MSc thesis in Geomatics

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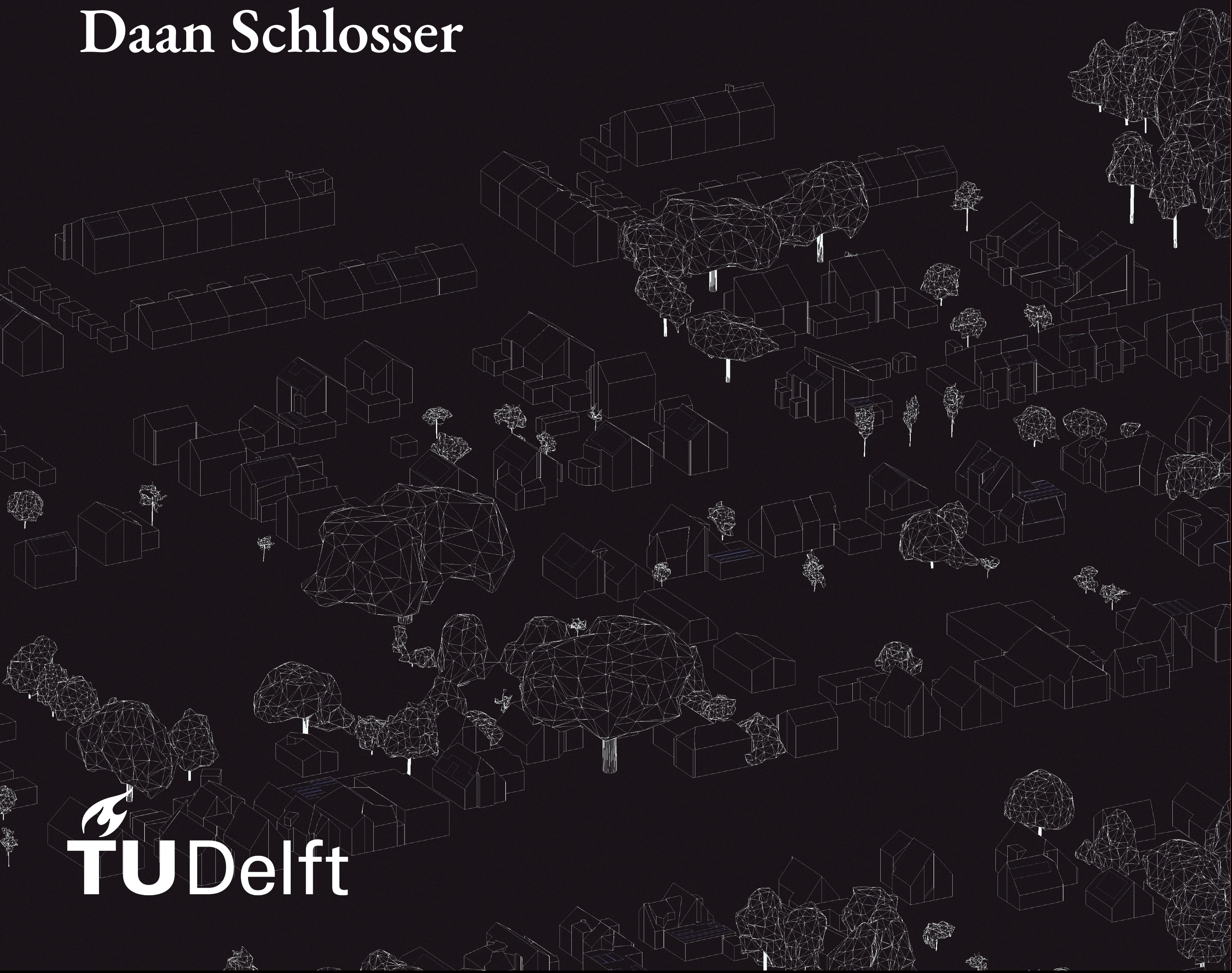
Investigation on the data model requirements for Building Renovation Passports

Daan Schlosser



TU Delft

MSc thesis in Geomatics

Investigation on the data model requirements for Building Renovation Passports

Daan Schlosser

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A thesis submitted to the Delft University of Technology in partial fulfillment of the requirements for the degree of Master of Science in Geomatics

Daan Schlosser: *Investigation on the data model requirements for Building Renovation Passports* (2026)

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Abstract

Reaching the European Union's 2050 climate targets depends on renovating a building stock that accounts for roughly 40% of EU energy use and 36% of energy-related greenhouse-gas emissions. Renovation is a staged, multi-year process that the Energy Performance Certificate, a single-point-in-time snapshot, cannot guide on its own. The recast Energy Performance of Buildings Directive answers this with two complementary instruments. The Digital Building Logbook is a repository for building data across the life cycle, and the Building Renovation Passport (BRP) is a stepwise renovation roadmap that draws on that data. Both depend on a data model that defines what building data is relevant and stores it in a reusable form. The data models proposed by existing BRP and logbook initiatives are mostly closed, or specified only as semi-structured Excel, so their coverage and completeness cannot be assessed and each new implementation starts its data modelling from scratch.

