbon calculations at the as-built state (CEN 2011, 2012; Pikas et al. 2024; Pügi 2025).

LCA module	Stage	Typical Data Needs (examples)
A1-A3	Raw material extraction, transport to manufacturer and manufacturing	Material type and quantities; upstream extraction and processing information; upstream transport modes and distances; manufacturing process energy impacts; packaging and production waste (typically available in EPDs and database factors)
A4	Transport to site	Delivery distances; transport and vehicle type; payload/load factor assumptions; number of trips and return trips; losses and damage
A5	Construction and installation	Site fuel and electricity use; temporary heating, cooling, drying; equipment and machinery use; temporary works and ancillary materials; water use; construction waste, transportation and treatment; site logistics
B1-B7	Use stage (commissioning and handover-relevant inputs)	As-built product information; declared performance and settings; refrigerant type and charge; commissioning records; maintenance requirements; replaceable components and service-life; adaptability and renovation relevant as-built information; installed renewables (e.g., PV capacity); fixture flow rates and water system configuration; metering/BMS readiness

LEAN CONSTRUCTION AND DOMAIN ENGINEERING

In lean construction, the aim is to minimize waste and maximize value through continuous improvement enabled by feedback loops (Koskela 2020). Visual management facilitates feedback loops by making production performance and management information transparent and actionable (Brady et al. 2018; Tezel and Aziz 2017). However, by and large, lean construction production management has not integrated environmental performance within its control loops. Embedding LCA within production management through digital data capture would support addressing data quality problems. This would allow project teams to monitor emissions alongside time, cost, and quality, and to respond to deviations as they emerge. This approach aligns with lean principles of empowering labor and building quality into processes (Tommelein 2019).

This integration can be enabled through modern software development approaches. LCNC platforms democratize software engineering and enable domain experts to rapidly prototype workflow-specific solutions with limited programming effort (Martinez and Pfister 2023). When combined with domain engineering, focused on formalizing the key concepts, data modelling, and rules for a selected domain (BREEAM reporting and LCA calculations in this research) (Bjørner 2021), LCNC enables developing a consistent, traceable and auditable

construction site carbon data management solution. As such, lean provides the production management logic, and domain engineering and LCNC provide a practical means.

ARTEFACT OBJECTIVES AND REQUIREMENTS

This research addresses the construction-phase BREEAM and carbon accounting gap: the absence of contractor-focused, standardized data management digital solution to capture, manage, and calculate emissions in line with BREEAM and LCA requirements. The proposed digital platform should integrate carbon data management into routine site workflows. The platform needs to be user-friendly and adaptable to different project types and contexts.

Requirements were structured using the FURPS framework (Mishra 2013). Functionally, first iteration focused on enabling monthly BREEAM data capture and reporting: users authenticate, select a reporting month, enter data by module (A1 to A3 materials, A4 transport, A5 site fuel, energy and waste, including certified wood), and generate summarized exports for SmartWaste (a platform used by sustainability consultant for BREEAM accounting). Each record needs to be linked to a user and calendar month, timestamped, and the month needs to be formally confirmed to lock entries for further editing. Second iteration focused on automating LCA calculations, where data structures and formulas rely on predefined emission factors (EPDs or the Estonian emissions database), automated unit-to-mass conversions, and A4 and A5 factors aligned with the Estonian Ministry of Climate database. See **Error! Reference source not found.** for the detailed summary of Use Cases.

Simplicity and usability were defined in this first phase as the main non-functional requirements. Specifically, each user view must have a clear purpose, minimal fields, and explicit guidance and status cues to support data reporting. Finally, the platform ought to be device-agnostic, supporting use on phones, tablets, and desktop computers. Overall, the prototype should provide a proof-of-concept for domain-centric LCNC development in construction BREEAM reporting and carbon management.

Table 2: Detailed overview of Use Cases (Subcontractor (SG), General Contractor (GC)).

