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A unified intelligence-augmented framework for building audits via physical and virtual inspection

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ABSTRACT

Building audits are essential for informed decision-making in maintenance, renovation, and end-of-life planning. However, current practices remain predominantly manual and time-consuming due to fragmented data, limiting resource-efficient management of existing building stock. This paper presents a unified, intelligence-augmented framework designed to enhance the efficiency and reliability of both physical and virtual building inspection workflows. Five core design principles of adaptability, accessibility, affordability, acceleration, and alignment are derived from a multi-phase formal analysis to guide the development of the R^2PIVS pipeline, which transforms the existing audit process into six modules: retrieval, reality capture, prediction, interaction, visualization, and summarization. The framework leverages human-AI collaboration in key building inventory tasks, including geometry measurement, visual assessment, and hazard estimation, through interactive annotation, model refinement, and output validation. Findings from expert elicitation studies indicate that the proposed application schema is promising for improving the efficiency and scalability of existing workflows. By aligning machine learning capabilities with domain-specific requirements, this research lays the foundation for a human-in-the-loop building audit system that enables standardized inspection and inventory information management to support circular construction practices throughout the building life cycle.

1. Introduction

Intelligence augmentation, which leverages the complementary strengths of computational intelligence and human expertise, presents a promising avenue for optimizing operational processes in circular construction. While intelligence augmentation shows significant promise in Architecture, Engineering, and Construction (AEC) sector, several critical knowledge gaps hinder its effective implementation. These include the lack of clarity on AI-applicable tasks, poorly defined human-AI interaction and interfaces, insufficient methods for capturing egocentric and contextual data, and limited understanding of the broader innovation impacts on the AEC industry (Zhang et al., 2021). As a result of the growing shortage of skilled labor and the urgent need for circular and regenerative building practices, digital transformation and automation of traditional workflows are no longer optional but necessary (Pedroso et al., 2024).

One critical area for digitization in the built environment is building audit practices, where the interplay between physical and digital environments along with the complexity of multi-modal, spatiotemporal data poses significant challenges for designing, deploying, and scaling adaptive human-in-the-loop systems. Pre-demolition and pre-renovation audits are essential for assessing the reuse potential of in situ building products, extending their material life cycles and implementing circular economy strategies through informed resource management. Despite the ntroduce of EU-wide protocols and guidelines (European Commission, 2024), the building audit process remains largely manual and non-standardized, which restricts sustainable management of existing building stock for large-scale material assessment and reuse. This inefficiency stems from such challenges as tight time window between demolition and reconstruction or renovation projects, high costs associated with expert inspections, and data inconsistencies that hinder comparability and usability.

To address the aforementioned issues, we present an intelligence-augmented framework for building audit workflows to support building inspection and documentation across physical and virtual environments. Drawing on the findings from a scoping review and stakeholder interviews, we identify core design principles that underpin the framework development: **(1) adaptability** to dynamic project life cycles and contextual workflows through flexible modularity; **(2) accessibility** and interaction with multi-granular, multi-modal data through

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a unified user interface; **(3) affordability** of a simplified workflow that minimizes manual interventions via low-touch automation for scalable implementation; **acceleration** of information exchange and integration through an end-to-end data pipeline; and **alignment** with real-world practices through synchronized and standardized iterative processes. Based on these principles, we introduce a conceptual **R^2PIVS pipeline** that structures key building audit phases, including desk study, field survey, inventory, management recommendations, and reporting, into distinct modules:

- **Retrieval**: Gathering relevant structured and unstructured building-specific data from external building databases and documentation.
- **Reality capture**: Acquiring multi-modal as-built asset data from a physical survey and scanning.
- **Prediction**: Inference geometry measurement, visual assessment, and hazard estimation of the built asset across multi-modal spatial representation using diverse machine learning models.
- **Interaction**: Facilitating guidance, feedback loops, and adaptive learning between human and machine learning models.
- **Visualization**: Visualizing raw input data, preliminary and revised prediction outputs with visual overlay on a interactive interface.
- **Summarization**: Structuring multi-granular data at the building-product level to ensure interoperability with downstream applications.

Through a participatory co-design process with experts in human-computer interaction (HCI) and circular construction, the proposed pipeline was transformed into a human-centered, model-driven framework characterized by module-associated dimensions, approaches, and attributes. Its modular, sequential, and iterative structure ensures high data quality by emphasizing accuracy at the building-product level, completeness at the room or floor level, consistency across audit instances and user inputs, uniqueness in component-level data aggregation, timeliness for real-time updates, and validity across heterogeneous data sources. The utility of the framework is demonstrated through use-case scenario mapping of both existing applications and potential intelligence-augmented inventory tasks, including machine learning-powered geometry measurement, visual inspection, and hazard estimation. Furthermore, the application schema derived from the framework was evaluated against stakeholder requirements through verification with industry professionals in expert user studies.

This study addresses the information gaps and data quality challenges that arise from the absence of a data pipeline tailored to practical building audit workflows. It makes three key contributions: **(1) Interdisciplinary and cross-sectoral synthesis** of research in HCI and circular construction practices, identifying user requirements, co-developing the design space, and verifying the implementation schema to inform the development of human-centered, intelligence-augmented building audit systems; **(2) Hybrid intelligence framework design** for mixed-initiative building audits, grounded in core design principles and conceptualized through the R^2PIVS pipeline to enable efficient data acquisition, synchronization, and standardization; and **(3) Inventory scenarios and application schema roadmap** for future system development, validated by expert users and to be elaborated in a subsequent paper focused on prototype implementation and testing. Scenario-based demonstrations highlight how human-in-the-loop interaction supports human oversight and fosters trust in predictive outputs, both crucial for real-world deployment in construction contexts. Finally, we discuss the study's limitations, outline future research directions, and identify opportunities for advancing domain-specific HCI development.

2. Methodology

A multi-phase formal analysis was conducted to identify design requirements and validate the proposed intelligence-augmented building audit application within both research and practice communities, as illustrated in Fig. 1. The process began with a scoping review to identify research gaps and assess available digital tools from a theoretical perspective, alongside stakeholder interviews to analyze practical needs. Subsequently, interdisciplinary experts were engaged to co-design an intelligence-augmented building audit pipeline, which was further elaborated into a conceptual framework. This framework was then applied to map use cases from existing inventory applications and prospective inventory scenarios. The usability and design considerations of the resulting application schema were evaluated through expert user studies.

2.1. Scoping review

A scoping review was conducted to explore the interdisciplinary literature up to 2025 at the intersection of human-machine collaboration and building audits. A keyword search on the Scopus database combined terms such as "intelligence augmentation," "digitalization," or "human-AI" with "building," "construction," and "audit" or "inventory." Title and abstract screening identified 25 relevant publications. To complement this search, snowballing techniques were applied to capture additional articles recommended by the databases and gray literature suggested by industry representatives. The collected literature was analyzed to identify common challenges in building audits, existing digital solutions, and potential areas of application. Insights from this analysis informed the development of the initial stakeholder interview guide and shaped the first iteration of design principles aimed at addressing the identified limitations.

