

# D4.2 Guidebook for structuring CE data

WP4 ENABLE - LARGE SCALE UPTAKE OF  
CIRCULAR SOLUTIONS



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## List of abbreviations

- 3D – Three-dimensional
- API – Application Programming Interface
- BCI – Building Circularity Indicator
- BIM – Building Information Modelling
- CCIM – Circular City Information Model
- CDW – Construction and Demolition Waste
- CE – Circular Economy
- CE Map – 3D web-based Circular Economy Map
- CIRC-BOOST – Boosting the uptake of circular integrated solutions in construction value chains
- CityGML – City Geography Markup Language
- CityJSON – CityJSON (JSON encoding of CityGML)
- CRS – Coordinate Reference System
- CSV – Comma-Separated Values
- D – Demolition
- D-score – Deconstructibility score
- EC – European Commission
- EoL – End-of-Life
- EU – European Union
- GA – Grant Agreement
- GFA – Gross Floor Area
- GIS – Geographic Information System
- ID – Identifier
- IFC – Industry Foundation Classes
- JSON – JavaScript Object Notation
- LCA – Life Cycle Assessment
- LCC – Life Cycle Costing
- LiDAR – Light Detection and Ranging
- LoD – Level of Detail (CityGML)
- LoW – EU List of Waste
- MCI – Material Circularity Indicator
- MFH – Multi-family house
- MIC – Material Intensity Coefficient
- MR – Major refurbishment

N/A – Not applicable  
PR – Partial renovation  
PU – Public (dissemination level)  
R-score – Recoverability score  
SFH – Single-family house  
SOG – Slab on Grade  
TD – Traditional (conventional) demolition  
UML – Unified Modeling Language  
URL – Uniform Resource Locator  
WDR – Waste Diversion Rate  
WP – Work Package  
WP4 – Work Package 4  
XRF – X-ray fluorescence

# 1 Executive summary

Deliverable D4.2 presents the Guidebook for structuring CE data that provides a practical, implementation-oriented reference for how Circular Economy (CE) related data should be structured to support the 3D web CE Map and the semantically enriched City Geography Mark-up Language (CityGML) [1] based building stock model developed in CIRC-BOOST (GA 101082068) Work Package 4 (WP4). This guidebook defines a common data backbone that makes circular information consistent, traceable, comparable, and replicable across different areas and national contexts. It clarifies what information is needed, how it should be organised into registers and templates, and how it connects end-to-end: from input datasets, through inventories and indicators to CE Map outputs.

At the core of the approach are three linked data registers, designed as tabular datasets connected through stable identifiers (e.g., `building_id` and `gml_id`) to ensure reliable joins between the register records and CityGML building objects:

- **Register 1** – The **Inventory registers** consist of two complementary sub-registers: (i) the Building stock register (building identification and typology classification) and (ii) the Building stock inventory data register (typology-based element/layer composition and material parameters), providing the reference keys and modelling assumptions needed to quantify the embedded materials.
- **Register 2** – The **Resource recovery register** provides a structured lookup of feasible end-of-life routes (reuse, recycling, other recovery, disposal) and documents key preconditions and required testing to support actionable recovery recommendations.
- **Register 3** – The **CDW & CE indicators register** defines the end-of-life Construction and Demolition Waste (CDW) and CE indicators and the assumptions that were made in generating the indicators, translating building and material inventory data into decision-relevant information. The indicators are calculated at the material level, aggregated hierarchically to building level, and assessed through scenario-based End-of-Life and treatment pathways, with constraint indicators contextualising achievable recovery.

This guidebook further introduces the **Circular City Information Model/Modelling (CCIM)** as a computational extension of the CityGML-based building stock model. CCIM links building geometry with Register 1 (using building IDs and typology from the Building stock register and element/layer definitions from the Building stock inventory data register) to derive material quantities at the building and city scale. These quantities, together with recovery-related information from Register 2, provide the direct input for the calculation of CDW and CE indicators defined in Register 3. All data from the three registers are consistently transferred into and structured within CCIM, which then provides a common and reliable basis for analysis, visualisation, and reporting within the CE Map.

Building on this structured data flow, the guidebook defines a **CE passport framework** as a standardised building-level output that compiles key building attributes, material quantities, recovery options, and indicator results into a clear and comparable format.

## 2 Introduction

### 2.1 CE Map at a glance

The CE Map is an open-source, 3D web-based tool designed to represent existing building stocks and their circular potential in a spatially explicit and decision-relevant way. It consolidates heterogeneous datasets into a consistent digital environment, enabling a range of stakeholders to explore where materials are embedded in the built environment, what recovery options exist, and how circular strategies can be supported through evidence-based planning.

Technically, the CE Map combines geospatial and building-related data to create a structured representation of the urban building stock. Geographic Information System (GIS) and Light Detection and Ranging (LiDAR) inputs are used to reconstruct building geometry in a CityGML format, forming the spatial backbone of the model. This geometric representation is then semantically enriched using national building typologies and related reference information, and further validated and refined through Building Information Modelling (BIM) based inputs for selected buildings. By integrating these sources, the CE Map supports a robust characterisation of building attributes and material composition, enabling consistent material quantity assessment and subsequent circularity analyses.

From a user perspective, the CE Map is an interactive 3D interface where each building is a clickable entry point to circularity-related information. For every building, the map presents a core profile based on GIS/CityGML data, such as location and geometry, age and structural characteristics, building footprint, number of storeys and floor area, supported by visual references. It then provides a material inventory with embedded materials and quantities structured by building elements, together with recommended recovery and treatment pathways and their key prerequisites. Finally, the map reports CDW and CE indicators at multiple levels (material, element, and whole-building), and enables on-click generation of a CE passport that compiles all building attributes, material quantities, treatment recommendations, and indicators into a structured, comparable format.

The CE Map supports multiple levels of detail and analysis, ranging from aggregated views at municipal or city scale to more detailed building-level exploration. It enables users to visualise material stocks, compare typologies and neighbourhoods, and understand how recovery potential varies across the urban fabric. Importantly, the CE Map is designed to be time-aware; by linking building stock data with renovation strategies and urban development plans, it can indicate when specific materials are expected to become available as waste. This temporal perspective supports anticipatory planning of treatment capacity, logistics, and infrastructure needs, turning material flow planning into a proactive rather than reactive process.

Overall, the CE Map serves as an integrating layer between raw data, analytical models and decision support. By transforming building information into structured, spatially referenced circular intelligence, it helps reposition buildings from resource consumers to potential material banks and provides a practical foundation for urban mining, resource planning, and zero-waste transition strategies.

### 2.2 Purpose and scope of the guidebook

This guidebook defines how CE-related data should be structured to enable consistent semantic enrichment of a CityGML-based building stock model and its use within the 3D web CE Map. Its purpose is to provide a common reference for organising building information, material inventories, recovery-related data, and CDW/CE indicators so that outputs are consistent, comparable, and replicable across different areas and national contexts.

The guidebook specifies the CE Map data backbone by defining the core data registers (building stock and inventory data, resource recovery pathways, and indicators) and the recommended approach for storing and linking these datasets in a CityGML-compatible format. In addition, it provides guidance on

selecting and assessing CDW and CE indicators and defines the CE passport framework and data template used to compile building-level circular information in a structured, reusable way.

The scope of this guidebook is data structuring and data representation. It explains what information is needed, how it should be organised into registers and templates, and how it connects end-to-end: from input datasets, through inventories and indicators, to CE passports and the CE Map. The guidebook is not intended to provide a general introduction to circular economy concepts, nor to describe software development in detail (e.g., platform architecture, coding, or user-interface design). It also does not prescribe detailed local data collection protocols; instead, it shows how available data can be mapped into a consistent structure. Worked examples (e.g., a single building type) are included to demonstrate the expected level of detail and to support dataset validation and replication.

By documenting a shared data structure, the guidebook supports both the initial development of the CE Map and its future extension. It can be used to review data completeness, align classifications and assumptions, and facilitate replication in new locations where local typologies, data sources, and availability may differ while the overall model logic remains consistent.

## 2.3 Target users and use cases

This guidebook is written for stakeholders who produce, structure, integrate, or extend CE-related building data for the CE Map and the semantically enriched CityGML building stock model. In line with the project approach, it documents the required building datasets, CDW and CE indicators, and the CE passport framework, and provides recommendations for structuring this information in CityGML-compatible data formats.

### 2.3.1 Target users

#### Primary target users

The primary target users for the application of the guidance to build the data backbone of the CE Map and to ensure the datasets remain consistent as the solution is extended to new areas or new countries are:

- **CE Map implementation teams** (WP4 technical contributors and associated data teams) who establish the initial data registers as part of developing the CE Map and its outputs (inventories, indicators, and CE passports).
- **Data stewards / future operators** responsible for verifying completeness and updating the registers when new datasets become available, when typologies or assumptions are refined, or when the CE Map is expanded to additional districts/cities.
- **Replication teams (new locations/countries)** who need a complete, reusable data structure (including candidate data sources) to adapt the approach to national typologies, material/waste classifications, and local data availability.
- **GIS / CityGML / BIM modellers** creating or updating 3D building stock models who need to ensure geometry, identifiers, and Level of Detail (LoD) choices enable robust attachment of semantic attributes, inventories, and indicator outputs.
- **Digital platform and software developers** implementing the platform data model, database schema, APIs and data pipelines that ingest the registers and support visualisation and CE passport generation.
- **Indicator developers and analysts** implementing or calibrating CDW/CE indicators who need clear input requirements, aggregation levels (material/element/building) and rules for storing and exposing results.

- **Circular economy experts and domain specialists** (e.g., circularity, resource management, and CDW experts) who use the guidebook to apply the project's indicator framework, including required inputs, recommended assumptions and guidance on interpreting results at the material, building-element, and whole-building levels.

## Secondary target users

While secondary target users may not directly implement the data model, these stakeholders benefit from the structured outputs (CE Map views, indicator results, CE passports) and may request extensions or contribute additional data:

- **City authorities / government agencies / policy makers** (urban development, environment, resilience, circular economy) using the results for planning, prioritisation and target setting.
- **CDW operators and waste management companies** planning collection, logistics and treatment capacity based on expected material streams.
- **Construction, renovation, and demolition stakeholders** supporting selective demolition, reuse and high-quality recycling.
- **Building owners and facility managers** using building-level outputs and CE passports to support renovation planning and improve data transparency.
- **Urban planning professionals and consultants** using aggregated results for scenario analysis and spatial planning.
- **Life Cycle Assessment (LCA) / Life Cycle Costing (LCC) assessors** using harmonised inventories and indicators for benchmarking and assessment workflows.
- **Smart city initiatives and industry associations** supporting adoption, standardisation, capacity building and replication (e.g., training programmes and guidance material based on the defined data structures).

### 2.3.2 Use cases

This guidebook supports the following core use cases:

1. **Structuring and documenting the building stock inventory register:** Define a minimum and recommended set of building attributes and material inventory fields (including classification rules and assumptions) so building stock information is consistent across areas and can be reused in modelling and reporting.
2. **Structuring and documenting the resource recovery register:** Define how treatment options (preparing for re-use (hereafter “reuse”), recycling, other recovery and disposal) and recovery preconditions (including required on-site or laboratory testing) are represented and linked to the material inventory to enable actionable recovery recommendations.
3. **Selecting, calculating, and storing CDW and CE indicators:** Provide guidance on indicator selection criteria, required inputs, calculation/assessment logic at different aggregation levels and a consistent structure for storing results for visualisation and reporting.
4. **Linking registers and outputs through a coherent data flow:** Define how building stock, recovery information and indicator outputs connect end-to-end so that results remain traceable and interpretable.
5. **Enriching CityGML models with CE attributes (CCIM integration):** Explain how the structured registers and indicator results are attached to CityGML building objects (and related model structures) to support interoperability and reuse.

6. **Generating CE passports from structured data:** Provide a CE passport framework and template that compiles building attributes, material quantities, recovery recommendations and indicators into a structured, comparable output, supporting on-demand generation and updates.
7. **Replication and scaling to new locations:** Enable consistent replication by defining the data model, candidate data sources and adaptation points (typologies, classification systems, indicator sets) required to transfer the approach to new cities/countries.

## 2.4 How to use this guide

This guidebook is designed to be used as a practical reference when setting up or extending WP4 CE datasets. The document follows the implementation logic from concepts and relationships, to register specifications, to model integration and outputs:

- **Chapter 3** explains the key concepts, core data registers, and the high-level end-to-end data flow.
- **Chapters 4, 5 & 6** define how to structure each register (building stock and inventory, resource recovery, and indicators), including required fields and worked examples.
- **Chapter 7** explains how structured information links into the Circular City Information Model (CCIM) and the semantically enriched CityGML environment.
- **Chapter 8** defines the CE passport framework and template used to compile building-level outputs in a consistent format.

The “single building type example” sections in 4.1.5, 4.2.5 and 5.4 can be used as reference templates when validating your own datasets. They illustrate the expected structure, naming logic, and level of detail for inventories, recovery information, and indicator outputs, and can be reused as a checklist when expanding the CE Map to new areas or adapting it to local typologies.

# 3 Circular economy data in the CE Map

## 3.1 Key concepts and terminology

This section defines the key terms used throughout the guidebook and clarifies how they are applied in the CE Map workflow. The definitions below are project-specific: they describe how terms are used in the context of the CityGML-based building stock model and the three core registers (inventory, recovery, indicators). Where relevant, terms are linked to their typical representation in tabular registers (e.g., identifiers, controlled vocabularies, units) to support consistent data structuring and replication.

Below is a deliverable-friendly glossary table format (Table 3-1). For each term, the first sentence gives the meaning in this guidebook, and the italic line indicates typical representation in registers and key notes.

Table 3-1 Key concepts and terminology

Term	Definition and representation
<b>CE Map</b>	A 3D web environment that visualises buildings and exposes CE-related information (inventories, recovery options, indicators, and CE passport outputs) linked to each building. <i>Representation/notes:</i> Enriched CityGML model + linked data registers for querying, filtering, and reporting.
<b>CityGML building object</b>	A single building entity in the 3D city model acting as the anchor for CE-related semantic data. <i>Representation/notes:</i> Linked via <i>gml_id</i> to register data.
<b>CityGML / CityJSON</b>	CityGML is the semantic 3D city model standard; CityJSON is a JSON encoding for processing and exchange. <i>Representation/notes:</i> Geometry + attributes; consistency depends on LoD.
<b>Level of Detail (LoD)</b>	A predefined level of geometric and semantic detail for representing city objects (LoD0–LoD4), enabling multi-scale modeling and use-case-dependent analysis within and across datasets [1].The geometric detail level of the building model determining what can be derived from geometry versus typology. <i>Representation/notes:</i> Stored as metadata (e.g. LoD2, LoD3).
<b>Semantic enrichment</b>	The attachment of non-geometric CE-related attributes (typology, materials, indicators) to CityGML buildings. <i>Representation/notes:</i> Implemented through identifier-based joins with registers.
<b>building_id</b>	Primary building identifier used consistently across all registers. <i>Representation/notes:</i> Stable text key for joins and versioning.
<b>gml_id</b>	Identifier of the corresponding CityGML building object. <i>Representation/notes:</i> Used to bind register data to geometry.
<b>Inventory registers</b>	Register 1 of the CE Map, defining building stock and material inventory data. <i>Representation/notes:</i> Composed of two sub-registers: the Building stock register and the Building stock inventory data register.
<b>Building stock register</b>	Register defining building identification and typology classification. <i>Representation/notes:</i> Stores <i>building_id</i> , location, construction period, SFH/MFH, urban fabric position, level configuration, <i>archetype_id</i> .

Term	Definition and representation
<b>Building stock inventory data register</b>	Register defining building elements, material layers, and parameters for quantity estimation. <i>Representation/notes:</i> Stores element types, layer structure, thickness, density, Material Intensity Coefficients (MICs), material categories; linked to geometry via identifiers.
<b>Building attribute</b>	A building-level descriptor required for inventory generation, analysis, and reporting. <i>Representation/notes:</i> Examples: address/location, construction year/period, function/type, floors, gross floor area, data source, last updated.
<b>Building stock</b>	The complete set of buildings within the mapped area represented in the 3D model and registers. <i>Representation/notes:</i> “Stock” refers to a population of buildings, not a single building.
<b>Building typology / building type</b>	A controlled classification of buildings used to describe construction characteristics consistently across the stock. <i>Representation/notes:</i> Stored as a controlled value (e.g., typology code) and used for comparability and replication.
<b>Archetype</b>	A representative model of a building type defining typical elements and material build-ups. <i>Representation/notes:</i> Used when detailed building-specific data are unavailable.
<b>Building element</b>	A functional building component used for inventory and indicator structuring. <i>Representation/notes:</i> Examples: slabs, walls, roofs, windows, doors.
<b>Layer</b>	A material layer within a building element (element build-up) used to represent composition and enable quantity estimation. <i>Representation/notes:</i> Typical fields: layer name/material, thickness, density/MIC references, position within element.
<b>Shearing layers</b>	A conceptual grouping of building parts by expected service life and replacement cycles, used to support time-aware scenarios when applicable. <i>Representation/notes:</i> Optional field; applied when modelling renovation cycles and waste generation timelines.
<b>Material</b>	A defined material entry used for inventory and mapping. <i>Representation/notes:</i> Linked to a material library and material category.
<b>Material library</b>	A controlled reference list of materials and key properties. <i>Representation/notes:</i> Minimum: material name, category, density; optional: recycled content defaults.
<b>MIC (Material Intensity Coefficient)</b>	A coefficient used to estimate material quantities from geometric proxies and typology assumptions. <i>Representation/notes:</i> Typically used for internal materials; units depend on approach (e.g., kg/m <sup>2</sup> ); stored in a MIC table and referenced by typology/element/material.
<b>Material category</b>	A harmonised classification used to group materials for reporting, mapping, and indicator calculations. <i>Representation/notes:</i> Controlled vocabulary (e.g., concrete-based, metals, timber) used for aggregation and comparability.
<b>Waste category</b>	A classification of expected CDW streams used for treatment planning and reporting. <i>Representation/notes:</i> Controlled vocabulary may be aligned with national/ EU List of Waste (LoW) groupings depending on the project setup.