ID	Use case	Description	Actor	Preconditions	Outcome
UC1	User login	Authenticate user and provide role-based access	SC, GC	User account exists	User logged in; actions linked to user ID
UC2	Select reporting month	Define calendar month for data entry or review	SC, GC	Logged in	All entries assigned to selected month
UC3	Enter A1–A3 data	Input delivered construction materials and quantities	SC, GC	Month selected	A1–A3 entry saved; CO ₂ updated
UC4	Enter A4 data	Input transport distance, vehicle type, and loads	SC, GC	Month selected	A4 entry saved; CO ₂ updated
UC5	Enter A5 fuel/energy data	Input on-site fuel or energy consumption	SC, GC	Month selected	A5 entry saved; CO ₂ updated
UC6	Enter timber delivery	Input timber data incl. certificates and documents	SC, GC	Month selected	Timber entry saved
UC7	View own data summary	Review and optionally export own entries	SC	Month selected	Summary view; optional CSV/XLSX export
UC8	View project CO ₂ totals	View cumulative A1–A5 emissions	SC, GC	Month selected	Project-level CO ₂ overview
UC9	Confirm reporting month	Lock monthly entries after submission	SC, GC	All required fields completed	Data locked; edits disabled
UC10	Enter full A5 site data	Input site-wide energy, waste, and utilities	GC	Admin role	Complete A5 dataset stored
UC11	Export data to SmartWaste	Export monthly data for certification reporting	GC	All users confirmed	SmartWaste-compatible Excel file
UC12	Manage users	Create, edit, activate/deactivate users	GC	Admin role	User accounts updated
UC13	Manage all entries	Review and correct subcontractor entries	GC	Admin role	Entries corrected or returned

BUILDING AND INTERVENTION

ITERATION 1

Architecture and Platform Choice

To meet functional and usability requirements, the artefact was decided to be implemented as a web-based application accessible from desktop and mobile devices. The digital solution was role-based with different user interfaces: (1) subcontractor views enabling structured data entry and self-monitoring, and (2) main contractor views enabling structured data entry and a dashboard providing overview, verification, and consolidated reporting. Because the co-author had limited prior software development experience, the prototype was decided to be built using a LCNC approach to enable rapid implementation and maintainability.

Several criteria guided platform selection: low or no licensing cost, sufficient capacity for storing data, support for LCNC development, the availability of learning resources for self-

regulated learning (Robal et al. 2024), and a stable user community. Based on these criteria, the Oracle Cloud and Oracle APEX were selected as the development environment. Oracle APEX supports a data-centric development approach and rapid creation of forms, tables, and dashboards through visual configuration, while still allowing the use of SQL or programming language where custom logic is required.

Digitizing Data Collection and Control

The first iteration was focused on replacing traditional BREEAM reporting with a structured database-enabled workflow. Core functions implemented included authentication (UC1), reporting month selection (UC2), entry of materials data (A1 to A3) (UC3), transport (A4) (UC4), basic A5 fuel and energy consumption (UC5), and wood product and material deliveries (UC6). The subcontractor interface was organized into four main entry categories: materials, fuel and energy, water, and wood. Each view had a dedicated table form to support consistent monthly reporting. For the wood category, additional functionality and fields were implemented to match BREEAM certification needs to satisfy stricter evidence requirements, for example, document uploads (e.g., certificates, delivery notes).

A month-based reporting structure was enforced: users were required to select the reporting month after login, and the system restricted date inputs to the selected month (future dates and out-of-period dates were blocked). All entries were linked to a user account and timestamped. A “month confirmation” mechanism was implemented to lock entries and prevent retrospective edits: users could confirm their month, but re-opening or overriding confirmation remained an administrator function to prevent accidental or premature lock-in. SQL scripts were used to implement row-level access (users see only their own entries) and rule-based confirmation checks. In addition, an administrative view was developed to highlight missing confirmations for the current and previous month, enabling the main contractor to follow up on incomplete reporting and distinguish between “no activity” and “missing submission”.

Finally, to reduce duplication of effort, the first iteration included an export workflow to support reporting in SmartWaste platform. Because SmartWaste platform uses English material nomenclature and template-based bulk upload, a mapping layer was created between local material vocabulary and SmartWaste terms. Based on this, the developed system generates an export file containing the SmartWaste-aligned terminology. However, due to the file-format constraints between platforms, the final upload required copying the output into the SmartWaste template. Nevertheless, the export functionality reduced manual re-entry and standardized the reporting outputs.