2.2. Stakeholder interviews

To understand current building audit practices and identify areas for improvement, semi-structured interviews were conducted with four industry representatives from the construction and demolition sectors. The primary aim was to derive design requirements to inform the development of an intelligence-augmented building audit application. Interview questions were tailored to the expertise and business focus of the participants, covering topics such as pre-demolition audit inventories and material recertification. The specific objectives were to: (1) map workflows involved in pre-demolition audits and material recertification practices, (2) identify priority building products for inventory, and (3) determine key attributes required for material redistribution. This process helped identify stakeholder needs and formulate design requirements to ensure practical alignment and adoption (Wik & Bergkvist, 2022). Following participant validation of the interview notes, recurring themes were extracted, and identified functionality gaps and opportunities in current practice informed the conceptualization of the design principles.

2.3. Framework co-development

Based on the consolidated design principles, the intelligence-augmented building audit pipeline was derived and transformed from existing workflows. Building upon this, a framework was co-created iteratively with seven human-computer interaction researchers and five circular construction researchers using a participatory design approach (Wik & Bergkvist, 2022). Each one-on-one hybrid session lasted approximately 30-45 minutes and included two interactive exercises focused on evaluating the logic, coherence, and attributes of the proposed intelligence-augmented building audit framework: the intelligence augmentation pipeline and the event sequence of inventory. The pipeline exercise began with a walk-through of the current pre-demolition audit workflow diagram, based on established EU guidelines and protocols (European Commission, 2024). A table detailing data specifications and sources at each workflow phase was then presented to illustrate the heterogeneity and multi-granularity of the information involved. Using this table as a reference, the comprehensive framework, including key dimensions, methodological approaches, and data attributes, was introduced, and geometry measurement of building elements was presented as a practical example. Researchers provided oral and written feedback

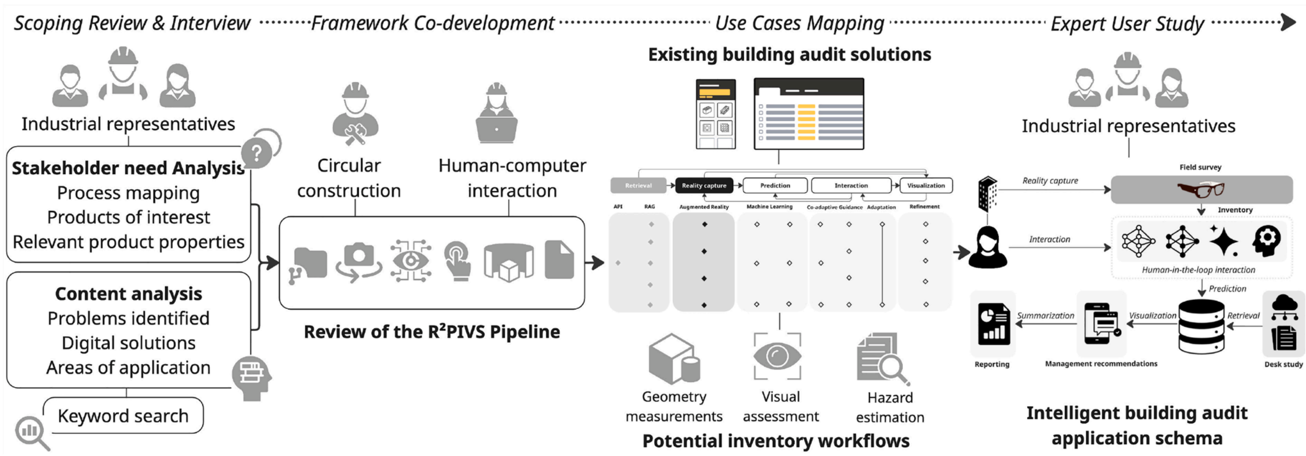


Fig. 1. A multi-phased formal analysis explores the design space of an intelligence-augmented building audit framework.

on the pipeline design, framework, and illustrative examples. Revisions were incorporated iteratively, and the updated versions informed subsequent sessions, ensuring progressive refinement and alignment with interdisciplinary requirements.

2.4. Use case mapping

The proposed framework was applied to map existing building audit applications and prospective inventory use-case scenarios. The functionalities of three existing building inventory management applications were systematically examined, summarized, and aligned with the corresponding modules, dimensions, and attributes of the framework. Similarly, the workflow of machine learning-assisted inventory tasks, including geometry measurement, visual assessment, and hazard estimation, were mapped for comparison.

2.5. Expert user studies

Expert user studies were conducted to evaluate the intelligence-augmented building audit application schema derived from the proposed framework. The objective was to assess usability, efficiency, and overall utility in relation to both the defined design space and real-world workflows. Eight companies representing key stakeholders in Switzerland's circular construction sector participated, including reuse consultants, material certification experts, and deconstruction contractors. Half of these companies had also participated in the earlier stakeholder interviews, ensuring continuity of insights. Their diverse expertise provided a representative evaluation across consulting, certification, and practical implementation contexts. The study procedure comprised three stages: a 15-minute conceptual presentation of the application structure and wireframes, a 15-minute open discussion, and post-session completion of an online survey containing open-ended questions and Likert-scale items. The survey protocol was approved by the institutional ethics committee. Feedback was collected across three evaluation criteria: modular workflow setup (adaptability principle); scalable and affordable information gathering and management (accessibility and affordability principles); and standardized data exchange (alignment and acceleration principles). Qualitative survey findings were synthesized thematically based on semantic agreement rates, while quantitative results were analyzed through averages and distributions.

3. Summative findings from multi-phased formal analysis

The theoretical and practical insights derived from a scoping review and stakeholder interviews inform the distillation of key design principles necessary to develop an intelligence-augmented building audit framework from diverse perspectives.

3.1. Scoping review of the interdisciplinary subjects

This section summarizes relevant findings from the scoping review at the intersection of building audit research and human-centered AI.

3.1.1. Digital circular transformation in construction

The challenges in current building audits and emerging digital solutions are analyzed to support circular construction practices.

Building audit workflow | To achieve decarbonization of the constructions sector, identifying material reuse potential from existing buildings is critical for reducing resource consumption and waste generation. A major challenge in implementing this circular strategy is the lack of building-specific material data in existing databases. Therefore, building audits are required to obtain up-to-date building status, inform tendering processes, and fulfill permit requirements (European Commission, 2024). Pre-renovation (or pre-demolition) audits are preparatory assessments that identify and quantify materials and products for reuse, recycling, or special handling due to hazardous substances (Wahlström et al., 2019). These audits inform material recovery pathways and generate verified building data. Such data can be integrated into digital building logbooks, linking resources like building renovation passports, material passports, and digital product passports (European Commission, 2024).

Pre-renovation audit comprises of five sequential phases, illustrated in Fig. 2. It begins with a **desk study**, where original construction records, maintenance protocols, and other relevant documents are reviewed (European Commission, 2024). During the **field survey**, building inspectors conduct on-site investigations to identify, measure, analyze, and sample building products for reuse and recycling potential. The collected data is compiled into an **inventory**, organized by floor, detailing the condition and estimated quantities of building components. The **management recommendations** phase assesses whether materials are uncontaminated, reusable, or recyclable, and identifies suitable waste disposal options (European Commission, 2024). Finally, the **report** summarizes findings and supports decision-making in construction and demolition waste management (Rašković et al., 2020).

Emerging digital building audit solutions | Despite existing guidelines for pre-renovation audits, inventories often lack standardization due to inconsistent data availability and accessibility. Building information is inherently complex and unique to each structure, which hampers interoperability and data reuse (Kuzminykh et al., 2024). Recent standards such as SIA 430:2023 (Swiss Society of Engineers and Architects , 2023) and DIN-SPEC 91481:2023 formalize audit procedures, but scaling these processes remains challenging due to labor-intensive data capture and unclear data governance, resulting in incomplete and incoherent datasets (Bellini et al., 2024; Shojaei et al., 2021; Wu et al., 2021).