Term	Definition and representation
<b>Treatment option / pathway</b>	A defined feasible end-of-life route for a material/element (reuse, recycling, other recovery, disposal <sup>1</sup> ). <i>Representation/notes:</i> Stored as categorical values with brief notes on feasibility and conditions.
<b>Recovery preconditions</b>	Requirements that must be met for a treatment option to be feasible or compliant. <i>Representation/notes:</i> Often includes required testing prior to reuse and recycling (e.g., contamination/hazard checks, coatings/adhesives).
<b>End-of-life (EoL)</b>	Life-cycle stage when renovation, refurbishment, or demolition generates CDW. <i>Representation/notes:</i> Used to scope scenarios and indicators.
<b>EoL scenario</b>	An intervention type used to estimate waste generation. <i>Representation/notes:</i> (PR) Partial renovation, (MR) Major refurbishment, Demolition (D); controls removal coefficients.
<b>Removal coefficient</b>	Factor (0–1) defining the share of material becoming waste under an EoL scenario. <i>Representation/notes:</i> Typology and element-specific; independent of treatment routing.
<b>Treatment assumption set (pessimistic / optimistic)</b>	Assumptions describing waste-management practice after waste generation. <i>Representation/notes:</i> pessimistic = typical practice; optimistic= enhanced CE practice (e.g. selective dismantling, better sorting).
<b>Treatment pathway shares</b>	Allocation of generated waste to treatment options. <i>Representation/notes:</i> Shares sum to 1 per material stream and scenario.
<b>CDW (Construction and Demolition Waste)</b>	Waste streams generated through renovation, refurbishment and demolition activities. <i>Representation/notes:</i> Reported in mass/volume; may be scenario and time-dependent where renovation plans are used.
<b>CE indicators</b>	Quantitative metrics describing circular performance (e.g., reuse potential, recyclability, circularity score) derived from inventory and recovery assumptions. <i>Representation/notes:</i> Stored with unit, scope, level (material/element/building) and version of definition.
<b>Indicator inputs and assumptions</b>	The parameters and rules used to compute indicator values and to ensure reproducibility. <i>Representation/notes:</i> Stored alongside results (e.g., factors, thresholds, service-life assumptions, scenario identifiers).
<b>Aggregation levels</b>	Levels at which quantities and indicators are stored and reported. <i>Representation/notes:</i> Material → element → building (optional system aggregation).
<b>CE passport</b>	A structured building-level output that compiles key inventory, recovery and indicator information into a consistent template. <i>Representation/notes:</i> Generated from register content using building identifiers; suitable for reporting and comparison.
<b>Data provenance</b>	Metadata describing where a value comes from and how/when it was produced or updated. <i>Representation/notes:</i> Typical fields: data_source, last_updated, method/assumption reference, confidence/validation flag (if used).

<sup>1</sup> Treatment categories follow the definitions and waste hierarchy set out in [Directive 2008/98/EC \(Waste Framework Directive\)](#), as amended.

Term	Definition and representation
<b>CCIM (Circular City Information Model/Modelling)</b>	A computational extension of the 3D city model that makes building material stocks explicit and supports CDW/CE indicator computation. Representation/notes: Implemented as a Python-based pipeline coupling CityGML geometry with typology, system and material tables.
<b>Waste Diversion Rate (WDR)</b>	The share of generated CDW diverted from landfill through reuse, recycling and/or other recovery. Representation/notes: Reported as %, derived from treatment pathway shares; headline end-of-life circularity metric.
<b>Constraint indicators (R-score, D-score, hazardous waste share)</b>	Indicators capturing constraints that may limit achievable recovery (e.g., toxicity/contamination/coatings, deconstructibility and hazardous fractions). Representation/notes: Reported as scores or %, used to contextualise or filter recovery potential.
<b>Dynamic building stock model</b>	External model producing time-dependent CDW flows. <i>Representation/notes:</i> Coupled to the CE Map for temporal analysis.

## 3.2 Core data registers in the CE Map

In the CE Map workflow, circular economy data is organised into three core data registers that serve as structured data sources for semantic enrichment and analytical processing. Each register is implemented as a tabular, versionable dataset with a clearly defined scope, level of detail and internal structure. Together, the registers provide the necessary building, element and material level information required to populate the CityGML building model with CE-related attributes and to support the calculation and aggregation of CDW and CE indicators.

### 3.2.1 The three core registers

The **Inventory Registers** are the reference dataset that describes the building stock and provides the primary keys for linking all circular information to each building in the CE Map. It is composed of two sub-registers: (i) the Building stock register, which contains building identifiers, address/location attributes and typology classification, and (ii) the Building stock inventory data sub-register, which defines typology-based element and layer composition and the parameters required for material quantification (e.g., layer thickness, density, Material Intensity Coefficient (MIC) values, material categories, and element position within the building). Together, these sub-registers provide the foundation for assigning materials to CityGML building models and for deriving embedded material quantities and subsequent indicators in a consistent, traceable manner.

The **Resource Recovery Data Register** is a structured lookup table that translates embedded building materials/components into practical end-of-life recovery routes. The register contains all identified building elements across all building types together with the materials composing each element all defined within the inventory registers. For each material layer, the register records treatment options in a binary (yes/no) structure for reuse, recycling, other recovery and disposal, and documents the key recovery preconditions and required testing prior to reuse and recycling (e.g. hazardous substances, past treatments, or contamination). For each element–material combination, the register then specifies feasible end-of-life treatment options in a clear hierarchy (reuse, recycle, other recovery and disposal) including concise notes describing under which conditions each option is allowed, recommended or realistic. Within the CE Map workflow, this register is used to consistently derive recommended treatment pathways and recovery potential for materials identified in the building inventory and to populate related outputs such as CDW/CE indicators and CE passport summaries in a comparable manner across buildings and building types.

The **CDW and CE Indicators Register** contains the selected set of construction and demolition waste and circular economy indicators for all building elements and materials defined in the Inventory Registers. It mirrors the typology-based element-material structure used in the inventory and stores all required input values, assumptions and metadata needed for indicator calculation. In particular, it includes end-of-life (EoL) scenarios (Partial renovation (PR), Major refurbishment (MR), Demolition (D)) with typology-based removal coefficients, treatment pathway shares (pessimistic and optimistic) and constraint descriptors/scores (e.g. R-score, D-score, and hazardous waste share). The indicator values are calculated at the material and building-element level and linked via stable identifiers to the corresponding elements in the CityGML model. These element-level results also serve as the basis for consistent aggregation and calculation of indicators at higher levels, such as building systems and whole buildings, ensuring traceability and comparability of results across the CE Map.

### 3.2.2 Register linking logic

The three core registers are linked through a consistent set of identifiers that ensures traceability of data from materials and building elements to individual buildings and higher aggregation levels. The Inventory registers (in particular, the Building stock register) provides the primary reference identifiers (e.g. building and typology IDs) used across all registers. Element and material level records in the Resource Recovery and CDW and CE Indicators registers reference these identifiers, enabling their association with the corresponding CityGML building objects during semantic enrichment.

This linking logic supports a structured data flow in which building attributes and typology-based data are first used to populate the CityGML model with semantic information, after which material quantities derived via the CCIM quantity-assessment workflow and indicator values are assessed and aggregated across the material–layer–element–building hierarchy, with optional aggregation to building systems for reporting. Where included, time-dependent CDW flows are derived through coupling with an external dynamic building stock model and linked back to buildings via identifiers, and indicator values are derived and aggregated to system and building level. The CE Map application then consumes the enriched CityGML model and derived outputs for visualisation, filtering and CE passport generation, while the registers remain external reference datasets.

## 3.3 High-level end-to-end data flow for the CE Map

Figure 3-1 illustrates the high-level end-to-end data flow of the CE Map. 3D building geometry is reconstructed from LiDAR point clouds and aerial imagery and represented in CityGML (LoD2/LoD3), providing the spatial backbone of the model. In parallel, Register 1 (Inventory registers) is populated using cadastre and addresses, archival documentation, national building typology and norms and material libraries, which together define building attributes and typology-based element and layer composition. Register 2 (Resource recovery) provides structured information on feasible end-of-life treatment options (reuse, recycling, other recovery, disposal) and their key preconditions. CCIM combines the CityGML geometry with Register 1 to estimate layer-based material volumes and masses and to support hierarchical aggregation from material to building level. Finally, Register 3 (CDW & CE indicators) uses material quantities from CCIM together with end-of-life scenarios and treatment shares to generate indicator results at material, element and building level, which are then visualised and reported through the CE Map (including CE passport outputs).

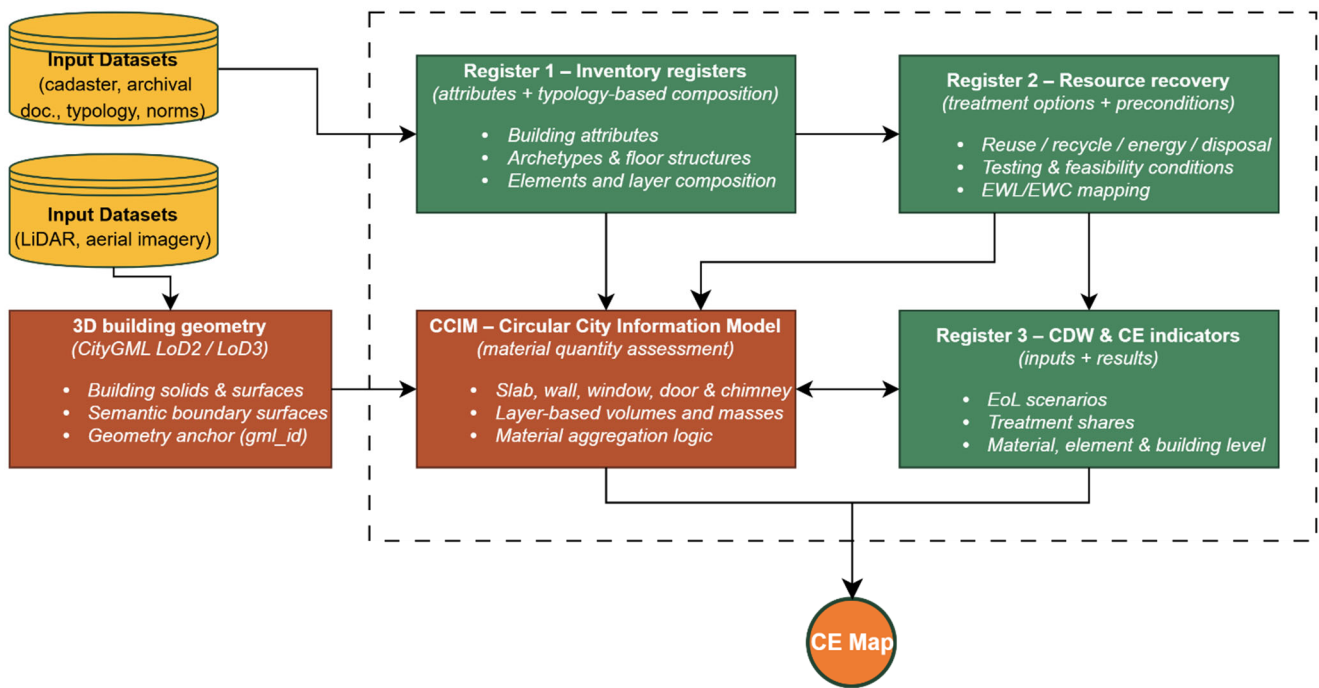


Figure 3-1 High-level end-to-end data flow diagram

## 4 Inventory registers

Inventory registers are designed to support the semantic enrichment of CityGML LoD3 models by systematically structuring and linking relevant building information. To achieve this, two complementary sub-registers with distinct but interdependent roles are defined.

The first sub-register (Building stock register) is dedicated to the identification and assignment of a building typology archetype for each building within the selected study area. This step is essential, as the typology classification provides the necessary contextual framework for subsequent data enrichment and serves as a prerequisite for the second sub-register. This sub-register is explained in Section 4.1.

The second sub-register (Building stock inventory data register) comprises a typology-based material library intended for the semantic enrichment of CityGML LoD3 models. It links building typologies to representative material compositions and related attributes, enabling a consistent, scalable, and transparent integration of material, CDW, and CE-relevant data within the CityGML data structure. This sub-register is explained in Section 4.2.

### 4.1 Building stock register

#### 4.1.1 Definition and role of the register

The Building stock register is dedicated to the identification and classification of existing buildings according to predefined typology archetypes within the selected study area. Its primary role is to assign each building a unique building ID and typological identity that provides the contextual framework for all subsequent data enrichment steps.

The typology assignment is a prerequisite for the Building stock inventory data register, as it determines:

- Construction systems and material assemblies;
- Rules for element and material layer assignment;
- Material intensity coefficients (MICs);
- Assumptions used in CDW and CE indicator assessment.

In this sense, the Building stock register functions as a link between CityGML LoD3 models and Building stock inventory data register, enabling scalable and harmonised modelling of large building stocks.

#### 4.1.2 Data types and selection criteria

The Building stock register is established as the primary classification layer for all buildings represented in the CityGML LoD3 model environment. Its purpose is to ensure unambiguous identification of each building instance and to enable consistent linking of geometric, typological and material related data across all registers.

For this purpose, a coding system is introduced, whereby each building is assigned a unique building ID derived from the street name and address number. This identifier serves as a stable reference key used consistently throughout all registers, including the Building stock inventory data register, CDW and CE indicator register and Circular city information modelling.

To assign a building typology archetype in accordance with the national typology (e.g., National typology of residential buildings in Serbia [2] for CE map in Belgrade, Serbia), a minimum set of attributes is required. These attributes were selected based on their relevance for typology classification and their availability at building stock scale. The required attributes include:

- Year of construction or construction period, used to assign the building to a corresponding typological period (e.g., A (<1919), B (1919-1945), C (1946–1960), D (1961-1970), E (1971–1980), F (1981-1990), G (1991-2011), H (>2013));
- Position within the urban fabric (e.g. freestanding, in a row, lamella, high-rise) which, in combination with the construction period, determines the final typology class;
- Identification if it is a single-family house (SFH) or multi-family house (MFH).

Furthermore, information on the building level configuration is required to support more precise data allocation in subsequent stages. Level configuration is expressed using a standardised notation describing the number and type of levels above and below ground (e.g., Po + Pr + n + Pk). In addition, building use represents a key attribute, given that the national building typologies cover exclusively residential buildings.

These attributes represent the minimum information necessary to ensure a consistent and reproducible typology assignment across heterogeneous building stocks.

### 4.1.3 Data sources and acquisition methods

The data included in the Building stock register originates from multiple complementary sources, reflecting the heterogeneous nature of information available for existing buildings. The acquisition strategy prioritises commonly available, non-intrusive data sources suitable for large-scale application. Table 4-1 summarises the data types included in the register, along with their corresponding data sources and acquisition methods.

*Table 4-1 Data types, data sources and acquisition methods for the Building stock register*

Data type	Data source	Purpose
Address and number	Cadastral data, National spatial geoportal	Identification of each building in the area (one address number is considered one building) used to generate unique building ID
Geographic coordinates	Cadastral data, National spatial geoportal	Used for spatial referencing
Construction year or period	Cadastral data, archival records, municipal records, literature	When exact year unavailable period-based assignment is applied
Building use	Cadastral data, visual inspection	Identification of residential buildings The CE map is developed only for residential buildings so building with other use are excluded
Building function	Cadastral data, visual inspection	Identification whether a house is a single-family house (SFH) or multi-family house (MFH) (e.g., per National Typology of Residential Buildings in Serbia SFH is considered a building with up to four dwelling units per entrance)
Position in urban fabric	Image recognition, Visual inspection	Identification if the building is freestanding, row, lamella or high-rise (there is automation potential)
Level configuration	Cadastral data, Google Street View, Google Earth Pro, point cloud	Identification whether a building is a freestanding or high-rise building per typology
Culture heritage status	Cadastral data	Used to flag special constraints

## 4.1.4 Data model and structuring

The Building stock register is structured as a tabular data model (Figure 4-1), in which each row represents a single building instance and each column represents a descriptive attribute required for typology assignment and subsequent data linking.

The register is organised into four logical attribute groups:

1. Identification and location attributes, including unique building ID, address, and coordinates;
2. Administrative attributes, such as cultural heritage status, and building use;
3. Typology-relevant attributes, including construction year or period, urban fabric position, and building function (SFH/MFH);
4. Level configuration attributes, describing the number and type of storeys above and below ground.

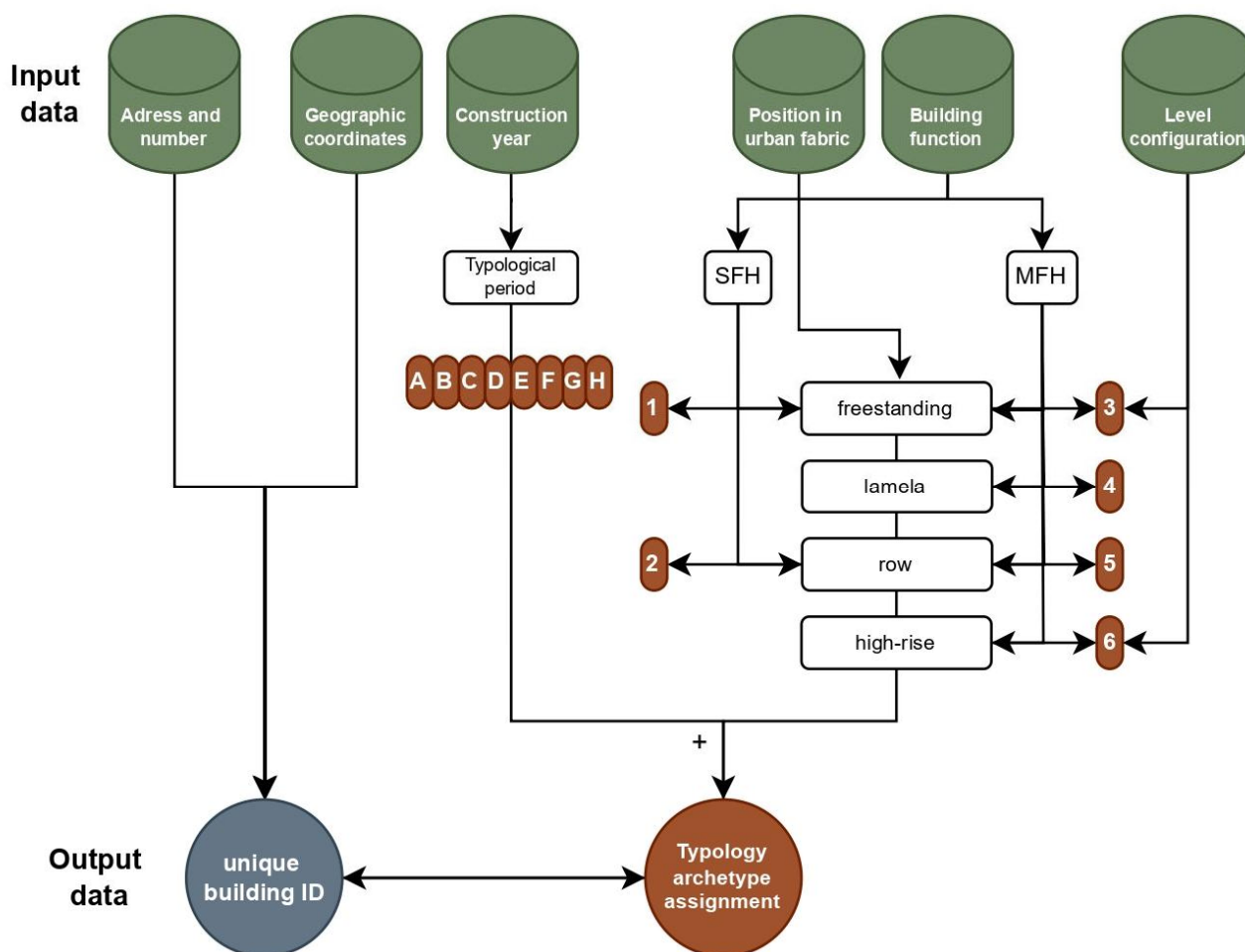


Figure 4-1 The Building stock register data structure

Typology assignment is performed using a rule-based classification approach, combining construction period, building function, level configuration and position within the urban fabric. For the CE map in Belgrade, the rules follow the definitions provided in the National Typology of Residential Buildings in Serbia [2] and are complemented, where applicable, by the Atlas of Family Housing in Serbia [3] for Belgrade region.

The assignment process follows hierarchical logic:



estimation of material types and quantities across large building stocks by combining geometry derived from CityGML LoD3 models with national building typologies and construction standards.

This integration allows consistent representation of buildings with different levels of available geometric detail and supports the aggregation of material information from the material layer level to the building level.