ITERATION 2

Extending the Data Model for Carbon Calculation

In the second iteration, the development was focused on Use Cases 8 and 10 (shown in **Error! Reference source not found.**), expanding the data model and computation capabilities for automating LCA calculations. Specifically, the database schema was extended with new tables for emission factors and additional A5 inputs, including electricity and district heating consumption, waste quantities, and waste treatment, each linked to corresponding emission factors. These new entities were integrated through links to existing central data tables (e.g., materials, users, reporting months), ensuring all inputs could be aggregated and traced consistently across A1 to A5 modules (see **Error! Reference source not found.**).

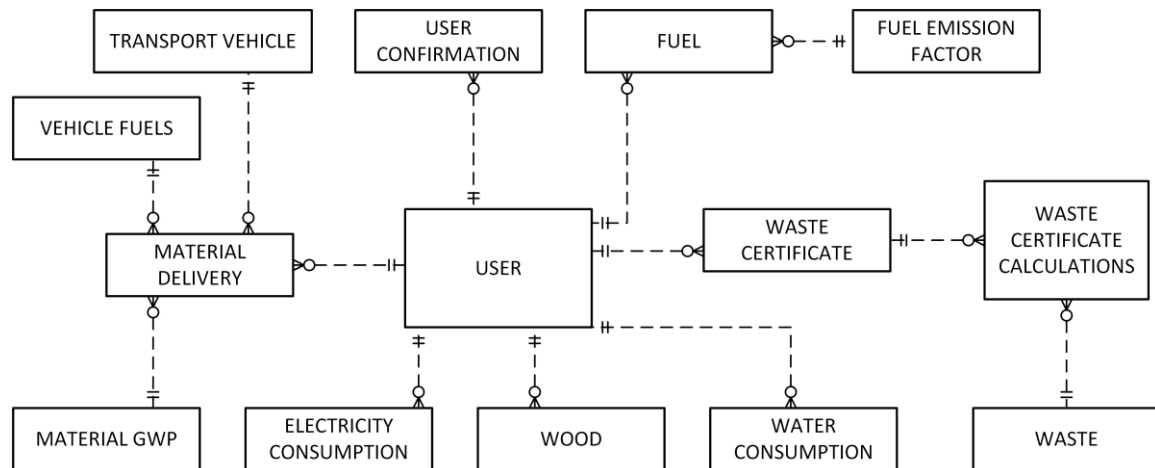


Figure 2: High-level LCA data model of the developed platform.

From Data Collection to Automated A1–A5 Carbon Accounting

The second iteration developed the BREEAM prototype into an automated LCA calculation system for construction embodied carbon. Two main functions were implemented: (1) full A5 data entry (electricity, district heating, and waste streams, in addition to fuels) (UC10), and (2) visual display of CO_{2e} results at project level and by category (UC8). A calculation module was developed to link each user entry to the correct emission factor and to apply the required unit conversions before calculation. The computation relied on two factor sources: (1) material production impacts (A1 to A3) taken from the Estonian construction materials database, with an option to override using product-specific EPD values; and (2) construction stage factors (A4 and A5) based on emission factors published by the Ministry of Climate. When an EPD was available, user entered the declared GWP value and its reference unit, which was stored and used to replace generic database values with product-specific accounting.

Users could input quantities in kilograms, cubic meters, or square meters depending on the material and information available per selected material. The system converted these values to kilograms using density or area mass values from the national database to ensure consistency. Importantly, the user interface restricted unit choices to those that could be reliably converted for the selected material, reducing data entry errors and preventing invalid calculations, an example of a data quality measure implemented in the digital solution.

Transport calculations (A4) were developed further by adding explicit vehicle type selection, which associated each transport record with the corresponding transport emission factor. Users provided delivery distance and vehicle type, and the system computed emissions based on the selected factor and transport type. For A5, forms were added to capture electricity and district heat consumption and to record waste volumes along with waste treatment types to enable a more complete representation of construction-site operations.

Real-time emission calculation was implemented using SQL-based triggers and calculation routines that execute automatically when a record is inserted or updated. For each entry, the system computed kgCO_{2e} and aggregated totals at project level across tables. A visual dashboard was used to support monitoring and interpretation, including breakdowns of A5 emissions by category, material quantities and embodied carbon by type, and transport distances over time. This operationalized the carbon performance feedback loops.