An open, formally specified geospatial data model for urban energy modelling already exists adjacent to this use case, the OGC City Geography Markup Language (CityGML) paired with its Energy Application Domain Extension (Energy ADE). Whether it is sufficient as a BRP data model has not been tested. This thesis tests it. It first synthesises a Minimum Set of Required Data (MSRD) from 14 existing and proposed European initiatives, distilling their recurring fields through an explicit relevance filter into a reference set of attributes a BRP needs. It then assesses how much of that MSRD the CityGML 2.0 + Energy ADE 3.0 (beta 8) data model can carry, mapping the set field by field, and tests the mapping at two scales on real Dutch building-stock data. The first is an audit-depth test on a single owner-occupier dwelling. The second is a city-scale breadth test on an entire municipality populated from open government sources (BAG, 3DBAG, EP-Online, and CBS statistics).

The MSRD comprises 276 fields, organised into 13 modules and 3 layers. The current CityGML + Energy ADE 3.0 (beta 8) data model covers roughly 95% of it, 262 of the 276 fields, with coverage complete for 8 of the 13 modules, including the entire assessment layer. The 14 uncovered fields are localised rather than spread across the model, most of them concentrated in the renovation-advice module, the staged roadmap that is the BRP's defining feature, where coverage falls to 73%. The two-scale implementation confirms that the mapping holds under real data: the schema produced XSD-valid output from the single audited dwelling up to roughly 94,000 buildings without structural failure. Bringing the Dutch open-data sources together in one model also did more than confirm fit. It made the data-quality problems of that stock visible and tractable, exposing patterns that the source datasets, read apart, do not reveal, and it located the situations the model carries only partially.

The CityGML + Energy ADE pairing is therefore a meaningful, strong, and near-complete starting point for a BRP data model, with the gaps localised rather than structural. The contribution is to show that an open, formally specified data model already covers most of what a BRP needs, to name precisely where it does not, and to consolidate the targeted extensions that would close those gaps as input to the further development of the Energy ADE. The MSRD and the two-scale test pipeline are released openly.

Keywords: *Building Renovation Passport, Digital Building Logbook, EPBD, CityGML, Energy ADE, data model, Minimum Set of Required Data, coverage mapping, Dutch building stock.*

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I would also like to thank the owner-occupier of the reference building I used, who very kindly invited me into his house, answered all my questions, and handed me all the data I could ask for to model his house as accurately as possible. For privacy reasons, I will not name him here, but without his help the individual building test case would not have been possible.

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My thanks also to Andreas Geiger, the developer of the KITModelViewer at the Karlsruhe Institute of Technology (KIT), who swiftly fixed the bugs I reported and was very kind in sending an updated build.

Finally, I would like to thank my friend Sten Kotten for his help in designing the front cover of this thesis.

Daan Schlosser
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Contents

List of abbreviations

Abbreviation	Expansion
3DBAG	3D *Basisregistratie Adressen en Gebouwen* (3D version of the BAG)
ADE	Application Domain Extension
API	Application Programming Interface
BAG	*Basisregistratie Adressen en Gebouwen* (Key Register of Addresses and Buildings)
BGT	*Basisregistratie Grootschalige Topografie* (Key Register of Large-scale Topography)
BIM	Building Information Modelling
BRP	Building Renovation Passport
CBS	*Centraal Bureau voor de Statistiek* (Statistics Netherlands)
CityGML	City Geography Markup Language
CityJSON	JSON encoding of the CityGML data model
DBL	Digital Building Logbook
EP-Online	Dutch national EPC and energy-label register, operated by RVO
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
EPSG	Coordinate reference system identifier (e.g. EPSG:28992, the Dutch national grid)
EU	European Union
GML	Geography Markup Language
IFC	Industry Foundation Classes
INSPIRE	Infrastructure for Spatial Information in Europe
JSON	JavaScript Object Notation
LoD	Level of Detail
LVG	*Landelijke Voorziening Gebouwgegevens* (National Building-Data Service)
MSRD	Minimum Set of Required Data
NAP	*Normaal Amsterdams Peil* (Amsterdam Ordnance Datum)
NTA	*Nederlandse Technische Afspraak* (Dutch energy-performance calculation standard)
OGC	Open Geospatial Consortium
PC6	Postcode-6 (Dutch six-character postcode area)
PDOK	*Publieke Dienstverlening Op de Kaart* (Public Services on the Map)
PV	Photovoltaic
RVO	*Rijksdienst voor Ondernemend Nederland* (Dutch Enterprise Agency)
SIG 3D	Special Interest Group 3D (CityGML standards working group)
SRI	Smart Readiness Indicator
UML	Unified Modeling Language
WFS	Web Feature Service (OGC standard for serving vector geodata)
XML	Extensible Markup Language
XSD	XML Schema Definition