The register is designed to support subsequent assessment stages, including CDW and CE indicators estimation and CE passport generation. By structuring building information into a unified inventory framework, the register ensures methodological consistency across all analytical steps of the study.

## 4.2.2 Data types and selection criteria

The Building stock inventory data register stores semantic and typology-based information required for estimating materials embedded in the existing building stock. The register does not contain geometric building models. Instead, it defines structured semantic data that can be linked to external geometric sources.

## 4.2.3 Data sources and acquisition methods

The data stored in the Building stock inventory data register are derived from typological and technical sources that describe representative construction practices of the study region.

Primary sources include national building typologies, construction standards, and technical documentation that define characteristic building assemblies for different construction periods and archetypes. Data acquisition involves systematic translation of typological information into structured inventory entries. For each building archetype, representative construction assemblies are decomposed into material layers and assigned standardized attributes.

The register is designed to be linked with external geometric datasets, such as CityGML LoD3 building models, during material quantification (Section 7). While geometry is not stored within the register itself, the inventory structure is compatible with geometry-based workflows and supports consistent integration with external data sources.

This separation between semantic inventory data and geometric input ensures flexibility, reproducibility and scalability of the modelling framework.

## 4.2.4 Data model and structuring

The Building Stock Inventory Data Register is structured using a hierarchical data model that reflects the physical composition of buildings and supports consistent, scalable assessment of material quantities across large building stocks.

The inventory data are organised into three interrelated levels, as illustrated in Figure 4-3:

- **Material layer level**, representing individual material layers that constitute each building element;
- **Element level**, describing internal and external building components;
- **Building level**, representing the complete building entity composed of elements formed from material layers.

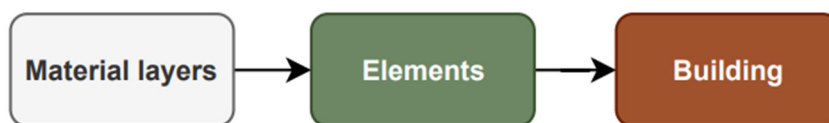


Figure 4-3 The inventory hierarchical data model

This hierarchical structure ensures consistency between geometry derived from CityGML LoD3 models and typology-based assumptions for the material data. It enables systematic aggregation and disaggregation of material information across multiple semantic levels (material–element–building), allowing transparent identification of material distribution within the building. The hierarchical data model further provides a foundation for subsequent estimation of CDW and CE indicators (Section 6), as well as for CE passport generation (Section 8).

As shown in Figure 4-4, the building components at the element level are classified into internal and external elements. This classification reflects both their physical position within the building and the limitations of the data available from CityGML LoD3 models. In addition to their functional role, this distinction supports different assessment approaches for internal and external components.

CityGML LoD3 models do not contain internal surfaces. As a result, the internal layout and distribution of internal components (such as internal walls, stairs, and doors) cannot be derived directly from the models. These components are therefore estimated by using typology-based material intensity coefficients (MICs).

In contrast, external components can be assessed more precisely because their geometry is explicitly represented in the LoD3 models. This includes roof shapes, wall surfaces, openings for windows and doors, balconies, chimneys, entrance doors etc. Although slabs are considered internal elements, their quantities can be estimated with relatively high accuracy because the gross floor area is available from the models.

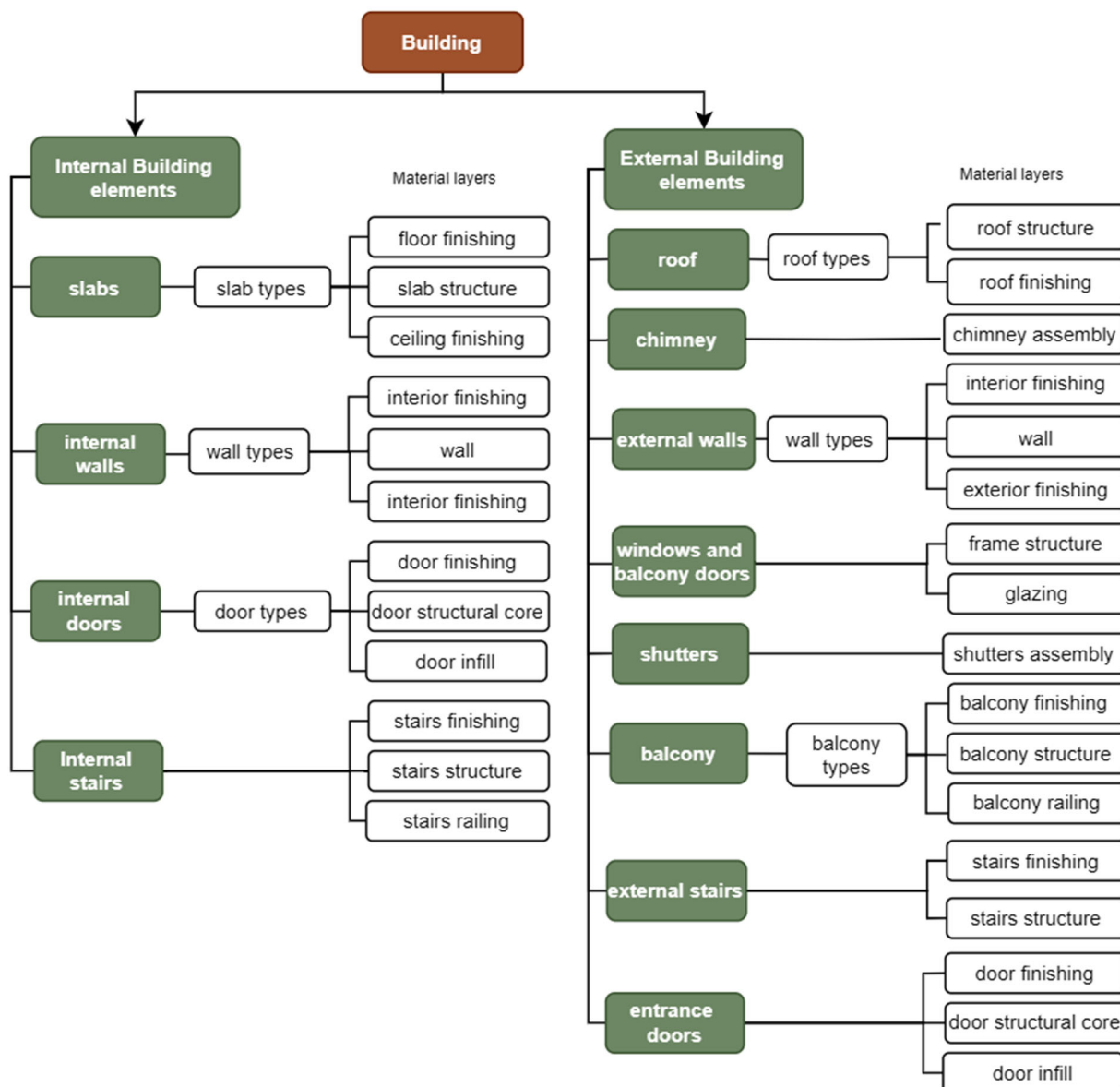


Figure 4-4 The hierarchical decomposition of a building

Figure 4-4 illustrates the hierarchical organisation of building elements and their associated material layers within the inventory register. At the highest level, the building is decomposed into internal and external elements. Each element is further subdivided into typological categories and corresponding material layers.

#### 4.2.4.1 Element types

Some elements are first divided into specific types before assigning material layers (e.g. slabs, internal and external walls, doors, roofs, and balcony types). This subdivision improves the accuracy of material assignments because different element types may have different construction assemblies. Each type is assigned a unique code to ensure unambiguous identification within the inventory and its location within the building.

The slab types are: Slab on Grade (SOG), Basement slab (B\_slab), Typical floor slab (T\_slab), and Attic slab (A\_slab). Their definitions are provided in Table 4-2.

Table 4-2 Slab types and descriptions

Slab code	Slab type name	Description
<b>SOG</b>	Slab on Grade	It refers to the first slab in contact with the ground, i.e., the slab on grade and implicitly includes all layers below and above it, which will be assigned as material layers. It can be below the basement, semi-basement or ground floor, depending on the level configuration. [typology]
<b>B_slab</b>	Basement slab	It refers to the slab above an unheated basement, where such a basement exists. If multiple basement levels exist (e.g. 2Po), a B_slab is assigned above each basement level. It implicitly includes all layers below and above the slab, which are assigned separately as material layers. [typology]
<b>T_slab</b>	Typical floor slab	It refers to slabs of typical floors that are neither above an unheated basement nor below an unheated attic.  This element represents a modification of typology-based slabs and usually adopts the same structural system as the basement or attic slab, combined with floor layers derived from the basement slab and ceiling layers derived from the attic slab.  It implicitly includes all layers below and above the slab, which are assigned separately as material layers. The slab above the semi-basement is also treated as a T_slab, as it is a living space meaning it is heated and above the ground floor. [modification of typology]
<b>A_slab</b>	Attic slab	It refers to the slab below the unheated attic. It includes all layers below and above it, which will be assigned as material layers. [typology]

Due to the lack of typology-based data enabling reliable differentiation between heated and non-heated zones within recessed floors and renovated attics, slabs below these spaces are uniformly classified as attic slabs (A\_slab). This modelling assumption ensures consistent material assignment.

The wall types are: Basement wall Above Ground (B\_wall\_AG), Basement wall Below Ground (B\_wall\_BG), External wall (E\_wall), Attic or recessed wall (A\_wall), Contact wall (C\_wall) and Parapet wall (P\_wall). Their definitions are provided in Table 4-3.

The internal walls are subdivided into internal partition walls (IP\_walls) and inter-unit walls (IU\_walls). This distinction reflects differences in thickness and construction and supports more accurate assignment of typology-based material coefficients.

Due to the absence of underground geometry in CityGML LoD3 models, basement walls are subdivided into two components: an above-ground part and a below-ground part, as defined in Table 4-3. This subdivision enables a geometry-driven yet typology-consistent estimation of basement wall quantities, while explicitly distinguishing between exposed and soil-contact conditions.

Table 4-3 Wall types and descriptions

Wall code	Wall type name	Description
<b>B_wall_AG</b>	Basement wall above ground	It refers to the portion of the basement or semi-basement wall exposed above the terrain level and is derived directly from LoD3 geometry. These walls are in contact with exterior air and implicitly include all internal and external facade finishing layers, as well, which will be assigned as material layers. This type of wall usually has different wall thickness than the above-ground heated levels, but with the same internal and external facade finishing layers. <a href="#">[geometry + modification of typology]</a>
<b>B_wall_BG</b>	Basement wall below ground	It represents the non-visible portion of the basement or semi-basement in contact with soil. Its height is calculated as the difference between the typology-based basement level height and the exposed height detected from geometry. This wall segment excludes external façade layers and includes only structural and underground-specific layers. <a href="#">[modification of typology]</a>
<b>E_wall</b>	External wall	External walls of heated above-ground levels exposed to outdoor conditions, excluding basement walls above ground and walls of attic or recessed storeys. These walls form the building envelope and are assigned material layers according to typological external wall constructions. <a href="#">[geometry + typology]</a>
<b>A_wall</b>	Attic or Recessed Floor wall	In several building archetypes, walls that are distinct from standard external walls (E_wall) occur at recessed upper storeys or attic levels. These walls are classified as A_wall and differ from E_walls in geometry, exposure conditions and typical construction assemblies. <a href="#">[geometry + typology]</a>
<b>C_wall</b>	Contact wall	Walls in direct physical contact with an adjacent building, without exposure to the outdoor environment. These walls typically lack an external plaster layer and are defined only for selected typological building types (lamella or building in a row) where such contact may occur. <a href="#">[geometry + typology]</a>
<b>P_wall</b>	Parapet wall	In some building archetypes, parapet walls are built using different construction materials than the main external walls (E_wall). For this reason, they are classified separately as P_wall. <a href="#">[geometry + typology]</a>

All exterior walls of heated above-ground spaces are classified as E\_wall, unless overridden by contact conditions. Walls of unheated attic spaces are also treated as E\_wall, consistent with the definition of the heated building envelope.

Gable walls and party walls are not introduced as separate wall categories. Due to the lack of reliable information on the use and thermal condition of spaces behind these walls, and the absence of consistent typology-based definitions, such walls are classified exclusively based on their exposure conditions. Accordingly, gable walls are treated as external walls (E\_wall), while walls in direct contact with adjacent buildings are classified as contact walls (C\_wall).

Contact walls are defined exclusively for typological building types that may be arranged in rows or blocks, resulting in direct contact with adjacent buildings. For the following building types, a contact wall may occur on one or two sides, depending on the actual building configuration:

B2\_a; C2–G2; B4–H4; B5–H5.

The assignment of the C\_wall follows a two-step logic:

1. Typological eligibility: only buildings belonging to the above-listed types may contain contact walls.
2. Geometric verification: the presence and number of contact walls (one or two sides) are determined based on LoD3 building geometry and adjacency relationships.

If no geometric contact with another building is detected, walls are classified as E\_wall, even if the typology allows for contact.

The roofs are classified into two categories: flat roofs (F\_roof) and pitched roofs (P\_roof). This distinction reflects differences in structural systems and material assemblies and supports typology-based assignment of material layers.

Internal doors are subdivided into internal room doors (R\_doors) and apartment entrance doors (A\_doors) to capture differences in material composition and performance.

The balcony elements are classified into balconies, loggias and terraces, reflecting differences in spatial configuration and construction assemblies.

#### 4.2.4.2 Material layer structure and attributes

Each building element defined in the Building Stock Inventory Data Register is decomposed into a set of representative material layers. A material layer represents the smallest unit of material description within the inventory model and corresponds to a physically distinguishable material layer within a building element.

Material layer modelling is based on national building typologies and construction standards and reflects typical construction practices for the corresponding building type and construction period. The decomposition into material layers enables consistent estimation of embedded material quantities and supports aggregation of materials across elements and buildings.

The building elements are first defined through the following attributes:

- Classification as internal or external building component;
- Position within the building element; and
- Typology archetype.

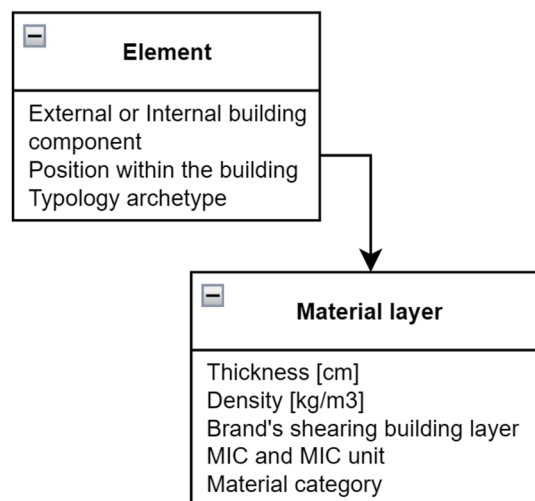


Figure 4-5 The element and material layer attributes

The material layers are then described through a standardized set of attributes (Figure 4-5) that define their geometric, physical, and semantic properties. Each material layer is characterised by:

- Thickness [cm];

- Density [kg/m<sup>3</sup>];
- Shearing building layer;
- Material intensity coefficient (MIC) and its unit;
- Material category.

These attributes provide the necessary input for calculating material quantities (Section 7).

MICs are applied to all material layers in the inventory model. For external elements with explicitly available geometry in CityGML LoD3 models, MICs are combined with measured geometric parameters (e.g., 1.00 m<sup>2</sup> of interior wall plaster per m<sup>2</sup> of wall surface). For internal elements, where geometry is not directly available, MICs are applied as typology-based assumptions to estimate material quantities (e.g., number of internal doors or m<sup>3</sup> of brick per m<sup>2</sup> of floor area). This approach ensures consistent material quantification across all elements while accounting for differences in data availability. MIC units are expressed as square or cubic meters of a given material per square meter of the corresponding element surface.

The material layers are additionally classified according to the shearing layers framework proposed by Stewart Brand [4] which distinguishes building components by their characteristic rates of change and service lives. As shown in Table 4-4, four shearing layers are considered in this project: structure, skin, space plan and stuff. The site and services layers are not considered in this project. The shearing layer classification is applied at the material layer level rather than at the element level, since a single building element may contain multiple material layers associated with different operational layers (Table 4-4).

*Table 4-4 Classification of material layers according to Brand's shearing layers*

Brand's shearing layers	Examples of material layers	Typical service life
Stuff	floor and ceiling finishings, internal and external wall finishings (interior side).	short
Space plan	non-structural internal partition walls, infill of skeletal systems; internal doors	medium
Skin	façade layers (exterior wall finishings); balcony windows and doors; external entrance doors; roof finishing (covering).	medium-long
Structure	load-bearing walls; beams; columns; balcony structure; roof structure; chimney structure; external and internal stairs structure.	long

The shearing layer classification groups material layers according to their functional role and expected replacement cycles. Structural layers represent long-life load-bearing components. Skin layers correspond to building envelope elements. Space plan layers include non-structural partitions and spatial organisation components. Stuff layers represent finishes and short-life surface materials. This classification provides the basis for scenario modelling and enables differentiated assessment of renovation, refurbishment, and demolition processes in subsequent CDW and CE analyses (Section 6).

## 4.2.5 Example: a single building type

This example illustrates the building stock inventory data model for slab elements (basement slab, typical floor slab, and attic slab), including representative material layers corresponding to the B5 building typology archetype (Figure 4-6).