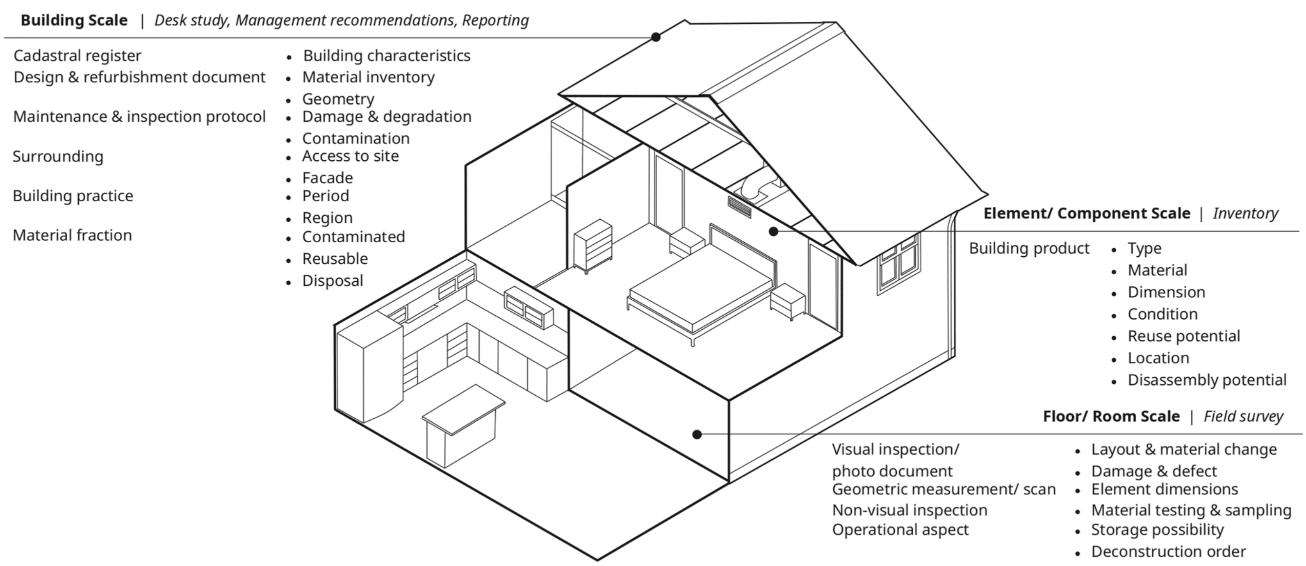


Fig. 2. Heterogeneous building audit information across various spatial scales: *Building-scale* data are assembled during desk study, management recommendations, and reporting phases. *Floor- or room-scale* data are compiled for inventory. *Element- or component-scale* data are gathered during on-site inspection.

Addressing these issues requires rethinking digitalization and automation of audits.

Various pilot tools support building audits. For instance, the Danish Material Atlas aids desk studies by providing data on construction products and reuse potential (Royal Danish Academy, 2025). Field surveys increasingly utilize digital twins and scan-to-BIM technologies for asset mapping, while mobile apps and portable LiDAR devices facilitate data collection and sharing from deconstruction to secondary material markets (Gordon & De Wolf, 2024; Kuzminykh et al., 2024; Mêda et al., 2023; Pedroso et al., 2024). Integration efforts with material cadastres and BIM aim to standardize databases and streamline data across audit stages (Pesta et al., 2024).

However, current approaches remain fragmented, often focusing on individual audit stages and limiting interoperability and holistic data management across the construction value chain (Bellini et al., 2024). An integrated digital platform providing an end-to-end pipeline from data acquisition to standardized reporting could improve transparency, traceability, and decision-making in building audits. A pilot by Omer et al. (2024) demonstrates this potential by using 3D digital models and augmented reality to automate demolition waste audits. Yet, challenges such as resource intensity, incomplete documentation, time-consuming model generation, and discrepancies in site surveys hinder scalability. These issues highlight the need for seamless digital solutions that integrate information across all audit phases (Bellini et al., 2024).

3.1.2. Human-centered AI in domain contexts

This section reviews existing research on mixed-initiative systems and co-adaptive guidance that are relevant to workflow augmentation.

Mixed-initiative systems | Mixed-initiative systems enhance model performance by integrating human expertise with machine efficiency, leveraging the complementary strengths of humans in handling complex tasks and models in achieving scalability and speed (Holter & El-Assady, 2024). Human oversight is essential in interactive machine learning, especially within semi-supervised pipelines involving pre-processing, annotation, and interactive labeling. However, designing scalable human-in-the-loop systems remains challenging due to contextual complexities in real-world applications (Wu et al., 2022), particularly in the construction domain, where domain-specific knowledge is highly fragmented.

The core research areas *visual interactive labeling* and *interactive machine learning* hold significant potential for addressing the lack of labeled data and integrating expert knowledge into validation processes in building audits. *Visual interactive labeling* enhances generalization by incorporating domain-specific ground-truth labels as open vocabularies and leveraging model confidence levels to identify uncertain instances, thereby reducing annotation workload while preserving label quality. Key approaches include interactive segmentation, vertex prediction, bounding box labeling, and active learning, all of which can be extended to 3D spatial labeling. A six-stage labeling pipeline, comprising pre-processing, training, visualization, candidate suggestion, user annotation, and feedback interpretation, supports scalable labeling workflows. Strategies such as instance-to-class assignment can improve efficiency by integrating building element and component annotations into inventory workflows (Bernard et al., 2018; Matt et al., 2025).

Additionally, *interactive machine learning* introduces shared control and agency, enabling humans to supervise, collaborate, and provide feedback for incremental model refinement. For building audits, combining visual labeling at the data level with interactive learning at the task level allows pre-trained models to be fine-tuned for specific objectives. The resulting predictions are synthesized within a human-in-the-loop framework that supports iterative refinement and expert-guided decision-making.

Co-Adaptive Guidance | Effective human-AI collaboration requires models adapting to human intentions, capabilities, and behaviors (Natarajan et al., 2024), thereby enabling more personalized and context-aware interaction. Co-adaptive guidance employs stage-wise visualization and feedback mechanisms to sustain shared understanding, prevent collaboration breakdowns, and enhance interpretability (Sperrle et al., 2023, 2024). Three key dimensions underpin this interaction: *agency*, *interaction*, and *adaptability*, operationalized through co-adaptive mechanisms embedded in the audit workflow to guide user attention to noisy data or uncertain instances (Holter & El-Assady, 2024). These dimensions are essential for designing domain-aware interfaces that foster trust, improve process transparency, and enhance interpretability.

3.2. Stakeholder need analysis

Findings from stakeholder interviews highlight a growing regulatory momentum toward circular construction, yet practical constraints, particularly market viability and material recertification, continue to limit its widespread adoption. There was a strong consensus on the need for a standardized data framework to harmonize heterogeneous empirical data from building inventories, enabling effective integration with cascading downstream tasks.