EVALUATION AND LEARNING

ITERATION 1: DATA MANAGEMENT AND USABILITY

The evaluation of the first iteration focused on assessing whether the prototype met its objective of improving data collection and management in the construction phase, when compared to existing spreadsheet- and email-based workflows. The prototype was used by five subcontractors, all of whom had prior experience submitting BREEAM related data via Excel and email. This provided a baseline for evaluating perceived usability and workflow fit.

Quantitative evaluation based on the SUS indicated a high level of perceived usability, with individual scores ranging from 75 to 97.5, and an average score of 89.5, corresponding to a “very good” usability level of the established digital solution. In addition, users reported that data submission became easier and faster compared to the previous workflow, indicating that the structured reporting logic and simple forms reduced administrative effort. These results suggest that the proposed digital solution was aligned with site practices.

Qualitative feedback provided useful learning for further development. Users highlighted gaps in material coverage for specialized works, requested the ability to enter multiple materials under a single delivery date, and suggested improvements to session handling and table sorting. These observations revealed that while the underlying workflow and data model was sound, greater flexibility was needed in the user interface. The evaluation confirmed that enforcing structured workflows (e.g., month selection, confirmation and locking) improved data consistency. The first iteration therefore validated the feasibility of replacing ad hoc reporting with a structured digital workflow.

ITERATION 2: CARBON CALCULATION AND SECTOR RELEVANCE

The evaluation of the second iteration focused on the platform ability to support the needs for accurate, transparent construction-phase carbon accounting. Two face-to-face demonstration sessions were conducted: one with a BREEAM practitioner and one with a construction sustainability researcher. The evaluation addressed the necessity and practical relevance of the proposed digital solution for capturing construction data for A1 to A5 modules and for automating carbon calculations.

Both experts confirmed the importance and relevance of monitoring carbon emissions based on real construction-phase data and emphasized that such an approach provides a more realistic and defensible representation of actual project impacts than assumed averaged values or model-based estimates. The experts also highlighted that delegating data entry to the actors who control the inputs (subcontractors and the main contractor) reduces errors and increases transparency, particularly when data entries are consolidated and validated within a single system. The ability to integrate product-specific EPD values, apply transport- and site-specific emission factors, and visualize results at project level was seen as an important benefit.

A key learning from the second iteration was the importance of embedding carbon accounting into routine site management activities rather than treating it as a separate reporting obligation. Experts noted that the platform’s dashboards and aggregation logic support increasing the awareness of emissions and have the potential to make carbon reporting a “normal” part of monthly site routines. Identified barriers to wider LCA adoption were not methodological but organizational, including data ownership, motivation, and the lack of tools that align with construction workflows. As such, the evaluation also reinforced the usefulness of the ADR approach: learning from real interventions revealed that technical feasibility alone is insufficient without usability, trust, and integration into existing practices.

DISCUSSION: FORMALIZING LEARNING

Although the artefact developed in this study had a relatively narrow scope, the ADR intervention generated insights at two complementary levels: (1) workflow and product-level learnings, and (2) domain engineering and LCNC approach learnings. Based on the two levels, (3) the design principles for the environmental data management platform are articulated.

WORKFLOW AND PRODUCT-RELATED LEARNINGS

The main learning is that construction-phase LCA accounting is primarily a data management problem. The pilot intervention sought to change subcontractors' daily data reporting practices. The current fragmented workflows lead to data submissions with poor quality, which are often the root cause of wasteful rework, inconsistent datasets, and limited traceability and auditability. Instead, data quality management should be designed into routine site operations through digital solutions that allocate reporting responsibility to those who generate and control data while still retaining oversight. Practically, this required implementing constraints (e.g., common units, mandatory fields, factor sources), traceability (who reported what and when), and quality assurance mechanisms such as locking, controlled overrides, and validation rules. Furthermore, converting subcontractor inputs into LCA-ready records required standardizing vocabulary and classifications (e.g., unit normalization, factor binding, controlled categorization), highlighting that automation often depends on executable domain rules. That is, well planned and domain engineered (Bjørner 2021) digital artefact can act as a mistake-proofing device (Tommelein 2019), endorsing proper action and behaviour for assuring high quality data.