	Elements and material layers	Thickness [cm]	Density [kg/m <sup>3</sup> ]	External or Internal building components	Position within the building	Shearing building layers	Typology archetype	MIC	MIC unit	Material category
<b>Element</b>	<b>Concrete slab 20cm</b>			Internal	B_slab		B5			
floor finishing	parquet	2,2	700			Stuff		1,00	m <sup>2</sup> parquet / m <sup>2</sup> floor	wood-based
	wooden subfloor	2,5	520			Stuff		1,00	m <sup>2</sup> subfloor/m <sup>2</sup> floor	wood-based
	sleepers 8/5cm in sand bedding	5	530			Stuff		0,16	m <sup>2</sup> sleepers/m <sup>2</sup> floor	wood-based
	sand bedding	5	1800			Stuff		0,84	m <sup>2</sup> sand/m <sup>2</sup> floor	stone-based
slab structure	reinforced concrete slab: concrete	20	2400			Structure		1,00	m <sup>2</sup> of concrete/m <sup>2</sup> of slab	concrete-based
	reinforced concrete slab: reinforcement	20	7850			Structure		0,01	m <sup>2</sup> of reinforcement /m <sup>2</sup> of concrete	metal-based
<b>Element</b>	<b>Ribbed concrete slab 25cm</b>			Internal	T_slab		B5			
floor finishing	parquet	2,2	700			Stuff		1,00	m <sup>2</sup> parquet / m <sup>2</sup> floor	wood-based
	wooden subfloor	2,4	520			Stuff		1,00	m <sup>2</sup> subfloor/m <sup>2</sup> floor	wood-based
	wooden sleepers	5	530			Stuff		0,16	m <sup>2</sup> sleepers/m <sup>2</sup> floor	wood-based
	sand bedding	5	1800			Stuff		0,84	m <sup>2</sup> sand/m <sup>2</sup> floor	stone-based
slab structure	semi prefabricated Herbst slab: concrete slab	5	2400			Structure		0,0432	m <sup>3</sup> concrete/m <sup>2</sup> slab	concrete-based
	semi prefabricated Herbst slab: prefabricated ribs	20	2500			Structure		0,0629	m <sup>3</sup> concrete/m <sup>2</sup> slab	concrete-based
	semi prefabricated Herbst slab: reinforcement (ribs)	0,8	7850			Structure		0,0002	m <sup>3</sup> reinforcement steel/m <sup>2</sup> slab	metal-based
ceiling finishing	straw-plaster ceiling: timber batten	5,7	530			Stuff		0,0145	m <sup>2</sup> timber battens/m <sup>2</sup> ceiling	wood-based
	straw-plaster ceiling: reed	0,8	150			Stuff		1,5	m <sup>2</sup> reed/m <sup>2</sup> ceiling	organic-misc.
	straw-plaster ceiling: lime-sand plaster	2,5	1600			Stuff		0,0320	m <sup>3</sup> mortar/m <sup>2</sup> ceiling	plaster-based
<b>Element</b>	<b>Wooden rafters slab 16/24cm</b>			Internal	A_slab		B5			
floor finishing	rammed earth	10	1500			Stuff		1,00	m <sup>2</sup> of rammed earth/m <sup>2</sup> of slab	soil-based
	wooden subfloor	2,5	520			Stuff		1,00	m <sup>2</sup> of subfloor/m <sup>2</sup> of floor	wood-based
slab structure	wooden rafters 16/24cm at 80cm distance	18	690			Structure		0,0480	m <sup>3</sup> of timber/m <sup>2</sup> of slab	wood-based
ceiling finishing	straw-plaster ceiling: timber batten	5,7	530			Stuff		0,0115	m <sup>2</sup> timber battens/m <sup>2</sup> ceiling	wood-based
	straw-plaster ceiling: reed	0,8	150			Stuff		1,5	m <sup>2</sup> reed/m <sup>2</sup> ceiling	organic-misc.
	straw-plaster ceiling: lime-sand plaster	2,5	1600			Stuff		0,0320	m <sup>3</sup> mortar/m <sup>2</sup> ceiling	plaster-based

Figure 4-6 Building stock inventory register example for slabs for building typology archetype B5

# 5 Resource recovery data register

## 5.1 Definition and role of the register

The Resource recovery register contains information on the potential reuse and recycling options for each element of the building stock, as well as other recovery possibilities and disposal. After the building stock is defined and quantified via the Building stock inventory data register, users can access the information needed to make a deconstruction plan that enables maximum possible reuse and recycling of the building material. The reuse and recycling options are defined in a way that allows the user to identify what actions are needed to safely and effectively reclaim the building materials and under what conditions the material can be utilized.

## 5.2 Data model and structuring

The data is structured in a binary manner. For each waste category, the treatment options are presented with a yes or no option. If the option is yes, this is further detailed i.e. further information is provided on how the material can be reused and/or recycled. The structure is illustrated in Figure 5-1 **Error! Reference source not found.** Information is presented on the recovery means and what kind of assessment has to be undertaken on-site to determine if the waste material is in such a state that it can be reused or recycled. For example, parquet in general can be reused but an assessment must be made on-site as to which type of adhesive was used to lay the parquet. If tar or asbestos glue was used, the parquet will probably be classified as a hazardous material. If other types of adhesives were used, the parquet has the potential to be reused if it was not treated with paints that contain heavy metals, was pressure treated or shows signs of rotting. When these conditions are met, the parquet can be reused or recycled as wood chips, particleboard, composite materials and for similar uses [5], [6].

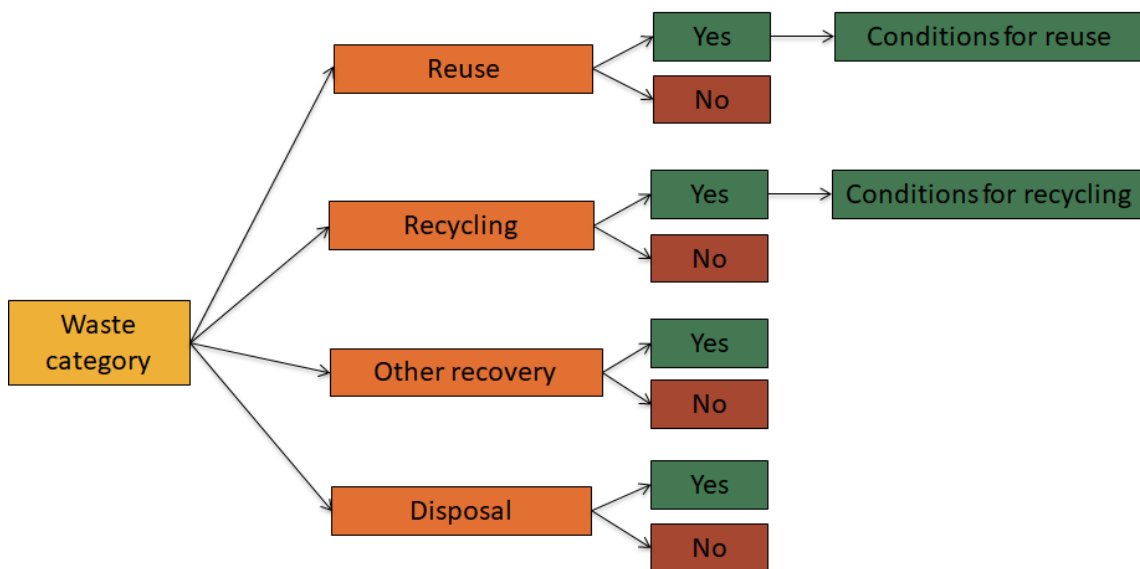


Figure 5-1 Data structure for waste treatment options

## 5.3 Waste treatment options

Four material treatment options are presented for each building material: reuse, recycling, other recovery and disposal. Reuse and recycling enable the best circularity of the building stock. Other recovery includes energy recovery that can be used for combustible materials such as wood, plastic, organic insulation

(thermal insulation, sound insulation) materials and bitumen based waterproofing membranes. It was assumed that disposal would be the least favourable treatment option.

## 5.4 Example: a single building type

A single building type B5 was chosen to present the treatment options contained in the Resource recovery data register. Selected building elements will be presented in this section with the treatment options. For B5 type buildings, the basement slab is comprised of a parquet, a wooden subfloor, sleepers 8/5cm in sand bedding and a reinforced concrete slab. The treatment options for parquet are specified in Section 5.2.

The wooden subfloor has similar treatment options. Reuse is possible if the subfloor is made of solid wood. Testing for hazardous substances prior to reuse/recycle includes: testing for the type of adhesive used and testing for prior treatments with paints that contain heavy metals. Pressure treated or rotting wood cannot be reused. As for the type of adhesive used, remains of tar or asbestos glue renders the wood hazardous; bituminous adhesive residues can be removed by taking appropriate precautions (personal protective equipment, air extraction, dust removal, etc.). Reuse should always have priority at the material treatment option. Recycling is the second most favourable option, and for the wooden subfloor recycling can occur after the same testing that is required for reuse is conducted, to assess the condition of the wood. Wood in good condition can be recycled and used as wood chips, particleboard, composite materials and for comparable uses [5], [6].

The sleepers can be directly reused if uncontaminated and structurally suitable. Testing for hazardous substances must be conducted prior to reuse. Other options for reuse include the sleepers being used as fill material for landscaping. As far as recycling goes, if uncontaminated, the sleepers can be recycled for the same purposes as other types of wood (for use as wood chips, in particleboard, in composite materials). The wood-based materials can be used for energy recovery. The sand bedding must be tested for hazardous substances prior to reuse. For example, testing of the sand with an X-ray fluorescence (XRF) analyser can determine if the sand contains any heavy metals. If the sand is uncontaminated and structurally suitable, it can be reused again for sand bedding or as fill material for landscaping. Recycling options for uncontaminated sand include the sand being incorporated into concrete mixes after proper testing to ensure it meets required standards.

The reinforced concrete slab can be recycled [7], [8]. Recycling involves breaking down the concrete into aggregates, which can be used as a base for roads, foundations, or even in new concrete production. Concrete slabs are crushed, separating the steel reinforcement (rebar) from the concrete. The steel rebar can be recycled at steel recycling facilities. The steel rebar cannot be reused. Table 5-1 presents the data for the basement slab in a tabular form.

Table 5-1 Waste categories and treatment options for the basement slab of a B5 type building

Table 5.1. Waste categories and treatment options for the basement slab (concrete slab 20 cm) of a B5 type building							
Waste category	Material category	Hazardous or non-hazardous waste	Classification code from LoW <sup>2</sup> [9]	TREATMENT OPTION			
				REUSE	RECYCLE	OTHER RECOVERY	DISPOSAL
Parquet	Wood-based	Potentially hazardous	17 02 01	Yes - Testing for hazardous substances prior to reuse/recycle: 1) Testing for the type of glue used: a) remains of tar or asbestos glue renders the wood hazardous; b) bituminous adhesive residues can be removed by taking appropriate precautions (personal protective equipment, air extraction, dust removal, etc.). These adhesives were used until the second half of the 20 <sup>th</sup> century. 2) Testing for prior treatments with paints that contain heavy metals. Pressure treated or rotting wood not to be reused.	Yes - Testing for hazardous substances prior to reuse/recycle: 1) Testing for the type of glue used: a) remains of tar or asbestos glue renders the wood hazardous; b) bituminous adhesive residues can be removed by taking appropriate precautions (personal protective equipment, air extraction, dust removal, etc.). These adhesives were used until the second half of the 20 <sup>th</sup> century. 2) Testing for prior treatments with paints that contain heavy metals. Pressure treated or rotting wood not to be reused. Recycling applications: wood chips, particleboard, composite materials.	Yes	Yes
Wooden subfloor	Wood-based	Potentially hazardous	17 02 01	Yes - If made of solid wood. Testing for hazardous substances prior to reuse/recycle: 1) Testing for the type of glue used: a) remains of tar or asbestos glue renders the wood hazardous; b) bituminous adhesive residues can be removed by taking appropriate precautions (personal protective equipment, air extraction, dust removal, etc.). These adhesives were used until the second half of the 20 <sup>th</sup> century. 2) Testing for prior treatments with paints that contain heavy metals. Pressure treated or rotting wood not to be reused.	Yes - Testing for hazardous substances prior to reuse/recycle: 1) Testing for the type of glue used: a) remains of tar or asbestos glue renders the wood hazardous; b) bituminous adhesive residues can be removed by taking appropriate precautions (personal protective equipment, air extraction, dust removal, etc.). These adhesives were used until the second half of the 20 <sup>th</sup> century. 2) Testing for prior treatments with paints that contain heavy metals. Pressure treated or rotting wood not to be reused. Recycling applications: wood chips, particleboard, composite materials.	Yes	Yes
Sleepers 8/5cm in sand bedding	Wood-based	Potentially hazardous	17 02 01	Yes. Direct reuse if uncontaminated and structurally suitable. Testing for hazardous substances prior to reuse/recycle: 1) testing of the sand; 2) testing the contamination of sleepers with sand; 3) testing if sleepers were treated with chemicals. Sleepers - reuse as garden and landscaping projects, such as raised beds, retaining walls, pathways.	Yes - As wood chips, particleboard, composite materials.	Yes	Yes
Sand bedding	Stone-based	Potentially hazardous	17 05 04	Yes. Direct reuse if uncontaminated and structurally suitable. Testing for hazardous substances prior to reuse. Reuse as fill material for landscaping.	Yes - Incorporated into concrete mixes after proper testing to ensure it meets required standards	No	Yes
Reinforced concrete slab: concrete	Concrete-based	Non-hazardous	17 01 01 17 04 05	No.	Yes - As recycled concrete aggregate. Recycling involves breaking down the concrete into aggregates, which can be used as a base for roads, foundations, or even in new concrete production. Concrete slabs are crushed, separating the steel reinforcement (rebar) from the concrete.	No	Yes
Reinforced concrete slab: reinforcement	Metal-based	Non-hazardous	17 04 05	No	Yes - Recycling possible at steel recycling facilities.	No	Yes

<sup>2</sup> List of Waste

The typical floor slab is made of a parquet, a wooden subfloor, wooden sleepers, sand bedding, a semi prefabricated Herbst slab and a straw-plaster ceiling. The reuse and recycling options for the first four listed building materials are discussed in the paragraph above. The Herbst slab can be recycled in the same manner as a reinforced concrete slab. The straw-plaster ceiling construction involves timber batten, reed and lime-sand plaster. The timber can be reused and recycled under the same conditions listed above for wood material. Reed and lime-sand plaster cannot be reused. Reed can be crushed and used as a filler, soil stabilizer, or compost additive if free from contaminants (no paint, asbestos or synthetic binders). Lime-sand plaster can be crushed and recycled for use as aggregate in new lime mortars, as a filler, soil stabilizer, or compost additive if free from contaminants (no paint, asbestos or synthetic binders). Table 5-2 presents the data for the floor slab in a tabular form.

The attic slab consists of rammed earth, a wooden subfloor, wooden rafters 16/24cm at 80cm distance and a straw-plaster ceiling. Rammed earth can be reused after testing for hazardous substances (e.g. heavy metals). Treatment options for the other materials have been previously listed. Table 5-3 presents the data for the attic slab in a tabular form.

The brick wall in a B5 type building has a decorative plaster Terranova on the outside, bricks, mortar and plaster on the inside. The inside and outside plaster can be crushed and recycled for use as aggregate in new lime mortars, as a filler, soil stabilizer, or compost additive if free from contaminants (no paint, asbestos, or synthetic binders). Bricks laid with lime-based mortar can be reused, while bricks bonded with cement-based mortar are difficult to salvage [5], [6] [10]. Bricks are usually reused for internal walls, partitions, landscaping projects. Bricks can be used for load-bearing purposes only if tested in a laboratory to confirm their integrity. Bricks can be recycled as aggregate for concrete, foundations and road bases; as pozzolanic material can be used as a cement replacement; for landscaping and green roofs.

Table 5-2 Waste categories and treatment options for the floor slab of a B5 type building

Table 5.2. Waste categories and treatment options for the Typical floor slab (ribbed concrete slab 25 cm) of a B5 type building

Waste category	Material category	Hazardous or non-hazardous waste	Classification code from LoW <sup>3</sup> [9]	TREATMENT OPTION			
				REUSE	RECYCLE	OTHER RECOVERY	DISPOSAL
Parquet	Wood-based	Potentially hazardous	17 02 01	Yes - Testing for hazardous substances prior to reuse/recycle: 1) Testing for the type of glue used: a) remains of tar or asbestos glue renders the wood hazardous; b) bituminous adhesive residues can be removed by taking appropriate precautions (personal protective equipment, air extraction, dust removal, etc.). These adhesives were used until the second half of the 20 <sup>th</sup> century. 2) Testing for prior treatments with paints that contain heavy metals. Pressure treated or rotting wood not to be reused.	Yes - Testing for hazardous substances prior to reuse/recycle: 1) Testing for the type of glue used: a) remains of tar or asbestos glue renders the wood hazardous; b) bituminous adhesive residues can be removed by taking appropriate precautions (personal protective equipment, air extraction, dust removal, etc.). These adhesives were used until the second half of the 20 <sup>th</sup> century. 2) Testing for prior treatments with paints that contain heavy metals. Pressure treated or rotting wood not to be reused. Recycling applications: wood chips, particleboard, composite materials.	Yes	Yes
Wooden subfloor	Wood-based	Potentially hazardous	17 02 01	Yes - If made of solid wood. Testing for hazardous substances prior to reuse/recycle: 1) Testing for the type of glue used: a) remains of tar or asbestos glue renders the wood hazardous; b) bituminous adhesive residues can be removed by taking appropriate precautions (personal protective equipment, air extraction, dust removal, etc.). These adhesives were used until the second half of the 20 <sup>th</sup> century. 2) Testing for prior treatments with paints that contain heavy metals. Pressure treated or rotting wood not to be reused.	Yes - Testing for hazardous substances prior to reuse/recycle: 1) Testing for the type of glue used: a) remains of tar or asbestos glue renders the wood hazardous; b) bituminous adhesive residues can be removed by taking appropriate precautions (personal protective equipment, air extraction, dust removal, etc.). These adhesives were used until the second half of the 20 <sup>th</sup> century. 2) Testing for prior treatments with paints that contain heavy metals. Pressure treated or rotting wood not to be reused. Recycling applications: wood chips, particleboard, composite materials.	Yes	Yes
Wooden sleepers	Wood-based	Potentially hazardous	17 02 01	Yes. Direct reuse if uncontaminated and structurally suitable. Testing for hazardous substances prior to reuse/recycle: 1) testing of the sand; 2) testing the contamination of sleepers with sand; 3) testing if sleepers were treated with chemicals. Sleepers - reuse as garden and landscaping projects, such as raised beds, retaining walls, pathways.	Yes - As wood chips, particleboard, composite materials.	Yes	Yes
Sand bedding	Stone-based	Potentially hazardous	17 05 04	Yes. Direct reuse if uncontaminated and structurally suitable. Testing for hazardous substances prior to reuse. Reuse as fill material for landscaping.	Yes - Incorporated into concrete mixes after proper testing to ensure it meets required standards.	No	Yes
Semi prefabricated Herbst slab: concrete slab	Concrete-based	Non-hazardous	17 01 01	No	Yes - As recycled concrete aggregate. Recycling involves breaking down the concrete into aggregates, which can be used as a base for roads, foundations, or even in new concrete production.	No	Yes
Semi prefabricated	Concrete-based	Non-hazardous	17 01 01	No	Yes - As recycled concrete aggregate. Recycling involves breaking down the concrete into aggregates, which can be used as a base for roads, foundations, or even in new	No	Yes

<sup>3</sup> List of Waste

**Table 5.2. Waste categories and treatment options for the Typical floor slab (ribbed concrete slab 25 cm) of a B5 type building**

Waste category	Material category	Hazardous or non-hazardous waste	Classification code from LoW <sup>3</sup> [9]	TREATMENT OPTION			
				REUSE	RECYCLE	OTHER RECOVERY	DISPOSAL
Herbst slab: prefabricated ribs					concrete production. Concrete slabs are crushed, separating the steel reinforcement (rebar) from the concrete.		
Semi prefabricated Herbst slab: reinforcement (ribs)	Metal-based	Non-hazardous	17 04 05	No	Yes - Recycling possible at steel recycling facilities.	No	Yes
Straw-plaster ceiling: timber batten	Wood-based	Potentially hazardous	17 02 01	Yes. Direct reuse if uncontaminated and structurally suitable. Testing for hazardous substances prior to reuse/recycle, i.e. if wood was treated with chemicals. Reuse as garden and landscaping projects, such as raised beds, retaining walls, pathways.	Yes - As wood chips, particleboard, composite materials.	Yes	Yes
Straw-plaster ceiling: reed	Organic-misc.	Potentially hazardous	17 09 04	No	Yes - Can be crushed and used as a filler, soil stabilizer, or compost additive if free from contaminants (no paint, asbestos, or synthetic binders).	Yes	Yes
Straw-plaster ceiling: lime-sand plaster	Plaster-based	Potentially hazardous	17 08 02	No	Yes - Can be crushed and recycled for use as aggregate in new lime mortars, as a filler, soil stabilizer, or compost additive if free from contaminants (no paint, asbestos, or synthetic binders).	No	Yes

Table 5-3 Waste categories and treatment options for the attic slab of a B5 type building

Table 5.3. Waste categories and treatment options for the attic slab (wooden rafters slab 16/24 cm) of a B5 type building