Regulatory momentum and practical constraints in circular construction | Building material inventories and reuse practices in Switzerland are guided by SIA 430 (2023) (Swiss Society of Engineers and Architects , 2023) and the EU Construction and Demolition Waste Management Protocol (European Commission, 2024). With an increasing number of Swiss cantons embedding these reuse standards into local building codes, the demand for building inventories is steadily rising. Despite regulatory advances, scalable reuse remains constrained by high storage costs, long lead times, and fragmented logistics. Standardized components with regional supply chains present strong reuse potential but require early-stage coordination, affordable pricing, and minimized storage duration. Otherwise, reclaimed materials struggle to compete with new products, which typically remain in storage for months than years.

Market viability and certification challenges in material reuse | The main barrier to broader adoption is supply uncertainty: reclaimed materials from demolition projects often arrive late, incomplete, or both. This risk drives clients to reserve materials on physical marketplaces up to four months in advance. Compared to online platforms, physical reuse hubs offer greater reliability in delivery and quality assurance. Currently, most marketplace activity involves equipment and interior elements, reflecting both demand and practicality, as these materials are easier to deconstruct, handle, and store. Structural components, which account for 70-80 % of a building's material mass, represent the greatest carbon and economic impact potential. They are also the only category currently eligible for recertification, although many clients bypass formal certification if a structural engineer verifies the element's integrity. Future digital inventory systems could streamline this process by linking individual components to their original location and structural specifications in the source building.

Harmonizing reuse data with standardized frameworks | Standardized frameworks such as DIN SPEC 91484 and Swiss Inv (Cirkla, 2024) enable consistent assessment and documentation of in situ building products across all actors in the value chain. They define requirements for information collection, process steps, stakeholder roles, and recommended tools, particularly for structural assets, while promoting unified data formats to ensure system compatibility and interoperability. As the sector increasingly embraces circularity, data harmonization has become a central objective. While GS1 standards are expected to influence future efforts, current implementations still lack standardized descriptors. Essential product attributes for reuse assessments include material type, dimensions, and quality, while attributes such as condition, disassembly potential, and reuse potential are crucial for inventory purposes. Assessing disassembly potential remains particularly challenging when critical details, such as joint types or fastening methods, are missing from building documentation. Digital tools, including AI-assisted platforms, are anticipated to address these challenges by enabling cross-project searches for comparable components, automatic dimension recognition, and integration of external product data.

3.3. 5A Design principles

The core design principles for shaping an intelligence-augmented building audit workflow were distilled from the summative findings of the formal analysis.

Adaptability via flexible modularity | ensures dynamic and context-aware intelligence across project life cycle and workflows. Building audit information is inherently building-specific, with varying levels of data availability. Therefore, a modular pipeline should accommodate real-world complexities with suitable digital techniques that can handle heterogeneous data sources and evolving conditions.

Accessibility via unified user interface | emphasizes the need for a harmonized, user-friendly interface for interacting with multi-granular and multi-modal building data. The system should be accessible to project teams with diverse technical backgrounds. To achieve this, dashboards, visualizations, and intuitive navigation tools should be designed with a low technical threshold to enable inspection of inventory data and project progress.

Affordability via low-touch automation | aims to minimize manual interventions and simplify workflows, thereby reducing the time and cost associated with building inspections and post-processing activities. Semi-automation supported by integrated machine learning models further enhances cost-effectiveness and enables scalable implementation across a broader range of building stock.

Acceleration via end-to-end integration | focuses on developing an efficient information pipeline that integrates data gathering, exchange, and post-processing across multiple sources and project phases within a single system. This necessitates the incorporation of machine learning models to automate key processes and streamline implementation.

Alignment via standardized iteration | emphasizes the synchronization and standardization of processes, including input data requirements, prediction outputs, user feedback, and downstream tasks, within real-world contexts. A product-specific index for multi-modal data, combined with iterative versioning mechanisms, enables comprehensive tracing and tracking of building project updates throughout the building life cycle.

4. Design space

The design space operationalizes the identified design requirements into task specifications aligned with the core design principles and seamlessly integrated across the various stages of the building audit workflow. This pipeline provided the foundational blueprint for co-developing a unified, intelligence-augmented framework in collaboration with interdisciplinary researchers.

4.1. Hybrid R^2PIVS pipeline

Grounded in the 5A design principles, the R^2PIVS pipeline-Retrieval, Reality Capture, Prediction, Interactive Visualization, and Supervision-was developed to operationalize an intelligence-augmented building audit workflow, as illustrated in Fig. 3.

4.1.1. Retrieval in desk study module

Information retrieval during the desk study involves acquiring as-designed documentation, including original floor plans, technical drawings, building images, maintenance records, and renovation histories. Leveraging vision-language models enables automated querying, inference, and summarization, reducing the manual effort traditionally required to collect and interpret these documents. *Application programming interfaces (API)* provide direct access to structured data like building registers, while *retrieval-augmented generation (RAG)* techniques facilitate the extraction of relevant unstructured data from building permit documents.

4.1.2. Reality capture in field survey module

Reality capture during field surveys documents the current state of buildings, capturing modifications, deviations, and adjustments accumulated over the building's life cycle. This process can be augmented through *AR-assisted building scanning* using mobile devices or smart glasses equipped with LiDAR and photogrammetry, enabling rapid, multi-modal data acquisition in the form of images, videos, and point clouds.

4.1.3. Prediction and interaction in inventory module

Machine learning prediction and interaction during inventory acts as a central part for human-AI collaboration for information extraction and assessment of existing buildings. The core *interactive machine learning* inventory tasks adopting a co-adaptive processes, categorized as follows:

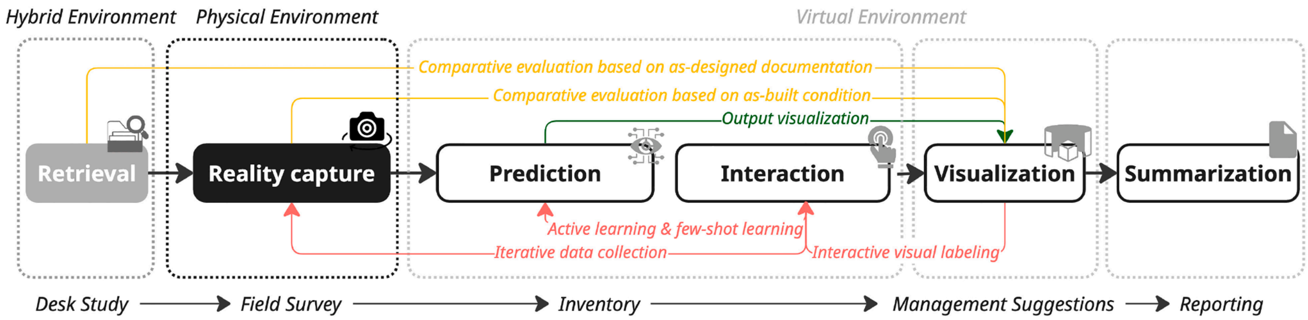


Fig. 3. R²PIVS pipeline: The intelligence-augmented building audit workflow is structured into sequential and interconnected modules. Dynamic information loops facilitate seamless data flow and integration. Arrows and colors indicate process flow: green for forward progression, pink for feedback loops, and yellow for reference data retrieval supporting human-in-the-loop evaluation.

Geometric measurement | predicts semantic labels, dimensions, and locations for building elements and components.

Visual inspection | segments building component instances, identifies material types and evaluates visual conditions.

Hazard estimation | infers the potential presence of hazardous materials by extrapolating patterns from historical inventories of similar buildings.