However, while the pilot demonstrated promising results, there are several opportunities for improvement. As this paper documents the first preliminary phase on digitizing monthly BREEAM reporting and extending the data model to automate A1 to A5 calculations, future research needs to extend the study to additional construction phases, projects, and project teams. Some focus should be placed on establishing as-designed and as-planned construction carbon targets and actively reducing it throughout the project delivery and building lifecycle stages. Future research should also link construction-stage decisions of modules A1 to A5 to downstream assumptions of the use stage (B-modules), to enable "as-built-to-use" learning. For instance, product or material substitutions made during construction may reduce upfront costs but increase maintenance (B2) or replacement (B4) needs due to smaller durability or the shortened service life.

In practice, there is also a significant overlap between BREEAM, construction LCA, commissioning, and as-built (BIM) data requirements and documentation. Future research should shift from parallel reporting to a more comprehensive approach, where the soon to be mandatory Digital Product Passports (DPPs) (Commission 2025; European Commission 2024) facilitate the flow of human and machine-readable data throughout the building lifecycle (Çetin et al. 2026). However, this still requires resolving semantic issues such as a lack of common vocabulary, including concepts and classifications, and the current reliance on unstructured static documents by establishing shared data dictionaries and ontologies to address information flow breakdowns (Pauwels and McGlinn 2022).

Furthermore, research on data governance and incentive mechanisms is required to make carbon data management a routine, accountable site activity (Pikas et al. 2024). Current barriers are often less technical than they are organizational (Çetin et al. 2026): the ambiguity of roles and responsibilities in terms of data accountability discourage sub-contractors from data management.

DOMAIN ENGINEERING AND LCNC LEARNINGS

A more general implication of the pilot study is that developing construction workflow specific solutions is fundamentally a domain engineering task, well supported by ADR methodology.

For example, a reliable digital solution depends on an executable data model that standardizes semantics (e.g., units, categories, and emission factors), and implements reusable rules for validation and quality assurance. This was evident in the pilot project, where iterative refinement of the schema and rules improved the consistency, traceability and auditability of subcontractor inputs.

The pilot further demonstrated the value of a LCNC approach in accelerating workflow implementation and enabling solutions to be shaped close to operations (Martinez and Pfister 2023). By lowering technical barriers, LCNC can empower construction domain experts as “citizen developers” to configure workflows aligned with site routines and information needs, supporting bottom-up innovation in a highly fragmented industry (Koskela and Kazi 2003). However, LCNC also has limitations, and effective delivery still requires skills in solution planning, requirements management, and data modelling, highlighting an important agenda for developing future digital roles, competencies and governance in construction organizations.

DESIGN PRINCIPLES FOR ENVIRONMENTAL DATA MANAGEMENT PLATFORM

Drawing on this preliminary ADR intervention, the following design principles (DP) are articulated to guide the development of construction-phase as-built environmental performance data management platforms:

- **DP1: Integration.** Reporting must be embedded into routine site management workflows rather than treated as an isolated administrative task.
- **DP2: Responsibility.** Data reporting responsibility must be allocated to the actors who generate and control data inputs (e.g., subcontractors), while general contractors retain oversight and focus on project-level consolidation.
- **DP3: Standardized Semantics.** LCA automation depends on a domain-engineered data model that standardize semantics (e.g., material and transport classifications, common attributes) and rules for calculations.
- **DP4: Mistake-Proofing and Auditability.** To ensure data quality and provide a stable audit trail, digital solutions must implement digital constraints, quality assurance mechanisms and confirmation mechanisms for carbon data disclosure.

CONCLUSIONS

Utilizing ADR and LCNC methodologies, this research demonstrates the feasibility of standardizing BREEAM reporting and automating A1 to A5 LCA calculations through a dedicated digital platform integrated into routine site workflows. Pilot results and expert feedback confirm that embedding rules and traceability into daily operations enhances data quality and readiness for as-built GWP disclosure, while also facilitating lean-aligned production management feedback loops. The study formalizes four core design principles for designing such platforms, including integration, responsibility, semantics, and auditability to position environmental performance as one key a production management metric. Future research should focus on scaling the evaluation across diverse projects, integrating DPPs, and establishing the organizational governance and incentive structures to support carbon data management as a routine contractor obligation.

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