Waste category	Material category	Hazardous or non-hazardous waste	Classification code from LoW <sup>4</sup> [9]	TREATMENT OPTION			
				REUSE	RECYCLE	OTHER RECOVERY	DISPOSAL
Rammed earth	Soil-based	Potentially hazardous	17 05 04	Yes - Testing for hazardous substances prior to reuse (e.g. heavy metals).	No	No	Yes
Wooden subfloor	Wood-based	Potentially hazardous	17 02 01	Yes - If made of solid wood. Testing for hazardous substances prior to reuse/recycle: 1) Testing for the type of glue used: a) remains of tar or asbestos glue renders the wood hazardous; b) bituminous adhesive residues can be removed by taking appropriate precautions (personal protective equipment, air extraction, dust removal, etc.). These adhesives were used until the second half of the 20th century. 2) Testing for prior treatments with paints that contain heavy metals. Pressure treated or rotting wood not to be reused.	Yes - Testing for hazardous substances prior to reuse/recycle: 1) Testing for the type of glue used: a) remains of tar or asbestos glue renders the wood hazardous; b) bituminous adhesive residues can be removed by taking appropriate precautions (personal protective equipment, air extraction, dust removal, etc.). These adhesives were used until the second half of the 20th century. 2) Testing for prior treatments with paints that contain heavy metals. Pressure treated or rotting wood not to be reused. Recycling applications: wood chips, particleboard, composite materials.	Yes	Yes
Wooden rafters 16/24cm at 80cm distance	Wood-based	Potentially hazardous	17 02 01	Yes - Suitability for reuse includes a visual inspection, identification creep (deformation), natural defects (knots), splits (oriented in the direction of the fibres) and cracks (cutting across the fibres), visible fungi, biological agents, xylophagous insects, areas of mould, humidity, discolouration, saw marks, oxidation of metal assemblies. Basic tests to be performed are: 1) Hardness test using a resistograph (detection of superficial areas of rot); 2) Screwdriver test (consists in causing a localised splinter using a blunt object. In healthy wood, the breakage occurs along the fibres while rotten wood tends to break in small pieces or in the middle of the fibres); 3) Mallet test that consists of gently striking the timber to detect the presence of empty or rotten areas (emitting a hollow sound); 4) Humidity measurement using a moisture meter. Additional tests: carried out to establish a more complete diagnosis of the condition of the elements, in particular if they are painted or covered, auscultation by drilling and coring (making it possible to detect internal deterioration of the wood and, if necessary, to determine thickness of residual healthy wood), various laboratory tests to detect the presence of fungi, to precisely identify the species, to measure the density or to detect the presence of dangerous substances.	Yes - Rafters can be transformed into flooring, cladding, doors, Stairs, furniture.	Yes	Yes

<sup>4</sup> List of Waste

Table 5.3. Waste categories and treatment options for the attic slab (wooden rafters slab 16/24 cm) of a B5 type building

Waste category	Material category	Hazardous or non-hazardous waste	Classification code from LoW <sup>4</sup> [9]	TREATMENT OPTION			
				REUSE	RECYCLE	OTHER RECOVERY	DISPOSAL
Straw-plaster ceiling: timber batten	wood-based	Potentially hazardous	17 02 01	Yes. Direct reuse if uncontaminated and structurally suitable. Testing for hazardous substances prior to reuse/recycle, i.e. if wood was treated with chemicals. Reuse as garden and landscaping projects, such as raised beds, retaining walls, pathways.	Yes - As wood chips, particleboard, composite materials.	Yes	Yes
Straw-plaster ceiling: reed	organic-misc.	Potentially hazardous	17 09 04	No	Yes - Can be crushed and used as a filler, soil stabilizer, or compost additive if free from contaminants (no paint, asbestos, or synthetic binders).	Yes	Yes
Straw-plaster ceiling: lime-sand plaster	plaster-based	Potentially hazardous	17 08 02	No	Yes - Can be crushed and recycled for use as aggregate in new lime mortars, as a filler, soil stabilizer, or compost additive if free from contaminants (no paint, asbestos, or synthetic binders).	Yes	Yes

# 6 CDW and CE indicators register

## 6.1 Definition and role of the register

The purpose of the CDW and CE indicators register is to define the set of CDW and CE indicators that are calculated for the EoL phase of existing residential buildings within the CE Map. The register specifies which indicators are selected, how they are interpreted, and under which assumptions they are assessed.

Unlike the building stock inventory data register, described in Section 4, which defines what inventory data exist and how they are structured, the CDW and CE indicators register establishes how this data is translated into decision-relevant information. In particular, it supports stakeholder decision-making related to demolition planning, selective dismantling, reuse, and high-quality recycling. In this sense, the register acts as a semantic and conceptual bridge between raw building and material data and higher-level information required for circular economy decision-making.

## 6.2 Selection criteria for the CDW and CE indicators

CDW and CE indicators are widely used across research literature, policy documents, and project deliverables; however, no single, universally accepted definition exists. In this work, CDW and CE indicators are interpreted as metrics describing the end-of-life performance of existing buildings. CDW indicators primarily quantify waste generation and material flows resulting from demolition, deconstruction, or renovation activities, while CE indicators interpret these flows in terms of recovery potential and circular performance. Together, they provide valuable decision-relevant information, linking physical waste quantities with circular economy objectives.

Given the nature of the CE map, which is based on large-scale CityGML LoD3 building stock models calibrated with typology-based information and BIM data (where available), the selection of indicators prioritises end-of-life-relevant performance that can be derived from limited but structured input data. Such input data include geometry- and typology-based material quantities, and scenario-based end-of-life treatment assumptions. Indicators that require intrusive building audits, detailed component-level as-built documentation, or comprehensive manufacturing and supply-chain information are therefore considered out of scope for stock-level implementation.

To avoid ad-hoc or purely literature-driven indicator selection, CDW and CE indicators were screened using a structured, multi-criteria approach tailored to the objectives and data environment of the CE map. The screening was conducted in two sequential steps:

1. **Decision-oriented classification**, identifying the role of each indicator in end-of-life decision-making; and
2. **Eligibility screening**, assessing whether the indicator can be reliably implemented at building stock scale using the available data.

This approach ensures that the final indicator set is both: (a) methodologically consistent with the intended use of CE passports for end-of-life assessment, and (b) practically implementable across large building stocks and multiple pilot contexts.

### 6.2.1 Decision-oriented classification

The decision-oriented classification reflects the key questions that arise when assessing end-of-life performance of existing buildings at stock scale. These questions include:

- What type and quantity of waste is generated at the end-of-life of a building?
- When will this waste become available as a material resource?

- What share of the generated waste can realistically remain in circulation as secondary material?
- Which constraints may prevent circular outcomes from being realised in practice?

Based on these decision needs, CDW and CE indicators were grouped into four functional classes, represented in Table 6-1.

*Table 6-1 Decision-oriented classification of indicators*

<b>Class A: Waste quantity indicators (What and how much?)</b>
<p>The waste quantity indicators describe the magnitude and structure of CDW at the EoL stage. At this stage, the quantities of materials embedded in the building stock are considered known and serve as input data for estimating the amount and composition of CDW generated during different EoL scenarios (renovation, selective deconstruction, and conventional demolition).</p> <p>Waste quantity indicators represent the minimum quantitative information required for CDW assessment and form the basis for all subsequent recovery and circularity analyses. Typical examples from the reviewed literature include waste quantities expressed in mass or volume, waste composition classified by material category and corresponding European Union LoW codes and intensity metrics normalised by reference units such as gross floor area.</p>
<b>Class B: Temporal and flow indicators (What and at what pace?)</b>
<p>Temporal and flow indicators support planning at building, neighbourhood and municipal scales by describing the timing and evolution of CDW generation. These indicators enable dynamic flow modelling and scenario-based forecasting by linking building stock material quantities with demolition and renovation rates and service life assumptions.</p> <p>Temporal indicators are derived through integration with an external dynamic building stock model, which provides time-dependent waste generation profiles under different demolition, renovation and circular economy scenarios. The CE Map itself remains a spatially explicit representation of building-level indicators, while temporal aggregation and forecasting are supported through coupling with the dynamic model.</p>
<b>Class C: Recovery potential indicators (What can remain in circulation?)</b>
<p>Recovery potential indicators interpret waste quantities in relation to CE objectives by estimating the share of generated waste that can be reused, recycled or otherwise recovered at EoL. These indicators are inherently scenario-dependent and express conditional performance rather than absolute quantities.</p> <p>In a building stock context, circularity potential indicators are typically computed using scenario-based treatment shares defined for individual material streams. Representative examples include reuse, recycling, and recovery shares, Waste Diversion Rate (WDR) and simplified circularity metrics derived from mass-flow logic, such as end-of-life-focused adaptations of Material Circularity Indicator (MCI) concepts.</p>
<b>Class D: Constraint indicators (What can prevent circular outcomes?)</b>
<p>Indicators in this class capture barriers that may limit the realisation of circular potential in practice. These include the presence of hazardous materials, contamination, coatings, and feasibility constraints related to dismantling and material separation.</p> <p>From the reviewed literature, operationally simple yet informative indicators such as the R-score (recyclable, reusable, non-toxic, uncoated) and D-score (demountable connections and prefabrication) were identified as suitable for large-scale applications. More detailed disassembly metrics, such as the Level of Disassembly, were assessed as difficult to scale without intrusive building audits and are therefore excluded from the core indicator set.</p>

## 6.2.2 Eligibility screening criteria

Following the decision-oriented classification, indicators were further evaluated against five eligibility criteria specifically designed for the data availability and modelling constraints of the CE Map, as shown in Table 6-2. While the decision-oriented classification defines the functional role of indicators within end-

of-life assessment, the eligibility criteria determine whether an indicator can be practically implemented within the CE Map data and modelling environment.

*Table 6-2 Eligibility screening criteria for indicators*

<b>Criterion 1. Operational relevance for end-of-life decision-making</b>
<p>The indicator must provide direct and actionable support for end-of-life decision-making related to demolition and deconstruction planning, recovery potential or CDW management. Indicators that are conceptually related to circular economy or end-of-life stages, but whose calculation logic primarily serves design-stage optimization or manufacturing processes, were excluded unless they could be robustly reformulated for end-of-life application using available building stock data.</p> <p>Building-level composite indices originally developed for design-stage assessment (e.g. Building Circularity Indicator (BCI) relying on product disassembly factors and Brand's layers) are not suitable for end-of-life-only building stock models, due to their dependence on detailed design documentation and component-level connection data that are typically unavailable for existing buildings.</p>
<b>Criterion 2. Data availability</b>
<p>Indicators must be computable using data that are available or can be consistently inferred within the CE Map data pipeline. In this work, available input data are limited to geometry and typology-based building stock inventory, including typology-based material intensity coefficients (MICs) used to estimate interior material quantities.</p> <p>Consequently, indicators that require extensive supplier or manufacturing data, detailed product specifications, or connection-level documentation are considered non-eligible for CE map implementation, unless a simplified, transparent, and scalable proxy approach can be clearly defined.</p>
<b>Criterion 3. Scalability potential</b>
<p>The indicator must be applicable to large building stocks with consistent and reproducible computational effort. Given that the CE Map targets hundreds of buildings across different urban contexts, preference was given to indicators that can be calculated in an automated manner based on rule-based logic, mass- or volume-based calculations, or ratio-based formulations.</p> <p>Indicators requiring manual inspection, expert judgment on a case-by-case basis, or on-site building audits (e.g. detailed disassembly assessments or connection-level surveys) were considered insufficiently scalable and therefore unsuitable for large-scale implementation.</p>
<b>Criterion 4. Interoperability</b>
<p>Indicators should be compatible with existing standards, classifications, and data structures relevant to CDW management and CE assessment. This includes alignment with the European Union LoW, harmonised waste treatment categories (reuse, recycling, other recovery, disposal), and emerging concepts related to digital building logbooks and circular economy passports.</p> <p>This criterion ensures that indicator outputs can be meaningfully aggregated, compared across pilot regions, and reused in downstream applications, such as municipal waste planning, reporting, or integration with life-cycle assessment frameworks as an optional enrichment layer.</p> <p>Indicators relying on highly project-specific definitions or proprietary classification systems were therefore deprioritised, as they limit transferability and cross-country comparability.</p>
<b>Criterion 5. Interpretability for end users</b>
<p>Indicator outputs must be understandable and interpretable by key stakeholder groups, including municipalities, urban planners, demolition contractors, and policy makers. Preference was given to indicators that produce transparent and intuitively interpretable results, such as absolute quantities, percentages, or clearly defined scores, which can be directly visualised and compared within the 3D web CE Map.</p> <p>In particular, indicators should support scenario-based exploration and “what-if” analyses, enabling users to compare pessimistic and optimistic circular end-of-life pathways, assess the impact of alternative treatment strategies, and identify buildings or areas with high recovery potential or elevated risk of landfilling.</p>

## 6.2.3 Final CDW and CE indicator set

Applying the decision-oriented classification (Section 6.2.1) and the eligibility screening criteria (Section 6.2.2) resulted in a final, compact set of CDW and CE indicators suitable for building-level EoL assessment within the CE Map.

The final indicator set consists of ten indicators grouped across the four decision-oriented classes defined in Section 6.2.1, are given in Table 6-3.

Table 6-3 The final indicator set

<b>Class A: Waste quantity indicators (What and how much?)</b>
<p><b>1. Total CDW mass [kg]</b></p> <p>Quantifies the total mass of CDW generated at the EoL of a building. This indicator represents the fundamental quantitative basis for all further CDW and CE assessments.</p> <p><b>2. Waste composition by material streams [% of total CDW mass]</b></p> <p>Describes the relative contribution of major material streams (e.g. concrete-based, wood-based, metal-based, glass-based etc.) to the total CDW mass. This indicator forms the basis for identifying suitable treatment and recovery pathways and supports mapping to LoW streams.</p> <p><b>3. Waste intensity [kg/m<sup>2</sup> GFA]</b></p> <p>Expresses the amount of CDW generated per unit of gross floor area, enabling comparison between buildings of different sizes and typologies.</p>
<b>Class B: Temporal and flow indicators (What and at what pace?)</b>
<p><b>4. Time-dependent CDW generation</b></p> <p>Describes what share of building stock (%) becomes available over time and when it becomes available, derived through coupling with an external dynamic building stock model incorporating demolition rates, renovation rates, and service-life assumptions.</p>
<b>Class C: Recovery potential indicators (What can remain in circulation?)</b>
<p><b>5. Reuse potential [% of total CDW mass]</b></p> <p>Estimates the share of materials and components suitable for direct reuse at end-of-life.</p> <p><b>6. Recycling potential [% of total CDW mass]</b></p> <p>Estimates the share of waste that can be recycled, considering material-specific recovery pathways.</p> <p><b>7. Waste Diversion Rate (WDR) [% of total CDW mass]</b></p> <p>Measures the share of CDW diverted from landfill through reuse, recycling, other recovery, or other treatment pathways. WDR serves as the primary headline circularity indicator at the end-of-life stage.</p>
<b>Class D: Constraint indicators (What can prevent circular outcomes?)</b>
<p><b>8. Recovery score (R-score) [-]</b></p> <p>A simplified recoverability indicator that expresses the percentage of recoverable building components and materials at the EoL. It captures key constraints affecting recovery, such as presence of toxic materials and coatings [11].</p> <p><b>9. Deconstructibility score (D-score) [-]</b></p> <p>A simplified deconstructibility indicator describing the ease with which a building or its components can be dismantled at EoL without causing excessive damage. It reflects the prevalence of demountable connections and prefabricated elements, and serves as a proxy for the feasibility of selective dismantling and component reuse under real demolition or deconstruction conditions [11].</p>

## 10. Hazardous waste share or hazard class [% or categorical]

Identifies the estimated share of hazardous materials that may restrict recovery options. Where quantitative estimation is not feasible, a categorical hazard class (e.g. low, medium, high) is assigned based on construction period and typological rules.

## 6.3 Assessment of CDW and CE indicators

For this stage, the quantities and types of materials embedded in the building stock are considered known and structured according to the hierarchical inventory model (material layer-element-building). These material quantities serve as the primary input for the assessment CDW and CE indicators. Figure 6-1 illustrates the assessment logic applied for CDW and CE indicators within the CE Map.

The assessment of indicators is performed through a two-step, scenario-based procedure, which explicitly separates:

- Waste generation based on different EoL scenarios, and
- Recovery potential based on different treatment pathways of scenario-based waste generation.

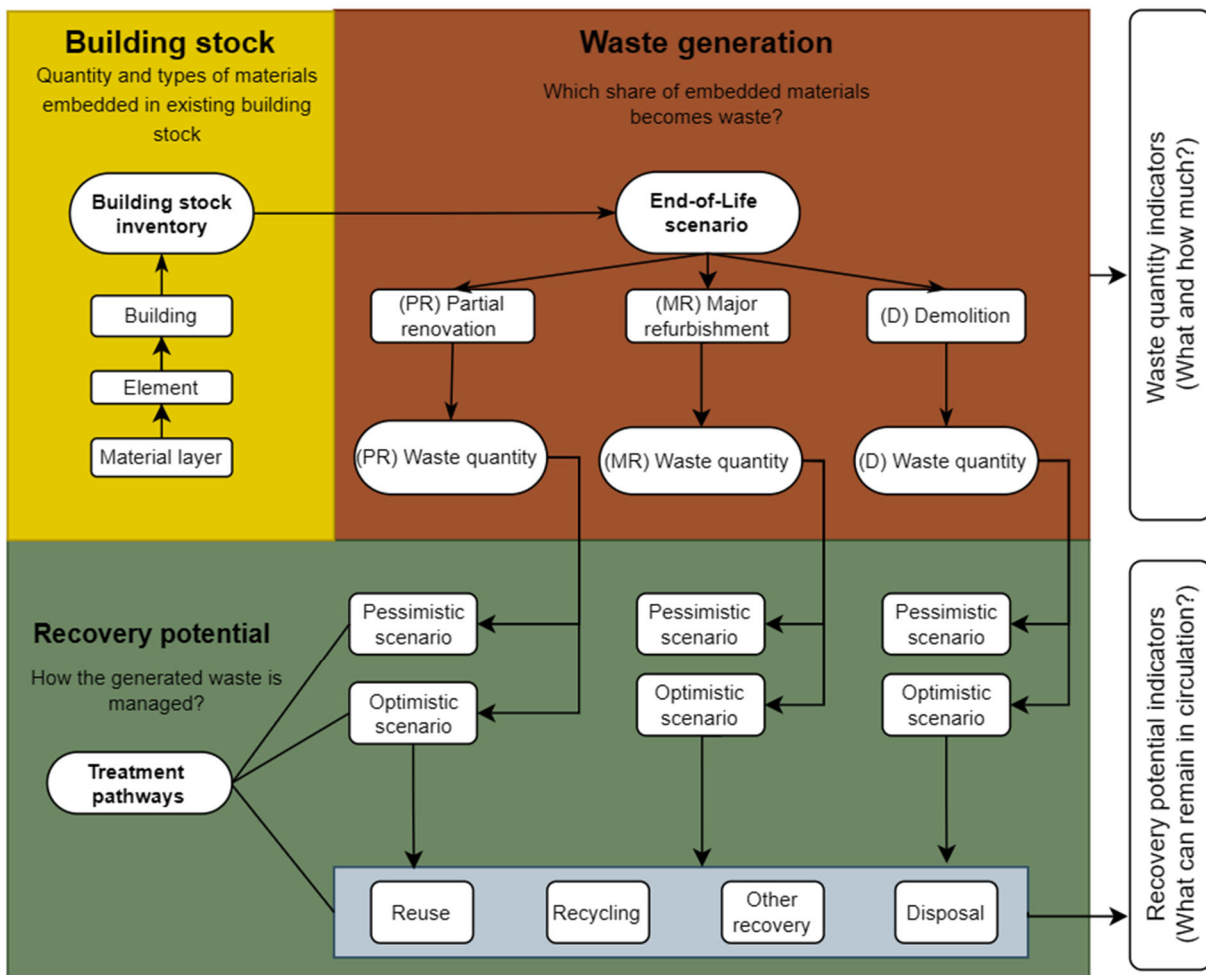


Figure 6-1 The assessment logic applied for Waste quantity and Recovery potential indicators

This separation distinguishes the effects of intervention choices (renovation, refurbishment, or demolition) from waste management strategies. It enables transparent comparison of alternative scenarios and supports evaluation of how different decisions influence waste quantities, recovery potential, and overall circular performance at material, element, and building scales.