4.1.4. *Visualization for management suggestions module*

Human-in-the-loop validation is performed by visually comparing model predictions with as-designed and as-built documentation. This comparison highlights discrepancies and prediction errors, prompting users to provide interactive labeling and, where necessary, initiate iterative data collection to improve input quality. Uncertain instances are flagged for annotation and incorporated into the training set via active learning, with diversity sampling strategies enhancing class representation. Few-shot learning is further supported through multi-modal user feedback, combining spatial annotations and textual corrections to *refine* model generalization, particularly for previously unseen object categories.

4.1.5. *Summarization for reporting module*

Raw input data from the retrieval and reality capture modules, along with preliminary and revised prediction outputs, are consolidated in a multimodal database to support *multi-granular retrieval* for downstream tasks. Product-specific information can be extracted to generate digital product passports or marketplace listings, while building-level information can be used for inventory reporting, regulatory compliance, and material reuse planning.

The proposed pipeline, aligning with the D5 digital circular workflow by De Wolf et al. (2024), strengthens data quality assurance by enabling streamlined processing within a unified application environment. Data completeness and timeliness are evaluated through analysis of SLAM trajectories during the reality capture module, ensuring adequate spatial coverage and up-to-date as-built information. Accuracy and consistency are assessed via user-led comparative evaluations, contrasting model predictions with data obtained from both reality capture and retrieval modules. Validity is verified through interactive visualization, while uniqueness of multi-modal data across varying levels of spatial aggregation supports comprehensive summarization.

4.2. *Framework co-development*

The co-design of the initial framework with cross-disciplinary researchers iteratively refined both process-driven interaction strategies and domain-aware interface design. HCI researchers focused on framework architecture, process flow, feedback integration, system generalization, and visualization and interaction design, while circular construction researchers emphasized alignment with real-world practices, decision-making processes, and digital tool development. This included the incorporation of domain knowledge into interaction design, performance monitoring, and integration with existing software and data systems.

Feedback integration and system generalization | To enhance interpretability, the framework is grounded in real-world contexts, with clearly defined entry points, key transitions, and rationales for user actions and data flows. Multiple feedback modalities are integrated via a coherent strategy that explicitly defines feedback loops in terms of both sequence and function, clarifying their role in supporting model learning. To assess generalizability and usability, the framework is demonstrated across a variety of inventory tasks, illustrating its adaptability to diverse use cases and practical scenarios.

Engagement strategies and interaction patterns | User engagement is supported through gamification elements, such as rewards for timely and accurate feedback, which motivate participation and reinforce user agency. Feedback drives real-time updates to visualizations, enhancing system responsiveness to evolving inputs and conditions. Comparative visualizations of multi-modal and temporal data further improve user understanding and interaction quality. Behavioral data, including action sequences and associated data points collected during interaction with augmented or reconstructed scenes, can reveal provenance patterns in inventory processes and highlight user priorities. Passive input data, such as attention maps, help identify the most salient elements to users. Aggregated feedback can then be applied in batch to refine baseline models, improving contextual performance for domain-specific tasks and supporting iterative system learning.

Integration with construction software and data systems | Given the complexity of multi-modal data, robust version control and unique identifiers for building components are essential. Experts highlighted the importance of interoperability with established BIM platforms, which could be achieved through dedicated plug-ins for widely used software such as Revit or Archicad. Validated predictions, grounded in as-built data, can accelerate documentation of existing structures for renovation or deconstruction, while also enhancing deliverables such as bills of materials, construction protocols, and floor plans for new builds.

4.3. *Finalized intelligence-augmented framework for building audit*

The finalized framework and its associated dimensions are designed to accommodate heterogeneous data sources and adapt to dynamic real-world conditions, as illustrated in Fig. 4. By integrating egocentric sensing devices and machine perception with interactive machine learning, the framework substantially accelerates both on-site inspection and post-processing workflows. It further enables spatially structured, model-specific representations at the building-product level, supporting a range of downstream information workflows. This approach enhances the cost-effectiveness of building inventories, not only for end-of-life structures but also as a standard practice in large-scale

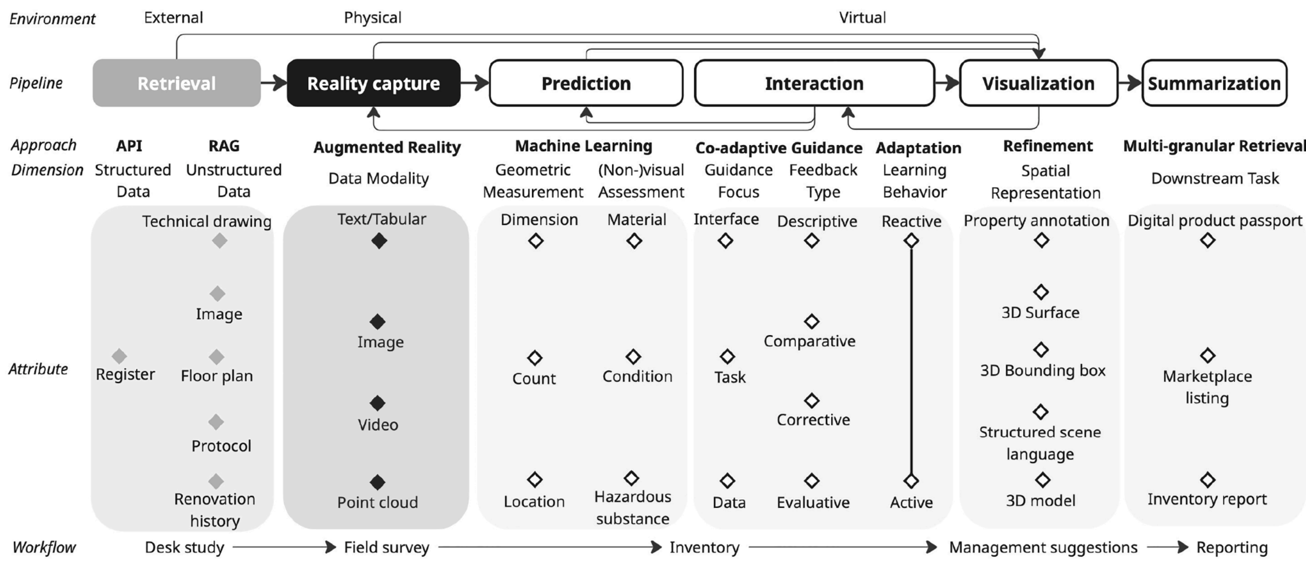


Fig. 4. An unified intelligence-augmented building audit framework illustrating its operating environment, dimensions, approaches, and attributes in a top-down structure.

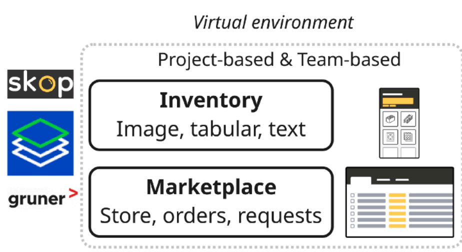


Fig. 5. Existing building inventory management applications primarily support product inventory and marketplace redistribution.

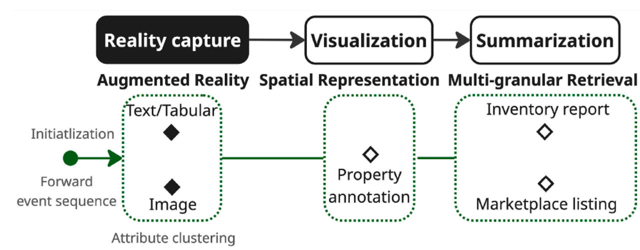


Fig. 6. Existing applications often involves reality capture, visualization, and summarization modules.

building stock assessments. Integrated feedback loops and prediction refinement mechanisms within the interaction and visualization components improve alignment between machine learning models and human decision-making, enabling domain-specific customization, enhanced interpretability, and continuous model adaptation.

5. Use cases mapping

The framework's applicability is illustrated by mapping building inventory management applications against intelligence-augmented inventory workflows.

5.1. Existing applications

Three building inventory management platforms were selected as representative examples: the French web applications *Skop* (Skop, 2025) and *Diag it* (Diag it, 2025), and the Swiss system *Gruner ReUse* (Gruner, 2025). These applications provide web- and mobile-based platforms that synchronize building inventory data with marketplace listings on a project-specific basis (Fig. 5).

Skop facilitates direct reuse, sale, or reconditioning of materials by providing material diagnostics, tracking, and logistics optimization, automating sourcing and supply through a configurable, project-based dashboard. *Diag it* integrates with the Cycle Up marketplace and supports reconditioning workflows by establishing supply channels and managing workshop operations. *Gruner ReUse* employs a geo-referenced inventory system based on the element-based building construction cost plan (eBKP-H), documenting each component with a product-specific datasheet containing properties relevant for online marketplace trading.

Fig. 6 highlights the framework modules most commonly implemented in existing building inventory management applications, namely, reality capture, visualization, and summarization. Textual and image-based documentation collected during on-site inspections can be uploaded and structured into tabular datasets that compile annotated properties of building components. The resulting product-specific information can then be exported as an inventory spreadsheet or seamlessly integrated with online material marketplaces to facilitate the trading of reusable components.

5.2. Intelligence-augmented inventory scenarios

Three representative inventory tasks-geometry measurement, visual assessment, and hazard estimation-are presented as illustrative use cases. While they share common interaction and visualization features, each is supported by a dedicated machine learning model that enriches various aspects of the inventory process. The presented models serve as examples and can be replaced with other state-of-the-art approaches suited for similar tasks.

In the workflow diagrams, color-coded sequences indicate process flow: green arrows represent forward progression, and pink arrows indicate backward flow for revision and feedback. Yellow highlights retrieval of reference data from retrieval or reality capture modules to support human-in-the-loop evaluation. A green circle marks the workflow start, and the review point denotes final verification of revised predictions before integration into downstream tasks.

5.2.1. Geometry measurement

Fig. 7 illustrates workflows for spatial geometry extraction, such as dimensions, counts, and locations of building elements, using reality capture data from Aria Glasses.

Element | Geometry measurement of primary building elements is supported by SceneScript (Avetisyan et al., 2024), an autoregressive scene understanding model that predicts dimensions, locations, and semantic labels of architectural elements (e.g., walls, doors, windows), as shown in Fig. 7a. The model outputs element-specific structured scene descriptions and 2D/3D bounding boxes, which users evaluate via 3D visual overlays. These overlays quantify spatial variance and intersection-over-union (IoU) metrics by comparing predictions against floor plans and point clouds. Users can tune inference parameters, such as inverse point distance standard deviation to reduce scan noise, or nucleus sampling thresholds to balance diversity and coherence, aligning predictions with spatial context. Significant errors are corrected through direct editing in the synchronized 3D interface or via numerical input. Validated layouts feed an active learning loop that incrementally refines model weights. These refined 3D element representations underpin scan-to-BIM processes and enrich digital twin reconstructions with semantic and visual attributes.

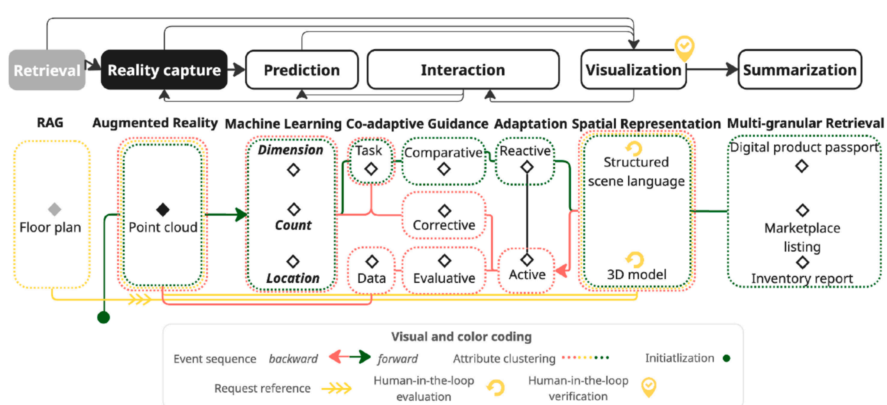
Component | Automatic cataloging and geometric measurement of indoor building components are supported by the EFM3D (Egocentric 3D Foundation Model) (Straub et al., 2024), as in Fig. 7b. Processing egocentric video and point cloud data, EFM3D identifies components and generates 3D bounding boxes and surface geometries. Candidate detections are validated against visual references to ensure accuracy. Errors in classification or geometry, including dimensions, positions, or orientations, are corrected interactively. Low-confidence instances are flagged for review. Final geometric data are organized hierarchically by semantic category, clustered by eBKP codes and dimensions, and aggregated for object counts. This structured inventory supports digital product passports and populates material reuse platforms with marketplace-ready listings.

5.2.2. Visual assessment

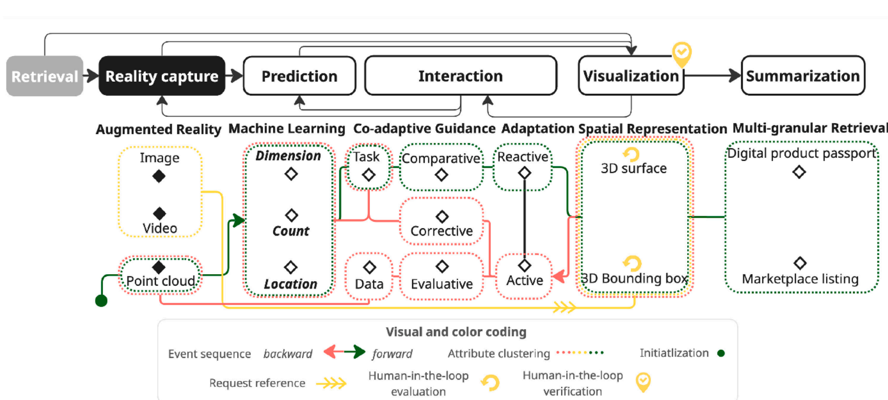
Fig. 8 shows the workflow for intelligence-augmented visual assessment of in situ building products using large vision-language models (LVLMs). Video sequences captured during field surveys are first processed by object detection models such as YOLO or transformer-based RF-DETR to segment and localize relevant features. Outputs are benchmarked against criteria from previous inventory records and online material marketplace data. LVLMs with few-shot learning then classify material types, condition labels, and descriptive attributes based on visual features. Annotation accuracy is validated against field-survey videos to ensure consistency with ground truth. An active learning loop with human-in-the-loop refinement allows users to correct outputs across modalities (textual, tabular, visual), enabling model fine-tuning. Validated outputs support digital product passports, marketplace listings, and inventory report generation, highlighting vision-language model's practical value in assessing in situ materials.