### 6.3.1 Waste generation through EoL scenarios

Waste generation is quantified by defining EoL scenarios, which describe different types of interventions applied to existing buildings. Three EoL scenarios are considered:

- **(PR) Partial renovation** primarily targets fast-changing layers, including finishes and selected envelope and system components, while preserving the spatial configuration and structural system;
- **(MR) Major refurbishment** represents a deep intervention in which all non-structural layers are removed and replaced, retaining only the primary load-bearing structure.
- **(D) Demolition** represents removal of the entire building structure.

Each scenario is quantified using material and element specific removal coefficients, which define the proportion of embedded materials that becomes waste. Removal coefficients are dimensionless values equal 0 and 1 and are applied consistently across buildings of the same typological type, and same EoL scenario.

For demolition, removal coefficients are equal to 1 for all material layers and elements, since the entire building is removed. Differences between demolition practices (e.g. conventional vs. selective dismantling) are not reflected in waste quantities but in subsequent treatment pathways. Renovation scenarios (partial renovation and major refurbishment) are characterised by partial removal, with coefficients varying according to element and material type and associated shearing layers.

The coefficients do not represent building-specific measurements, but standardised, typology-based assumptions reflecting typical EoL practices. Their purpose is to enable consistent estimation of waste quantities across large building stocks rather than to reproduce exact outcomes for individual buildings.

### 6.3.2 Calculation of waste quantity indicators

Waste quantity indicators are calculated by applying the scenario-specific removal coefficients to the embedded material quantities derived from the building stock inventory. For each building and EoL scenario, the resulting waste quantities are expressed in mass and classified according to material categories and corresponding LoW streams.

Waste quantity indicators describe how much waste is generated under a given intervention scenario. At this stage, no assumptions are made regarding waste treatment or recovery; the indicators purely reflect the magnitude and composition of generated CDW.

### 6.3.3 Treatment pathways and circularity potential indicators

The recovery of generated waste is assessed through treatment pathway assumptions which allocate waste quantities to reuse, recycling, other recovery or disposal. Treatment pathways are defined independently of waste generation and are applied only after waste quantities have been established.

For each material stream and EoL scenario, treatment pathways are quantified using scenario-based treatment shares, with the sum of shares equal to one. Two alternative treatment assumptions are considered:

- **A pessimistic scenario**, representing current waste management practices; and
- **An optimistic scenario**, representing enhanced CE practices achievable through better sorting, selective dismantling, and improved recovery infrastructure.

Treatment shares are derived from literature, policy targets, and regional or Eurostat data and are formulated as location and building-specific, but configurable parameters. This approach allows consistent implementation across all buildings within a pilot area while enabling future adaptation to other regions or countries.

Recovery potential indicators, such as reuse potential, recycling potential, and WDR, are calculated by combining waste quantities with treatment pathway shares. These indicators express conditional circular performance, as their values depend on both the selected EoL scenario and the assumed treatment pathway.

### 6.3.4 Role of constraint indicators

Constraint indicators are used to capture factors that may limit achievable recovery potential in practice. Indicators such as R-score, D-score, and hazardous waste share act as contextual modifiers rather than direct inputs to waste generation.

They provide additional information on deconstructability, material compatibility, and safety constraints, and help evaluate whether optimistic recovery assumptions are realistic for specific building typologies.

### 6.3.5 Hierarchical aggregation of indicators

CDW and CE indicators follow the same hierarchical structure as the inventory model. Indicators are first calculated at the material layer level and subsequently aggregated to element and building levels.

EoL scenarios and treatment pathways are applied exclusively at the material layer level. Aggregation is performed without altering underlying assumptions. This ensures consistency between inventory data, indicator assessment, and CE passport structure, while enabling flexible representation of results at multiple semantic levels within the CE Map.

# 7 Circular City Information Modelling

The term City Information Model/Modelling (CIM) is commonly used to describe a city-scale digital information framework that extends building-scale information modelling concepts to the urban domain, typically by integrating geometric, semantic, and infrastructural data from multiple sources (e.g., GIS, BIM, and related urban datasets) [12], [13]. While the term is widely used in research and practice, its definition is not yet fully standardized across the field; recent standardization efforts (e.g., ISO 37187) focus primarily on CIM platforms and data exchange/sharing requirements rather than a single canonical definition of CIM itself [14]. The term is often traced to early AEC discourse, including Lachmi Khemlani's 2005 AECbytes article, with a later dedicated overview published in 2016 [12], [13].

Circular City Information Modelling (CCIM) in this work is conceived as a computational extension of 3D city models that makes building material stocks explicit and queryable at the urban scale. The objective is not only to represent buildings geometrically, but to embed them in a data structure capable of:

- Assigning construction systems (slabs, walls, roofs) according to building archetypes and vertical configuration;
- Deriving material stock quantities (volumes and masses) per building, per archetype and for the entire city; and
- Supporting the calculation of circularity indicators of each building based on its material composition and construction systems.

To achieve this, a 3D city model of buildings is coupled with core data registers (see Section 3.2) describing building archetypes, corresponding building system hierarchical breakdown, and a material catalogue with densities and categories. The result is a Python-based CCIM where each building is instantiated as an object described by:

- Geometric representation (acquired from a CityGML model);
- Typology-based element assignments (with material layer structure);
- Computed Material Quantities; and
- Computed Circularity Indicators.

## 7.1 CCIM structure

### 7.1.1 Geometric and semantic requirements

From a CCIM perspective, the geometric requirements are driven by two things at once:

1. What the material-quantity pipeline actually needs (areas, interfaces, bounding boxes); and
2. What the LoD3 modelling specification prescribes as mandatory or recommended content for buildings and their installations.

#### 7.1.1.1 Geometric requirements

At a minimum, the 3D building model must provide:

##### 1. Building solids and semantic boundary surfaces

- Each building is represented with a watertight shell whose boundary surfaces are semantically distinguished as *walls*, *roofs* and, where available, *ground* surfaces.
- Vertices are in a consistent metric system; if captured in millimetres (typical for scan-to-BIM workflows), they are rescaled to metres before area and volume computations.
- These semantic surfaces are the basis for:
  - footprint extraction (from the lowest nearly horizontal surfaces),

- wall area extraction (from vertical surfaces), and
- roof metrics (from roof surfaces).

## 2. Footprint geometry

- For each building, one or more horizontal rings of boundary vertices at the lowest Z-level are required. Rings with negligible Z-variation are treated as horizontal; the mean Z of each ring is computed, and rings whose mean Z is near the minimum are considered footprint candidates.
- These rings are projected to the XY plane and their area computed using the shoelace formula; the sum of the areas of all lowest-level rings yields the building footprint area.
- The footprint is also used to derive a bounding rectangle (for contact-wall detection and roof span) and to tie slab areas to the gross floor extent.

## 3. Wall surfaces and relation to the ground plane

- Wall faces must be explicitly represented (e.g. as *WallSurface* semantics or an equivalent encoding of vertical building envelope). For each wall patch, minimum and maximum Z and 3D surface area are required.
- A ground level per building is estimated from ground surfaces or, in their absence, from the lower envelope of vertex elevations.

## 4. Windows and doors as planar openings

- Openings in walls are modelled via a semantic hierarchy of the form:  
*Building* → *WallSurface* → *Opening* → *Window/Door*.
- Each window or door is represented as a set of planar surfaces (e.g. *MultiSurface* or *CompositeSurface*) coplanar with the host wall, i.e. as a flat polygon in the wall plane rather than as a volumetric, extruded body.
- This representation is important for future CCIM extensions (e.g. net-wall area, solid–void ratios, thermal loss approximations), even if the current material-stock pipeline does not yet subtract openings from wall areas.

## 5. Roof surfaces and 3D form

- Roofs are represented as explicit surfaces forming the upper envelope of the building shell. Individual roof planes are distinguishable by their normal vectors and can be grouped into planar clusters.
- For each roof plane, slope (angle to horizontal), area and orientation are computable from the geometry. Shared edges between planes can be identified and classified as convex or concave.
- Together with the footprint rectangle, these metrics support:
  - roof area and horizontal projection,
  - roof span (shorter side of the footprint rectangle), and
  - classification into roof types (flat, shed, gable, hip, pyramid hip, mansard, complex).

## 6. Balconies, chimneys, loggias and other building installations

The LoD3 specification requires several subordinate structures to be modelled as **Building Installations** attached to the building, each with its own geometry and role:

- **Chimneys**: modelled as separate solids or surface sets (stack, caps, vents), distinct from the roof geometry.
- **Balconies**: modelled separately from the main building shell, typically as incomplete prisms or surface sets representing slab and railing, attached semantically as balcony installations.
- **Loggias**: modelled respecting the exterior wall contour, with additional surfaces for loggia floor and railing; these are grouped semantically as loggia installations.
- **Entrance staircases**: modelled as distinct building installations; exact steps may be simplified to a ramp or prism with approximate slope, while railings are represented as separate railing installations (surface elements).

- **Fire escape stairs:** represented as bounding-box-like prisms that encompass the actual stair geometry, again as distinct building installations.

While these elements are not yet explicitly quantified in the present material-stock pipeline, their presence in the geometry is important: they affect the true extent of walls and roofs, influence potential future estimates of secondary material stocks (e.g. railing steel, balcony slabs), and provide a consistent semantic structure for expansion.

## 7. Optional structural details and simplification rules

The LoD3 specification also defines a set of **optional or conditionally required features** and simplification rules that affect how detailed the geometry must be:

- **Columns:** may be modelled as BuildingConstructiveElements or BuildingInstallations with explicit volumetric geometry.
- **Cantilevers:** overhangs less than a threshold (e.g. 1 m) may be neglected; larger overhangs should be modelled, as they influence envelope area and potential material quantities.
- **Niches:** only “deep” niches that function as lightwells spanning from ground to roof and containing windows are modelled; shallow façade recesses are ignored.
- **Canopies:** lightweight awnings and improvised small canopies may be neglected; more substantial canopy-like structures (e.g. steel-and-glass verandas or lift shafts with walls and roofs) are modelled as building installations with appropriate roles.
- **Flat roofs with overhanging parapet walls:** short wall overhangs above the roof are represented by extending wall surfaces a small distance above the roof plane (e.g. ~0.5 m), rather than as separate elaborate elements.
- **Facade ornaments:** decorative façade elements are systematically neglected to avoid unnecessary geometric complexity.

These rules strike a balance between geometric fidelity and modelling effort. For CCIM, they ensure that structurally and materially significant elements are present (and can be quantified later), while purely decorative or marginal geometries are excluded.

## 8. Treatment of deviations and typical floors

- Where buildings have typical repeated floors, deviations from the original pattern (e.g. filled-in windows, enclosed balconies) are not modelled individually from floor to floor; instead, the geometry of the “original” typical floor is repeated.
- For non-typical levels—such as ground floors, basements, recessed levels, attics—geometry is followed more faithfully, including local deviations.
- This convention ensures that the CCIM geometry reflects the typological intent of the building (which is central for archetype-based material assignment), while keeping the model tractable and internally consistent.

Taken together, these geometric requirements ensure that the city model provides all the spatial information needed to:

- Derive robust footprint areas and roof spans;
- Distinguish basement vs. above-ground wall segments;
- Approximate mutual adjacency and contact walls;
- And keep open a clear path for incorporating openings, installations and secondary elements into future material and circularity assessments.

## 7.1.1.2 Semantic requirements

Beyond geometry, the semantic organisation of the city model is critical for automatic processing. The CCIM pipeline relies on the CityGML-style semantic hierarchy to discover and classify surfaces and installations without manual intervention.

The key semantic requirements are:

### 1. Buildings, parts and installations

- Each building is represented as a **building feature** (e.g. `=G?B£#PDG?DIB`) that may be subdivided into building parts (e.g. `=G?B£#PDG?DIB1<MO`) when appropriate (e.g. complex or segmented blocks).
- Elements such as balconies, loggias, chimneys, entrance staircases, canopies, fire-escape stairs, railings and similar are modeled as **building installations** (e.g. `=G?B£#PDG?DIB*INO<GG<ODJI`) semantically attached to the building or building part.
- Installations carry a **role** or type attribute (e.g. “balcony”, “loggia”, “chimney”, “staircase”, “fire\_escape”, “canopy”) that allows the algorithm to later distinguish these elements if they are to be separately quantified.

### 2. Boundary surfaces of the building shell

- The building shell is decomposed into **boundary surfaces** such as:
  - `=G?B£8<GG4PMA<>@` (vertical envelope),
  - `=G?B£3JJA4PMA<>@` (upper envelope),
  - `=G?B£(MJPI?4PMA<>@` (contact with terrain),
  - and, optionally, other specialised surface types (e.g. `=G?B£0PO@M$@DGDIB4PMA<>@`, `=G?B£0PO@M'GJJM4PMA<>@` for overhangs and exposed slabs).
- Each boundary surface is linked to its geometry (typically a multi-surface). The classification into *wall*, *roof* and *ground* is the primary semantic key that the CCIM uses to:
  - select surfaces for wall-area computation,
  - select surfaces for roof analysis, and
  - estimate ground level and basement segmentation.

### 3. Openings: windows and doors

- Openings in walls follow a semantic hierarchy of the form:

**Building → WallSurface → Opening → Window/Door**

where:

- `=G?B£8<GG4PMA<>@` contains one or more `=G?B£JK@IDIB` elements,
- each opening references a `=G?B£8DI?JR` or `=G?B£%JJM` (subclasses of `=G?B£0K@IDIB`).
- Windows and doors are geometrically represented as planar polygons coplanar with the host wall.
- Even if net-of-openings wall areas are not yet subtracted in the current material-stock pipeline, having this hierarchy in place enables later computation of solid-void ratios, window-to-wall ratios or refined material models.

### 4. Semantic organisation of installations

- For subordinate structures, consistent semantic hierarchies are expected, for example:
  - **Building** → BuildingInstallation (role "chimney") → geometry of chimney stack and cap;

- **Building** → BuildingInstallation (role "balcony") → balcony slab and railing surfaces;
- **Building** → BuildingInstallation (role "loggia") → interior loggia floor, walls and railings;
- **Building** → BuildingInstallation (role "staircase") → entrance stair solids or surfaces;
- **Building** → BuildingInstallation (role "fire\_escape") → bounding prism of fire-escape stairs;
- **Building** → BuildingInstallation (role "canopy") → canopy roof and supports.
- This consistent semantic pattern means that, once the CCIM pipeline is extended to these elements, the algorithm can automatically collect and classify the relevant geometries based only on their installation role.

## 5. Attributes for classification and filtering

- Buildings, boundary surfaces, openings and installations may carry additional attributes (e.g. function, usage, role, lifecycle state) that can be used to:
  - filter subsets of buildings (by use or typology),
  - filter specific surfaces (e.g. only external roofs, only accessible roofs), or
  - assign alternative construction systems based on usage.
- While the current pipeline primarily uses archetype and floor-structure information from external tables, the semantic attributes in the CityGML model provide a natural extension point for more nuanced CCIM classification in future work.

In practical terms, these semantic requirements ensure that the algorithm can:

- Reliably identify *which* polygons are walls, roofs, ground or openings,
- Distinguish the main building shell from installations, and exploit the semantic hierarchy (Building → BoundarySurface → Opening / BuildingInstallation) to classify every relevant surface or mesh into the correct analytical category (slab-supporting floor, wall, roof, installation).

### 7.1.1.3 Material requirements

The material requirements specify what needs to be known about construction systems and their constituent materials so that geometry and semantics can be translated into material quantities and, ultimately, circularity indicators.

At minimum, the material datasets must provide the following.

#### 1. System / product level (slab and wall types)

As described in Section 4, each construction system (slab type, wall type, foundation, roof component, etc.) is represented by:

- **System name and family**

A human-readable name (e.g. “external wall – heavy masonry with EPS insulation”, “inter-storey slab – reinforced concrete with screed”) and its family (e.g. external wall, basement wall, contact wall, slab-on-grade, inter-storey slab, balcony slab).

This family is what the data model refers to as `NG<=αA<HDGT` (SOG, B\_slab, T\_slab, A\_slab) or `R<GGαA<HDGT` (B\_wall\_AG, B\_wall\_BG, E\_wall, A\_wall, C\_wall, P\_wall, I\_wall).

- **External / internal classification**

A flag indicating whether the system belongs to the external envelope or to the internal partitioning. This is particularly important for walls (external vs internal), but may also apply to slabs (e.g. balcony slabs vs internal floor slabs).

- **Position within the building**

A categorical field that describes where the system sits in the building (e.g. basement, above basement, above grade, attic, roof, contact with soil or neighbouring building). This position is used to align the system with:

- the level sequence derived from the floor structure, and
- the geometric segmentation of walls above/below ground.

- **Brand shearing layer classification**

An assignment of the system to one of Brand’s “shearing layers” (structure, skin, space plan, stuff). This does not affect geometry or volumes directly, but is essential for:

- distinguishing long-lived structural systems from shorter-lived finishes and services, and
- supporting future circularity indicators that depend on expected replacement cycles or adaptability.

- **Typology link (archetypes)**

A list of archetypes (e.g. B1, B2, C5 or similar) for which this system is valid. This list is what the code turns into the rule tables

(archetype,slab\_family) → SlabType, (archetype,wall\_family)→WallType.

In other words, it is the bridge between typology and construction system.

- **Assumptions and sources at system level**

Free-text fields for assumptions (e.g. “typical panelised façade system from period X”, “standard basement wall detail for this archetype”) and references to the standards, norms or atlases from which the system was derived. These ensure transparency and traceability of system definitions.

At this level, the requirement is that every slab and wall family used in the CCIM has at least one system entry, with clear archetype and position mapping. This is what allows the algorithm to automatically select the correct construction system for each slab interface and wall segment.

## 2. Layer level (material and geometry)

Below each system header, the table lists one or more layer rows that define the material build-up. For each layer, the minimum required attributes are:

- **Layer name / description**

A descriptive name (e.g. “reinforced concrete”, “hollow brick”, “external render”, “EPS insulation”, “gypsum plasterboard”).

- **Thickness**

A geometric thickness given in centimetres, which is converted to metres in the data model. This thickness, combined with areas derived from geometry, is the basis for volumetric calculations:

$$V_{\text{layer}} = A \times t_{\text{layer}}$$

- **Density [kg/m<sup>3</sup>]**

A volume mass density for the layer material. Where available, this density is taken from a material catalogue (or from the same master table) and used to convert volumes to masses:

$$M_{\text{layer}} = V_{\text{layer}} \times \rho_{\text{layer}}$$

- **Material category (primary classification)**

A categorical label linking the layer to a **material family** (e.g. concrete, clay masonry, stone, wood, metal, glass, insulation, bituminous materials, plaster, screed, etc.). This enables aggregation by

category (e.g. all concretes, all thermal insulations) and supports circularity indicators defined at category level (e.g. share of bio-based mass).

- **MIC and MIC unit (intensity coefficients)**

A Material Intensity Coefficient (MIC), typically derived from national norms and standards, with an explicit unit (e.g. kg/m<sup>2</sup>, kg/m<sup>3</sup>, kg/m per linear unit). This provides an alternative, normative route to quantity assessment, for example when accurate geometry is missing or heavily simplified:

- geometry-based route: area × thickness × density,
- MIC-based route: area × MIC (for surface-related MICs) or other compatible combinations.

The requirement is that MICs, when present, are accompanied by a unit and a reference to their source.

- **Source at layer level**

A field indicating the source of the density and/or MIC values (normative documents, technical specifications, LCA databases). This supports critical review of the underlying numbers and allows replacement or refinement as better data becomes available.

Optionally, the layer rows can also record alternative expert-defined material categories, notes on classification ambiguities and links to external classification systems (e.g. national material codes). In the current implementation, the primary category is used directly; alternative categories and notes are preserved for future refinements of the category scheme.

### 3. Waste, hazard and treatment metadata

A characteristic feature of the Excel structure is that material layers are already enriched with **end-of-life-oriented metadata**, which CCIM can leverage for circularity analysis. For each layer, the following columns are either required or highly recommended:

- **Hazardous vs non-hazardous**

An explicit tag classifying the layer (or material) as hazardous or non-hazardous from a waste-management perspective. This is important for:

- filtering hazardous fractions in material stocks,
- estimating the share of mass that requires special treatment, and
- guiding circularity indicators that penalise hazardous materials.

- **European Union List of Waste (LoW) code**

A classification code from the European List of Waste [9], specifying the expected **waste code** for the material when it enters the waste stream (e.g. concrete, brick, insulation, bituminous mixtures with or without tar, etc.).

This gives a direct link between material stocks in buildings and their regulatory waste categories, enabling:

- scenario analysis for demolition and selective dismantling,
- compatibility with waste-flow statistics, and
- integration with waste-management planning tools.

- **Possible methods and notes about selective demolition**

A qualitative description of how the layer or system can be selectively removed (e.g. detachable panels vs cast-in-place concrete, dry vs wet joints, accessibility constraints). These notes inform the feasibility and cost of recovering materials and can be used to weight circularity indices by realistic recoverability, not just theoretical recyclability.

- **Treatment options (REUSE / RECYCLE / OTHER RECOVERY / DISPOSAL)**

For each layer (or at least each system), there are fields describing **possible treatment alternatives**:

- **Alternative 1 – REUSE**: whether and how the material can be reused as is (e.g. intact bricks, timber elements, façade panels).
- **Alternative 2 – RECYCLE**: feasible recycling pathways (e.g. crushing and reusing concrete as aggregate, remelting metals).
- **Alternative 3 – OTHER RECOVERY**: suitability of the material for energy recovery (e.g. waste wood, some polymers) or backfilling if higher-order loops are not feasible.
- **Alternative 4 – DISPOSAL**: cases where only landfill or equivalent disposal is realistically possible.

These fields do not change geometric or mass calculations, but they are crucial for **interpreting** the stocks in a circularity framework: they allow each mass of material to be partitioned into theoretically and practically recoverable fractions, and to be associated with different hierarchy levels (reuse, recycle, other recovery, disposal).

#### 4. Normative and product-level data (optional but recommended)

In addition to the system and layer information, the material tables may contain normative product data, such as:

- nominal dimensions of standard products (e.g. brick sizes),
- unit volumes per piece,
- normative consumption per unit of area or volume,
- typical densities for composite products (e.g. lightweight blocks, prefabricated panels).

This data are not strictly required for the geometry-based CCIM pipeline, but they provide:

- a second, norm-based check on the plausibility of computed quantities,
- a way to estimate quantities in cases where geometry is simplified or missing (e.g. internal walls), and
- a bridge to national norms and cost-estimation practices.

## 7.1.2 Circular City data model

To keep the data model readable, it is presented in two complementary UML diagrams (Figure 7-1 and Figure 7-2). Both diagrams depict the same **Building** class, but from different viewpoints: the first focuses on the physical decomposition into elements and material definitions, while the second focuses on circularity assessment outputs (scenarios, assumptions, and indicators). Attributes and relationships that are not essential for a given viewpoint are intentionally omitted to improve clarity without changing the underlying model.

The data model describing the **core physical representation of a building** as it is needed for geometry-driven and archetype-driven material quantification is shown in Figure 7-1. The central class is #PDG?DIB, which holds identifiers (\*%, "M>C@OTK@), basic geometric descriptors (AJJOKMDIO@<M@<@HX, AGJJMN, AGJJM@NOMDIB), and address information (<??M@NN@KMDH<MT, <??M@NN@N@JOC@M). The physical envelope and attached components are represented as **instances** (@NG<=@DINO<I>@N, @R<GG@DINO<I>@N, @RDI?JR@DINO<I>@N, @?JJM@DINO<I>@N, @=<G>JIT@DINO<I>@N, @>CDHI@T@DINO<I>@N) that carry **measured quantities** (primarily areas, and for chimneys also simplified volumetric descriptors). This matches the typical workflow where the model extracts

surfaces/parts from CityGML/CityJSON, classifies them into element groups, and stores the resulting quantities as instances.

A key design choice is the separation between **element instances** (e.g., 8<GG, 8DI?JR) and their **type definitions** (e.g., 8<GG5TK@, 8DI?JR5TK@). The “Type” classes capture the *repeatable construction logic*: layered build-ups (G<T@MN), total thickness, family keys (e.g., R<GG?A<HDGT, RDI?JR?A<HDGT), and mapping hooks (<M>C@OTK@?F@TN, KJNDODJI?F@T) that allow one type definition to be reused across many buildings or many elements. This keeps the building instances lightweight and makes it possible to maintain a consistent library of constructions (e.g., typical façade build-ups for a given archetype) while still storing geometry-derived quantities at the instance level.

Material description is kept intentionally generic via .<O@MD<G and -<T@M. Each -<T@M binds a .<O@MD<G to a thickness and optionally a MIC indicator (HD>?Q<GP@, HD>?PIDO) to support cases where full layering is unknown and quantity estimation uses intensities instead of explicit geometry-derived volumes. With this structure, material quantities can be computed in a consistent way across element types: (a) **layer-based** volume/mass (area × thickness × density) when thickness and density are known, and (b) **MIC-based** estimation when only intensity factors are available. This physical model view therefore provides the necessary backbone for producing a per-building material inventory that later feeds circularity assessment.

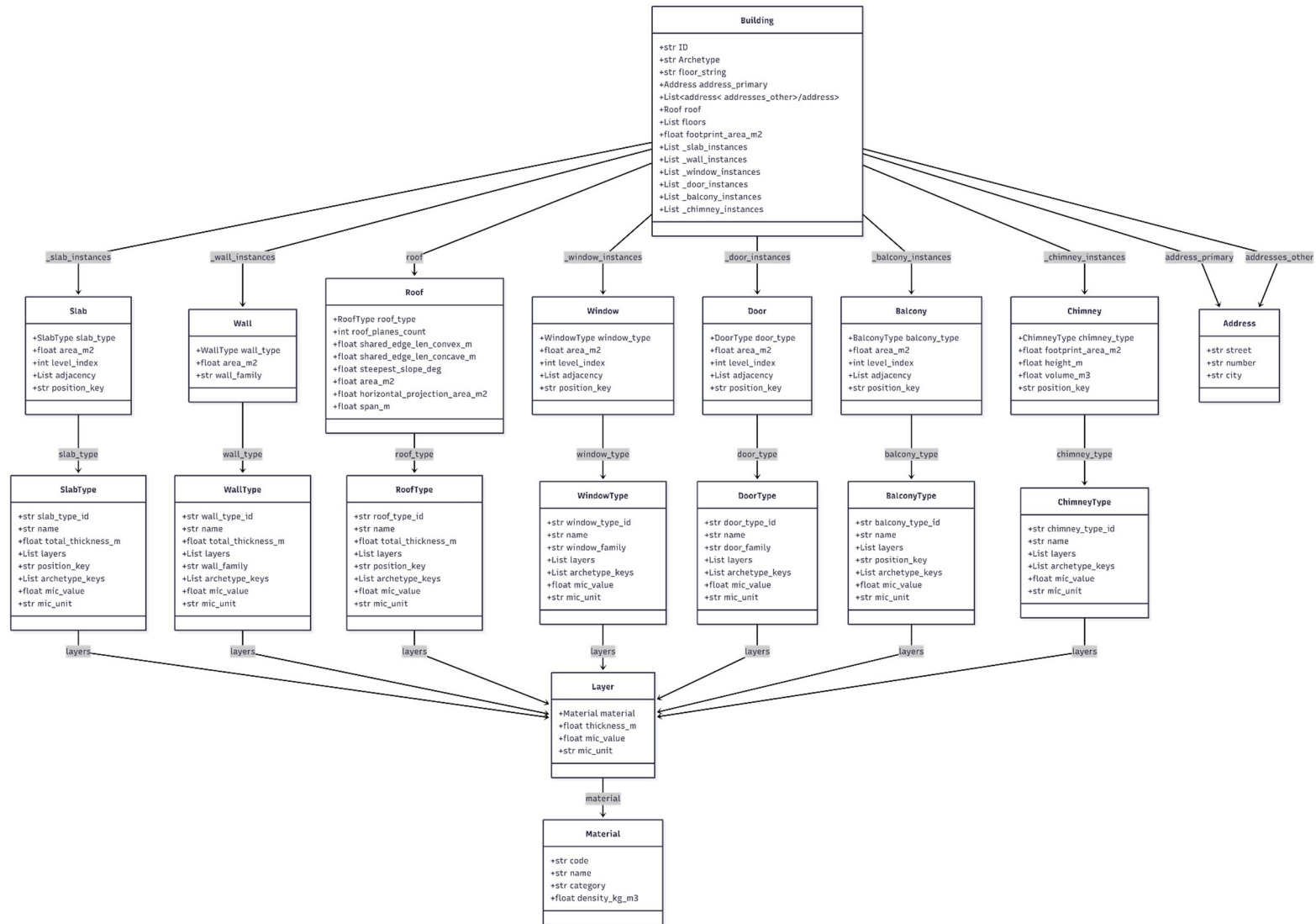


Figure 7-1 The building physical model view (UML)

Building decomposed into element instances (slabs, walls, roof, windows, doors, balconies, chimneys) linked to reusable type definitions and layered materials (Material–Layer) for quantity take-off.

Circularity-related outputs are attached to a building in a way that is **comparable, repeatable, and transparent about assumptions**, as shown in Figure 7-2. The core idea is that circularity metrics are not just single values; they are results of an “assessment run” captured by `$DM>PG<MDOT"NN@NNH@IO`, which stores metadata such as calculation provenance (`<NN@NNH@IO&D?`, timestamps, model/version tags) and a set of scenario-dependent results (`N>@I<MDJ&M@NPGON`). This makes the assessment reproducible and allows the building to hold multiple evaluation runs over time if the input data or methods evolve.

Each `4>@I<MDJ"NN@NNH@IO3@NPGO` represents the circularity performance of a building under a specific **EoL scenario** (`&J-4>@I<MDJ`) and a specific **treatment assumption set** (`5M@<OH@IO"NNPHKODJI4@O`). This structure supports the common need to compare, for example, “renovation vs. traditional demolition” and “pessimistic vs. optimistic sorting/treatment shares”, without overwriting results or losing the context required to interpret them. The scenario result stores both (1) a flexible list of computed indicators (`DI?D><OJM&Q<GP@N`) and (2) a small set of “high-signal” aggregated fields (e.g., total CDW mass, waste intensity, reuse/recycling potentials, WDR, and constraint indicators like R-score, D-score, hazardous share). The “explicit fields + generic list” pattern keeps the model readable for key outputs while still allowing you to extend the indicator catalog without breaking the schema.

Finally, `*I?D><OJM%ADIDODJI + *I?D><OJM7<GP@` provide a scalable way to manage a growing catalog of circularity indicators. Definitions capture semantics (name, unit, class/group, scope level, version), while values store the numeric outputs and—optionally—where they apply (`N>JK@&G@Q@G` and `N>JK@&M@A&D?`). That optional scoping is important because it lets you keep the *building-level* result view clean while still enabling drill-down later (e.g., an indicator value tied to a specific wall type, window type, or material stream). In combination, this circularity assessment model turns raw material inventories into well-structured, scenario-aware indicators that can be compared across buildings, neighborhoods, and cities.

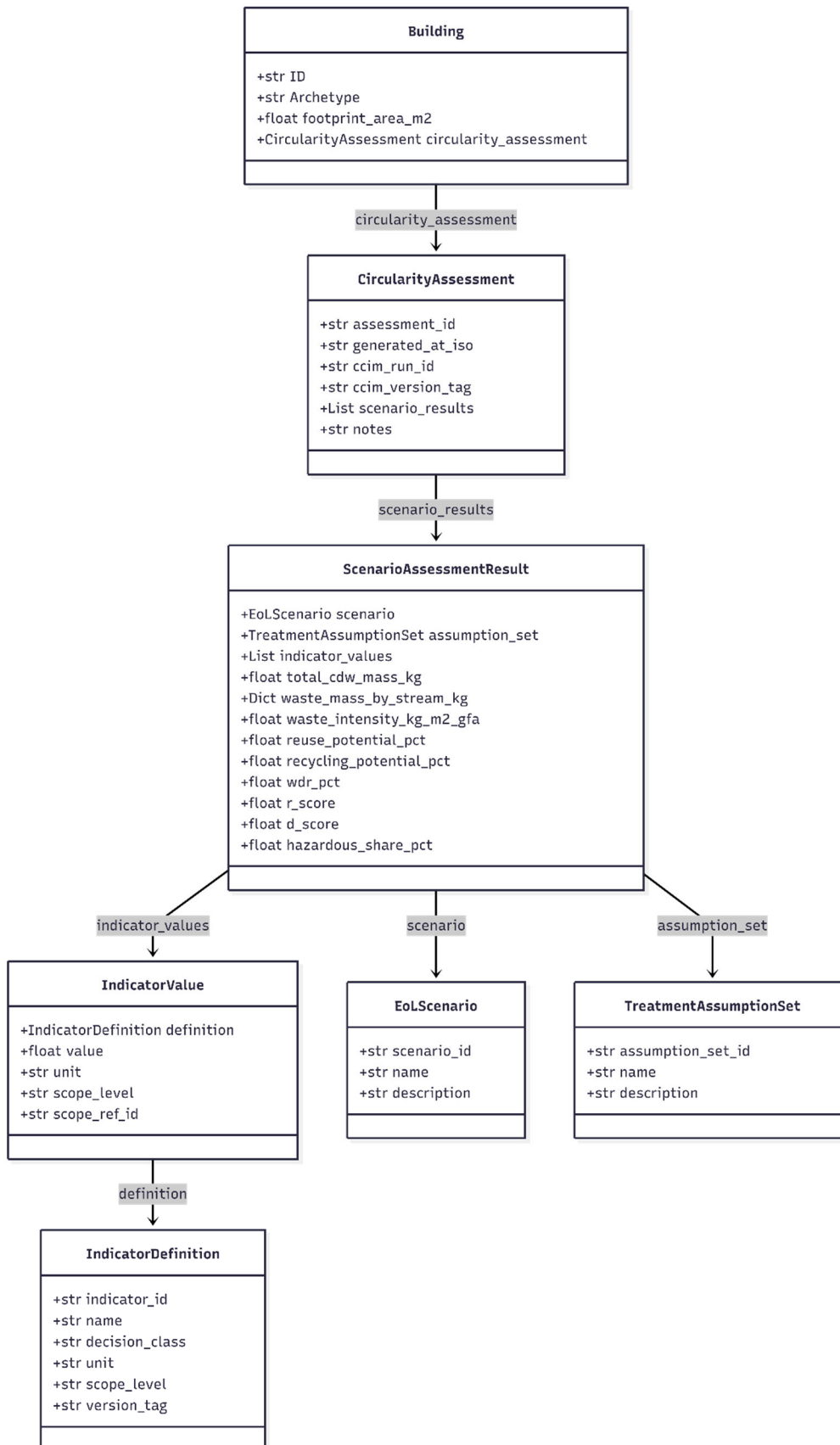


Figure 7-2 Building circularity assessment view (UML)

Building linked to CircularityAssessment, storing indicator results by end-of-life scenario and treatment assumptions via ScenarioAssessmentResult and IndicatorDefinition/Value.

# 8 Framework for the CE passport

This chapter defines the framework, data model, and template of the CE passport generated for individual buildings within the CE Map. The passport is produced from the semantically enriched CityGML building object, the linked CE data registers, and CCIM outputs, ensuring that all reported values remain traceable to the underlying data backbone. The chapter specifies how passport information is structured and updated so that outputs are comparable across buildings and can be regenerated consistently when datasets or assumptions are refined.

## 8.1 CE passport concept and background

### 8.1.1 What the CE passport is

The CE passport is a standardised, building-level digital record designed to support circular economy assessment and end-of-life decision-making for the existing building stock. Within the CE Map workflow, the passport serves as a harmonised reporting output that consolidates, for a single building, (i) building identification and contextual attributes, (ii) a quantified material inventory, (iii) feasible recovery and treatment pathways (reuse, recycling, other recovery, disposal) with relevant prerequisites, and (iv) CDW/CE indicator results under explicitly defined scenarios. In this sense, the CE passport operationalises the building-as-a-material-bank concept by translating heterogeneous datasets into a single, comparable building record. The passport is not a new data source. It is a generated output produced from the semantically enriched CityGML model, the linked CE registers, and CCIM-derived quantities and results. This is important because it keeps the passport consistent with the underlying datasets and enables comparable outputs across buildings.

### 8.1.2 Scope and boundaries

#### Scope and boundaries

The CE passport in this guidebook is defined for building-stock-scale applications, meaning that it must be applicable to large numbers of existing buildings represented in the CE Map. In this context, building-specific product documentation (e.g. manufacturer and product identifiers, detailed as-built component records) is typically not available in a consistent manner across the stock. The passport therefore relies on CityGML-based geometry combined with typology-based definitions of building elements and material layers, enabling consistent material quantification and indicator assessment across all buildings.

The passport is explicitly scoped to the EoL phase and to intervention-based EoL scenarios, namely (PR) Partial renovation, (MR) Major refurbishment, and (D) Demolition. These scenarios define waste generation through typology-based removal coefficients, while recovery outcomes are assessed separately through treatment pathway assumptions. The passport focuses on material quantities, feasible recovery routes, and CDW/CE indicators that describe waste generation and recovery performance under clearly defined assumptions.

The CE passport has clear boundaries to avoid over-interpretation:

- **It is not an as-built dossier** and does not replace detailed building documentation, BIM models, or regulatory compliance files.
- **It does not guarantee reuse or recycling outcomes.** It reports feasibility and prerequisites based on structured recovery knowledge, while actual implementation requires project-specific checks and compliance procedures.
- **Its accuracy depends on the available level of detail.** Where geometry and building-specific data are limited, quantities and constraints are derived from typology-based assumptions. Such

cases must be flagged through provenance and data-quality fields so users can correctly interpret the results.