5.2.3. Hazard estimation

Fig. 9 illustrates a hybrid knowledge graph-based retrieval-augmented generation (RAG) workflow used to infer the potential presence of hazardous substances (e.g., asbestos, PCB). The process measures



(a) Element-level measurement



(b) Component-level measurement

Fig. 7. Geometry measurement of building elements and components with point cloud as input data and structured scene language and bounding box as primary output.

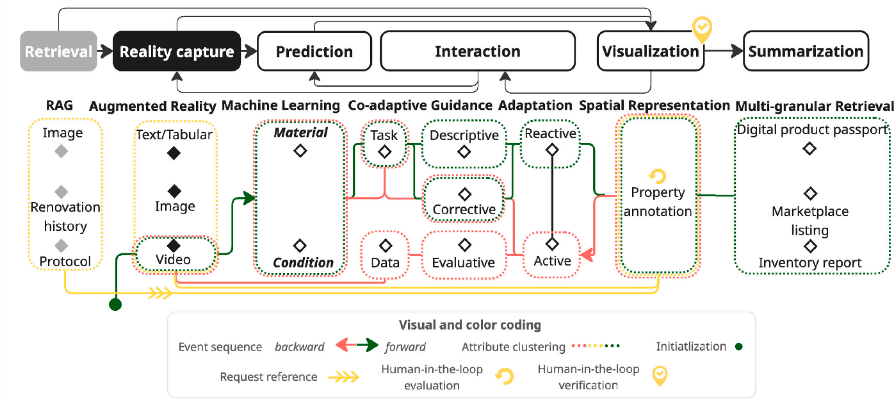


Fig. 8. Visual assessment of building products with visuals as input data and property annotation box as primary output.

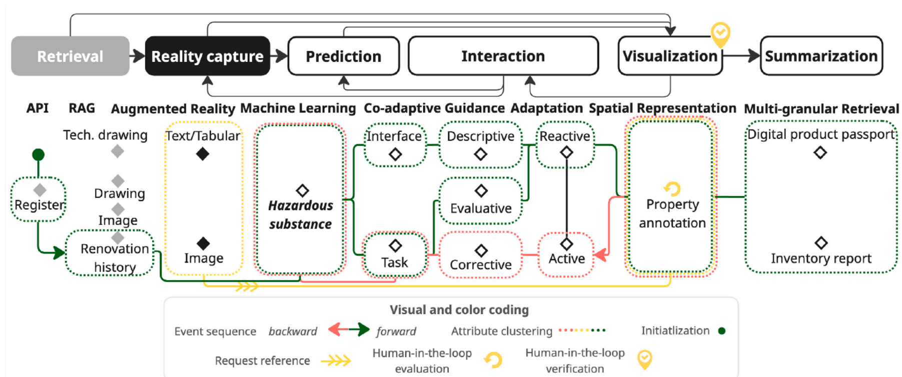


Fig. 9. Hazard estimation of in situ building products with building register and renovation history as input data and property annotation as primary output.

semantic similarity between user queries and historical environmental records. Content extraction algorithms process textual, tabular, and graphical data from past renovation and demolition documents, chunking, embedding, and storing them in a vector database. Additional context is retrieved from building registers and external APIs. User queries are embedded with the same model and undergo two-stage similarity search-first at the building level (e.g., typology, age), then feature level (e.g., construction system)-to find semantically related reference cases. Retrieved context supports a large language model to generate grounded responses estimating hazard likelihood. Predictions are validated against lab analyses, annotated documents, and survey imagery. High-risk classifications are appended to component profiles and structured into digital product passports and inventory reports, supporting regulatory compliance and informed renovation decisions.

6. Expert user study

This section synthesizes feedback from eight expert user studies conducted within the Swiss circular construction sector. Overall, stakeholders regarded the proposed framework as a robust foundation for developing a digital platform that enables intelligence-augmented building audits and fosters more effective collaboration across project stakeholders.

6.1. Proposed intelligence building audit schema

Operationalizing the framework as an integrated, web-based application with an intuitive visualization interface significantly enhances its accessibility and usability for building professionals. Such an implementation facilitates the seamless incorporation of intelligence-augmented audit workflows into standard industry practice. Fig. 10 illustrates the proposed application schema and its deployment across core building audit modules. The practical implementation of the user workflow in a proof-of-concept prototype will be structured as an application skeleton, consisting of backend databases that support a frontend module with a sequential workflow. In parallel, the functionalities of individual tasks within each module will be developed as plug-and-play components using a platform-based design approach (Sulzer et al., 2023).

The application schema commences with retrieving building documentation, which provides a foundational reference for on-site inspection planning and establishes baseline conditions for subsequent comparative analyses. Material listings from marketplaces and inventory data from city archives are appended to this foundation, while point clouds and video data serve as inputs for machine learning models performing tasks such as geometric extraction, component identification, and condition assessment. An interactive visualization interface enables domain experts to systematically compare model outputs with original design specifications and captured spatial data. Through human-in-the-loop supervision, users iteratively refine spatial labeling and prediction outputs by providing corrective feedback, thereby improving model accuracy and reliability. In cases of incomplete or low-quality input data, co-adaptive guidance supports iterative data enrichment and model adaptation, leveraging active learning and few-shot learning to efficiently integrate domain expertise. Finally, raw inputs, preliminary predictions, and refined outputs are consolidated within a multi-modal database, ensuring traceability, interoperability, and seamless integration into downstream tasks such as material recertification, reuse planning, and BIM reconstruction.

6.2. Thematic feedback on the proposed application schema

Qualitative feedback from expert user studies suggests a generally positive perception of the modular workflow, with moderate industry relevance and potential impact of the components related to prospec-

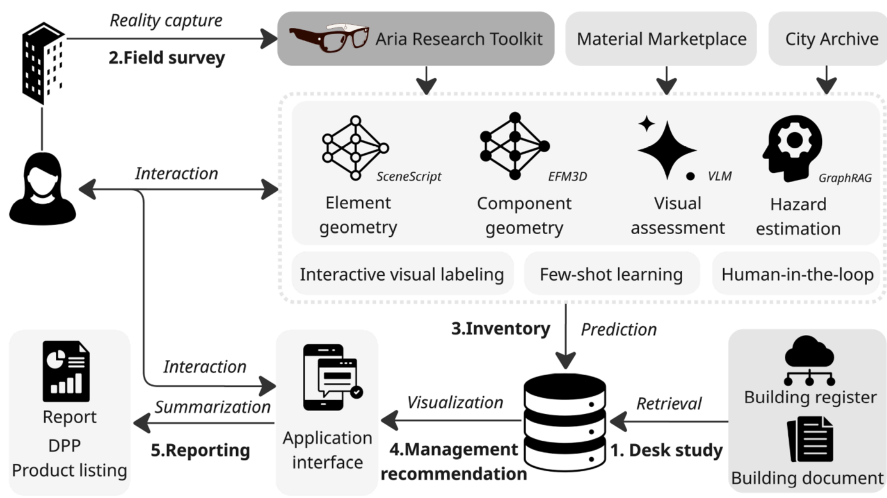


Fig. 10. Operational schema of intelligence-augmented application based on the proposed framework.

tive information gathering and standardized data exchange. The survey questions are available in Appendix A.

6.2.1. Modular workflow setup

All experts acknowledged the value of the modular setup, which represents the five steps of a building audit workflow. They highlighted its flexibility to support iterative in situ material assessment processes. The framework enables preliminary screening while also providing comprehensive documentation for detailed investigations when reuse decisions are made at later project stages. The inventory module, which integrates multiple machine learning models, was recognized as particularly relevant for practice, as each model contributes to different spatial scales and dimensions of building object inventories. Meanwhile, experts stressed the importance of ensuring data exchangeability and interoperability with renovation and demolition management software.

6.2.2. Information gathering and management

The first part of the survey evaluated the framework as a digital building logbook, featuring a unified user interface and low-touch automation. Three-quarters of the experts regarded it as a scalable solution for building information collection and management. Furthermore, half of the experts agreed that the framework can enable cost-effective, cross-project collaboration. The concept underlying the framework thus demonstrates substantial potential for further development and practical alignment. Experts emphasized that a simplified workflow, embedded in a user-friendly interface, will be essential for industrial adoption.

6.2.3. Standardized data exchange

Five out of seven experts indicated that the framework meets the objectives of standardized data iteration and supports seamless workflow integration with task breakdown structures. They emphasized the advantage of its tagging alignment with the eBKP code and SwissInv norms, which allows practitioners to generate consistent outputs. The framework's value proposition lies in its ability to complement existing processes and tools by integrating selective attributes, such as protected elements, pollutants, or CO_2 savings. In doing so, it can foster the establishment of a standardized inventory tool that facilitates the exchange of reusable building materials as they become available.

7. Discussions

This section reflects on the applicability of the proposed framework and application schema, highlights its current limitations, and identifies broader research opportunities for addressing domain-specific challenges in circular construction from a human-computer interaction perspective.

7.1. Limitations and future work

Although the proposed intelligence-augmented framework and application schema show promise in enhancing the efficiency and effectiveness of building inventory tasks, several limitations remain. Key challenges include improving model performance under sparse or limited feedback conditions, effectively synthesizing multi-modal data, and integrating BIM data into structured attribute representations within interactive interfaces.

LFW1 Performance improvement with limited feedback | Co-adaptive guidance mechanisms in the interaction module rely on spatial interactive labeling to refine instance descriptions, correct misclassifications, evaluate spatial relationships, and reconcile multi-modal inputs. Low-level co-adaptive guidance, such as point cloud quality control using context-sensitive thresholds, can be relatively straightforwardly incorporated into model fine-tuning. Mid-level strategies, however, require substantial annotated user feedback, limiting their ability to achieve immediate performance gains, particularly during early deployment. High-level mechanisms, such as progressive disclosure interfaces adapted to user expertise and holographic overlays for context-aware suggestions, depend on meta-models that learn from user interaction histories and environmental cues. These capabilities could be further explored in broader adoption scenarios where accumulated interaction logs enable more personalized and adaptive interface behaviors.

LFW2 Multi-modal representation and visualization | Harmonizing and visualizing multi-modal data across different spatial granularities remains challenging. Information presentation directly affects user orientation and the quality of feedback. Optimizing how data layers are selected and overlaid for specific prediction tasks requires further investigation, ideally in collaboration with domain experts, to improve decision-making during validation. Developing a prototyping system that incorporates co-adaptive visual guidance and translates user feedback into actionable insights would help assess feasibility and refine these mechanisms.

LFW3 Integration of building information modeling | The framework was initially designed for existing building stock, which often lacks comprehensive BIM. Advancements in scan-to-BIM techniques, however, enable potential integration of BIM within the retrieval and reality capture modules, enriching data and improving alignment across spatial and semantic layers. For new construction, pre-existing BIM, comprising detailed floor plans, bills of materials, and maintenance protocols, can be directly leveraged to support multiple modules of the proposed application schema.

7.2. Research opportunities

The proposed intelligence-augmented framework demonstrates the potential of using the Aria Research Toolkit for field survey but is not limited to it. Conventional scanning and interaction tools can also be integrated across workflow components. For instance, ARCore or ARKit and Open3D enable spatial scanning, Detectron2 and Roboflow support object and defect detection, MRTK or MediaPipe facilitate gesture- and voice-based feedback, NLP models provide adaptive inspection guidance, and Azure Spatial Anchors allow persistent spatial annotations. Future research opportunities include enabling real-time interaction through egocentric devices, capturing and analyzing interaction patterns to optimize user experience, and integrating the framework with established domain-specific software to enhance interoperability, efficiency, and adoption in circular construction workflows.

RO1 Real-time interaction in hybrid environments | Egocentric toolkits are emerging as powerful platforms for reality capture due to their open-source ML models, public datasets, and integrated perception services. These capabilities support AR-guided inspections and real-time spatial feedback. Integration with AR-enabled cameras or smart glasses with holographic computing in mixed-reality environments could further enhance dynamic, context-aware building assessments.

RO2 Bi-directional interaction patterns | Interaction patterns can be analyzed from both human and model perspectives. For users, minimizing intervention effort can be achieved through gamified interfaces and implicit feedback captured via attention maps or heatmaps to identify salient elements. From the model perspective, the goal is to accelerate learning and efficiently update weights with limited but high-value feedback, which is critical for practical, industry-ready applications where user input is sparse.

RO3 System Design and Integration with Domain Software | The proposed pipeline follows a "status inventory" approach, systematically capturing comprehensive and up-to-date data on existing buildings to support scalable, continuous assessment documented in a digital building logbook. As raw inputs, preliminary and refined predictions, and human feedback accumulate, the outputs should be compatible with mainstream architecture, engineering, and construction software to maximize the usability of building- and product-specific information. Integration via browser plug-ins for platforms such as Revit and Archicad can enable seamless interaction with web applications. To ensure interoperability with architectural design and building management systems, the pipeline should emphasize modular design and support multi-model, multi-granular data retrieval, which are key considerations for database configuration and downstream task planning.

8. Conclusion

To the best of the authors' knowledge, this study is the first to explore how an intelligence-augmented building audit framework can be created and support circular construction experts in achieving more scalable, efficient, and adaptive workflows. By identifying key design principles and user requirements, the proposed framework establishes a theoretical foundation for hybrid, mixed-initiative systems in construction contexts. Our findings demonstrate how interactive spatial labeling combined with machine learning can enhance a wide range of building inventory tasks. While this work primarily focused on streamlining audit workflows, future research should investigate real-time interaction patterns and deeper integration with domain-specific software. The expert-validated application schema presented here offers a strong basis for developing a technical prototype, advancing efforts toward cost-effective, intelligence-augmented audits of existing building stock.

CRediT authorship contribution statement

Pei-Yu Wu: Conceptualization, Methodology, Data curation, Formal analysis, Validation, Writing – original draft, Writing – review & editing, Visualization; **Mennatallah El-Assady:** Supervision, Writing – review & editing; **Catherine De Wolf:** Supervision, Funding acquisition, Writing – review & editing, Project administration.

Data availability

The authors do not have permission to share data.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. User study questions

1. Do you think the application is a scalable and cost-effective digital platform to collaborate across projects?
2. What do you think about the modular setup of the building audit workflow in modules (e.g., desk study, field survey, inventory, management suggestions, reporting) for the web app?
3. In what ways do you think the application supports a seamless workflow and facilitates standardized information exchange?

Supplementary material

Supplementary material associated with this article can be found in the online version at 10.1016/j.eswa.2025.130514.

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