In the CE Map workflow, EoL scenarios (PR/MR/D) control waste generation through typology-based removal coefficients, while the pessimistic/optimistic assumption sets represent differences in treatment routing (e.g. conventional practice versus selective dismantling and enhanced sorting).

### 8.1.3 Core principle: linking quantification with actionability

A core design objective is to connect quantification with actionability. Quantification means that the passport reports explicit material quantities (mass and/or volume) derived through CCIM, structured by building, element, layer, and material. Actionability means that these quantities are directly linked to what stakeholders must decide at EoL: which routes are feasible (reuse, recycling, other recovery, disposal), what conditions can prevent those routes (e.g., contamination, coatings, hazardous substances), and what checks are required before reuse or recycling can be recommended. The indicator results then provide the decision context by showing how alternative EoL choices (renovation, selective deconstruction, conventional demolition) and treatment assumptions (pessimistic vs optimistic) change expected waste generation and achievable recovery.

### 8.1.4 Relation to digital building logbook principles

The CE passport is aligned with the main functional expectations of digital building logbook approaches [14], without requiring the same level of product documentation for every existing building. The alignment is achieved through operational features built into the CE Map data backbone:

- **Traceability and provenance:** every passport references the versions of the underlying datasets and indicates whether values are geometry-derived or typology-derived.
- **Interoperability:** the passport is anchored to a CityGML building object and uses stable identifiers (e.g., `building_id` and `gml_id`) to enable consistent joins between the 3D model, the registers, and computed outputs.
- **Updatability:** the passport is designed to be regenerated when registers, assumptions, or indicator definitions evolve, avoiding manual “drift” between data and reported results.
- **Comparability:** standardised fields, units, and classification logic make results comparable across buildings and across replication contexts.

In short, the passport operationalises logbook-like requirements in a building-stock modelling setting: it prioritises consistent structure, clear provenance, and repeatable generation over exhaustive product documentation.

### 8.1.5 How to interpret results

Because the CE passport is designed for decision support, its results must be interpreted using the following principles:

1. **Waste generation is scenario-driven.** The share of materials becoming waste is determined by the selected EoL intervention scenario—(PR) Partial renovation, (MR) Major refurbishment, or (D) Demolition—through typology-based removal coefficients. A passport value is therefore meaningful only when interpreted together with the corresponding EoL scenario label (PR/MR/D).
2. **Recovery performance is practice-driven.** Recovery performance depends on the selected treatment assumption (pessimistic vs optimistic) and the associated treatment share. The pessimistic assumptions represent typical or current waste-management practice, while optimistic assumptions represent enhanced circular practice enabled by better sorting, selective dismantling, and improved recovery infrastructure.

- 3. Constraints explain limits, not just scores.** Constraint indicators (e.g. hazardous material share, recoverability or deconstructibility proxies) are used to explain why high recovery shares may not be achievable in practice for certain buildings or material streams. Their role is interpretive rather than generative, clarifying the boundary between theoretical circular potential and realistic implementation conditions.

Making these interpretation rules explicit prevents common misuse, such as comparing results derived under different assumptions, treating a single indicator as an absolute truth, or overlooking the prerequisites required to achieve improved recovery outcomes.

### 8.1.6 Lifecycle of the passport

The CE passport is treated as a reproducible snapshot of the CE Map pipeline at a given point in time. Each passport must record the input dataset versions (CityGML and the three registers) and the computational run context (CCIM version/run), so the output can be reproduced and audited. When any relevant input changes—register updates, revised material parameters, new recovery rules, or updated indicator definitions—the passport should not be edited manually; it should be regenerated from the updated backbone to avoid inconsistencies between reported results and their source data.

The passport is standardised yet extensible. A fixed core dataset is generated for every building to ensure comparability and scalable updates, while optional extensions can be added when higher-resolution inputs are available and decision-relevant (e.g., product documentation or environmental declarations). Extensions enrich the same structure without changing the core template, so comparability across the building stock is preserved over time.

## 8.2 CE passport data model

This section defines the CE passport data model and the reporting template used in the CE Map. The data model specifies which entities and identifiers are used, how information is organised hierarchically, and how quantities, recovery guidance, and indicator results are stored so that passports can be generated consistently for many buildings and compared across a building stock.

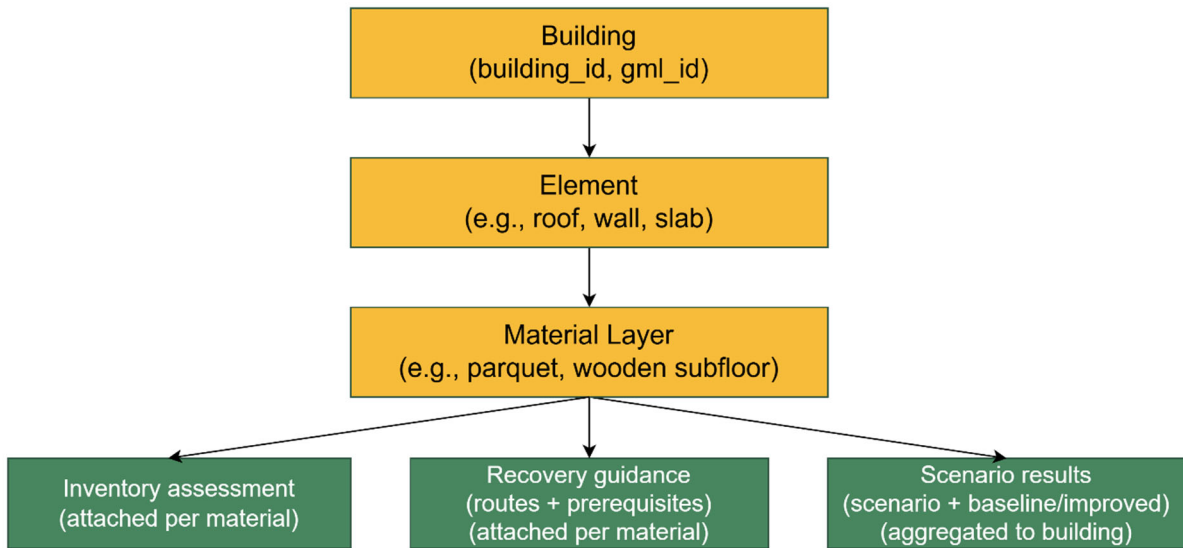
### 8.2.1 Data entities and hierarchy

The CE passport stores material-related information in a hierarchy (*Figure 8-1***Error! Reference source not found.**) that reflects how quantities and indicators are computed:

Building → Element → Material Layer

This hierarchy is required for three concrete reasons:

- **Quantity assessment** is performed per material (volume and mass) and then aggregated to layer, element, and building totals.
- **Recovery feasibility and prerequisites** are defined for specific material streams and are therefore stored per material entry.
- **Indicator modelling** applies scenarios and treatment assumptions at material level and then aggregates results upward without changing those assumptions.



*Key rule: Scenarios and treatment assumptions are applied at material layer level and aggregated upward.*

*Figure 8-1 CE passport hierarchy and attachment of recovery guidance and scenario results*

## 8.2.2 Proposed passport structure

The passport is divided into sections (A-F) to keep it easy to navigate. Each section answers a practical question and corresponds to a part of the data pipeline: A and B ensure identification, traceability and basic building context; C documents the embedded material stock (“what is in the building”); D summarises feasible end-of-life routes and prerequisites (“what can be done with it”); E reports CDW and CE indicators under defined scenarios (“what the outcomes look like”); and F provides optional evidence and exportable tables. A short Dashboard is placed at the very beginning of the document where the users can find the “key message” while details come later in A-F sections. This separation makes the passport readable for non-experts while maintaining a consistent hierarchy for calculations and aggregation.

### 0. Passport dashboard

- building\_id, gml\_id, location, GFA
- key totals (mass/volume), top material categories
- headline results (WDR, reuse/recycling potential) per scenario (pessimistic/optimistic)
- key constraints + data quality flag

### A. Passport metadata and provenance

- passport\_id, generation date/time
- data versions: CityGML dataset; Register 1/2/3 versions; CCIM run\_id + CCIM version tag
- data sources and quality flags: geometry-derived vs typology-based
- indicator/scenario set reference (so results remain comparable over time)
- units and reference systems (default units; CRS if spatial exports are used)

### B. Building profile (CityGML + inventory register)

- building\_id and gml\_id
- location (address/coordinates, administrative area)

- basic geometry: LoD, footprint, height, storeys, gross floor area
- typology: construction period/year, use type, structural system/archetype

### C. Material inventory (CCIM outputs)

- summary totals: total mass/volume; totals by material category and by system (if you use “system”)
- detailed breakdown: **element** → **layer** → **material**
- for each layer/material: thickness + density/MIC reference + calculated volume/mass
- mapping to waste/material categories (and LoW codes)

### D. Recovery and treatment recommendations (resource recovery register)

- per relevant material (optionally grouped by element): reuse/recycling/other recovery /disposal feasibility
- recommended pathway order (Reuse > Recycle > Other recovery > Disposal)
- prerequisites and required on-site/lab testing
- required-checks status (required / not required / unknown) to prevent over-interpretation

### E. CDW & CE indicator results (indicator register outputs)

- results stored as **scenario blocks**: (scenario = PR / MR / D) × (assumption set = pessimistic / optimistic)
- waste quantities, waste composition, waste intensity
- reuse/recycling potential and WDR
- constraint indicators (recoverability/deconstructibility scores, hazardous share/class)
- optional time-dependent waste flows if a dynamic stock model is coupled
- (optional export) element-level or material-level results if you want drill-down in CE Map

### F. Appendices and links

- detailed tables exported as CSV/JSON (with file naming convention)
- links to source documents, BIM/IFC models (if available), and supporting evidence
- glossary / definitions (WDR, scenarios, pessimistic/optimistic, MIC, LoD)

## 8.2.3 Proposed data tree structure

The CE passport data tree defines the logical organisation of passport information, independent of its visual presentation in the CE Map or exported reports. It distinguishes between a dashboard view (Section 0 - Passport dashboard), which provides a concise overview for screening and comparison, and the underlying structured data modules (A–F), which store the complete set of information required for traceability, aggregation, and reuse.

Some fields in the CE passport data model are defined as optional and are populated only when reliable and building-specific data are available. This applies in particular to product-level identification, detailed material properties, condition and defect information, disassembly parameters, and extended indicator sets. When such data are not available at building-stock scale, the corresponding fields remain empty or

are flagged accordingly, while the core passport structure and comparability across buildings are preserved. The following Figure 8-2 illustrates the logical structure of the CE passport data model.

The figure shows the dashboard view (Section 0 - Passport dashboard) and the underlying CE passport modules (A-F), including the hierarchy used to store material inventory and scenario-based indicator results.

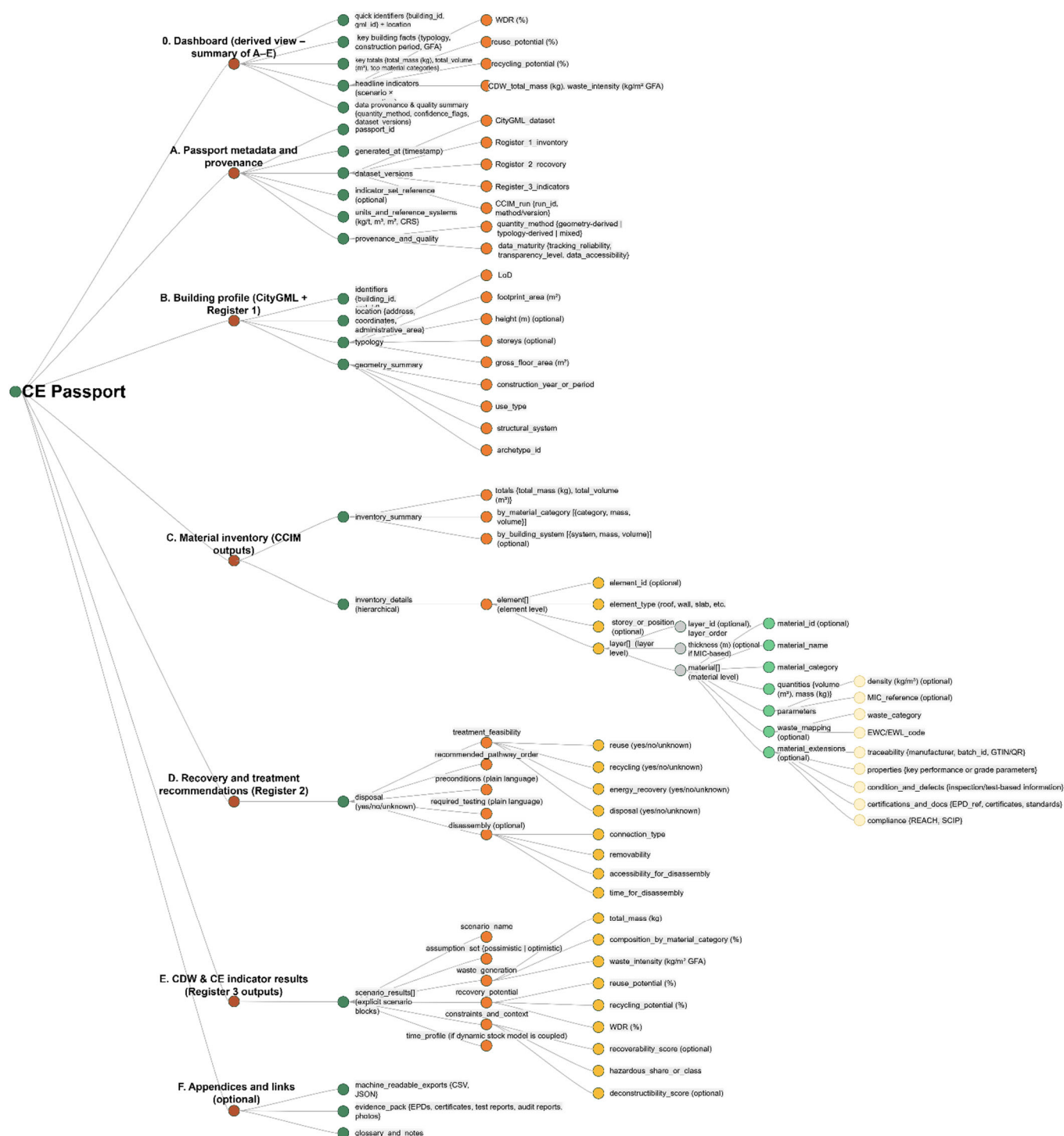


Figure 8-2 CE passport data tree (logical structure for one building)

## 8.3 Output formats and interoperability

The same data model should be exported in two aligned formats:

- Human-readable report (PDF/HTML): Modules A–F + 0 - Dashboard with summaries first and drill-down tables after.
- Machine-readable export (JSON/CSV): the same fields in a strict schema following Building → Element → Material Layer, plus scenario blocks.

# 9 Conclusions

Deliverable D4.2 provides an implementation-oriented guide for structuring CE data to support the development and use of the 3D web-based CE Map. This guidebook is based on a semantically enriched CityGML building stock model as the core input, which provides the geometric and semantic reference for circular economy assessment at building-stock scale.

The guidebook defines a coherent data backbone composed of three linked registers—(i) Inventory registers (comprising the Building stock register and the Building stock inventory data register), (ii) the Resource recovery data register, and (iii) the CDW & CE indicators register—and explains how these datasets are structured, linked through stable identifiers, and integrated through the CCIM for scenario-based end-of-life assessment. In this workflow, CityGML LoD3 provides the spatial and semantic foundation, while CCIM acts as a computational layer that derives material quantities and hierarchical aggregations from the enriched CityGML model using typology-based rules and material parameters.

By formalising the data logic from building geometry and typology-driven inventories to recovery guidance and scenario-based indicator assessment, D4.2 ensures that CE-related information remains traceable, comparable, and reproducible across buildings and aggregation levels. The defined hierarchy (building–element–layer–material) and the consistent application of end-of-life scenarios and treatment assumptions at material level provide a transparent basis for aggregating results to building, neighbourhood, and city scale within the CE Map.

The guidebook also defines standardised building-level outputs derived from the CE Map data backbone, including the CE passport as a structured reporting view. These outputs are generated automatically from the underlying datasets and serve to support interpretation, communication, and data reuse, without introducing additional data silos or manual data handling.

By distinguishing between core data requirements necessary for consistent building-stock-scale implementation and optional fields that depend on the availability of reliable, building-specific information, D4.2 explicitly addresses common data constraints while enabling progressive enrichment over time. The clear separation between fixed framework elements (data logic, identifiers, hierarchies, and indicator structures) and context-specific adaptations (typologies, classification mappings, and scenario parameters) supports replication of the CE Map approach beyond the CIRC-BOOST pilots and facilitates its application in other cities and national contexts.

## **Methodological note**

*The methodology, data structures, and scenario logic presented in this document reflect the current stage of development of the CE Map within WP4 of the CIRC-BOOST project. As the project progresses and additional datasets, validation results, or stakeholder inputs become available, selected modelling parameters may be refined or further specified. Such refinements will not alter the core conceptual framework but may improve accuracy, regional adaptability, and practical applicability.*

# 10 References

- [1] Open Geospatial Consortium, “OGC City Geography Markup Language (CityGML) Encoding Standard,” 2012.
- [2] D. I. A. R. A. R. L. Đ. N. Ć. I. M. N. Milica Jovanović Popović, “National Typology of Residential Buildings in Serbia,” Faculty of Architecture, University of Belgrade; GIZ – Deutsche Gesellschaft für Internationale Zusammenarbeit, Belgrade, 2013.
- [3] D. I. A. R. A. R. L. Đ. N. Ć. I. M. N. Milica Jovanović Popović, “Atlas of Family Housing in Serbia,” Faculty of Architecture, University of Belgrade; GIZ – Deutsche Gesellschaft für Internationale Zusammenarbeit, Belgrade, 2013.
- [4] S. Brand, *How Buildings Learn: What Happens After They’re Built*, New York: Penguin Books, 1995.
- [5] “Facilitating the circulation of reclaimed building elements in Northwestern Europe,” 2021.
- [6] “Skills4Reuse,” Nordic Sustainable Construction, 2024. [Online]. Available: <https://www.en.skills4reuse.com/>. [Accessed 19 01 2024].
- [7] V. K. U. Venkrbec, “Suitability of recycled concrete aggregates from precast panel buildings deconstructed at expired lifespan for structural use,” *Journal of Cleaner Production*, vol. 247, no. 119593, 2020.
- [8] C. B. N. F. C. Kűpfer, “Reuse of cut concrete slabs in new buildings for circular ultra-low-carbon floor designs,” *Journal of Cleaner Production*, vol. 448, no. 141566, 2024.
- [9] “Commission Decision 2000/532/EC on the List of Waste (LoW) amended by Commission Decision 2014/955/EU and Annex III of the Waste Framework Directive 2008/98/EC (WFD), amended by regulation 1357/2014, consolidated in 2023,” Official Journal of the European Communities, 2023.
- [10] “Reuse of Clay Brickwork General Guide,” 2023.
- [11] E. S. B. M. M. M. Islam Atta, “Digitizing material passport for sustainable construction projects using BIM,” *Journal of Building Engineering*, vol. 43, no. 103233, 2021.
- [12] L. Khemlani, “Hurricanes and their Aftermath: How Can Technology Help?,” AECbytes, 2005.
- [13] L. Khemlani, “City Information Modeling,” AECbytes, 2016.
- [14] “Smart community infrastructures --- Guidance on data exchange and sharing of city information modelling platform,” ISO, Geneva, 2026.

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