Table 1: Recurring abbreviations and acronyms used throughout this thesis. Italics denote Dutch-language terms.

Glossary of Dutch terms

Dutch term	**English translation and/or explanation**
Basisregistratie Adressen en Gebouwen (BAG)	Key Register of Addresses and Buildings
Basisregistratie Grootschalige Topografie (BGT)	Key Register of Large-scale Topography
Centraal Bureau voor de Statistiek (CBS)	Statistics Netherlands
Federatief Datastelsel (FDS)	Federated Data System
Gebouwrenovatiepaspoort	Dutch Building Renovation Passport
Kadaster	Dutch Land Registry
Landelijke Voorziening Gebouwgegevens (LVG)	National Building-Data Service
Maatwerkadvies	Building-specific renovation advice
MijnOverheid	Dutch government's citizen-facing personal portal
Pand / panden	BAG building footprint / premises
Verblijfsobject / verblijfsobjecten	BAG legal usable-area unit / residence-object

Table 2: Recurring Dutch terms with English translations and, where appropriate, brief contextual notes. Italics denote Dutch-language terms; for institutional acronyms, see Table 1.

1. Introduction

1.1. Problem statement

Climate change and its consequences represent one of the most pressing global challenges, primarily driven by greenhouse gas (GHG) emissions [1]. The scientific consensus, established by the Intergovernmental Panel on Climate Change (IPCC), concludes that limiting global warming to 1.5 °C above pre-industrial levels is essential to avoid catastrophic climate impacts [2]. Beyond this threshold, the world faces dramatically increased risks to health, livelihoods, food security, water supply, and economic stability [1]. In response, the European Union (EU) has, through the European Climate Law (Regulation (EU) 2021/1119), legally committed to reducing net GHG emissions to zero by 2050, with an intermediate target of a 55% reduction relative to 1990 by 2030 [3].

The built environment is one of the largest contributors to this problem. In the EU, buildings account for approximately 40% of total energy consumption, over half of gas consumption, and 36% of energy-related GHG emissions [4], with residential buildings alone accounting for 26% of final energy consumption [5]. This stems from the poor energy performance of the existing building stock. About 75% of the EU building stock is energy-inefficient, 85% was constructed before 2001, and 85 to 95% of today's buildings will still be standing and in use in 2050 [6]. Achieving the EU climate goals therefore requires a substantial volume of building renovation. That renovation, however, is proceeding too slowly. Fabbri et al. [7] estimate that the current EU annual renovation rate of about 1.2% must increase to 2 to 3% per year to meet the 2050 objectives. Closing that gap, in turn, requires instruments that guide renovation across multi-year, multi-stage journeys, not only instruments that disclose performance at a single point in time.

The EU's principal existing instrument for disclosing a building's energy performance is the Energy Performance Certificate (EPC), introduced through the original Energy Performance of Buildings Directive (EPBD) in 2002 [8]. An EPC is a regulatory snapshot of a building's current energy performance, issued at construction, sale, letting, or major renovation, with a maximum validity of 10 years (Art. 20(1) and 19(13) of the 2024 recast) [4]. As a renovation handbook, however, the EPC has clear limitations. It does not track changes over time. Although the recast EPBD requires EPCs to include recommendations for cost-effective improvements (Art. 19(5)) [4], those recommendations remain generic, are not delivered as a sequenced roadmap, and do not capture the information dependencies between successive measures. The certificate therefore leaves open the question of how to act on its findings, which measures to take, in which order, and with which information dependencies between them [7, 9].

In response to these limitations, and to bridge the information gaps across the renovation process, the EU has introduced two complementary instruments, the Digital Building Logbook (DBL) and the Building Renovation Passport (BRP). A DBL is a common repository for all relevant building data throughout a building's life cycle, including its energy performance certificate, BRP, smart-readiness indicator (SRI), and lifecycle global warming potential data [4, 10]. Its stated aim is to facilitate transparency, trust, informed decision-making, and information sharing across the parties involved in a building's life cycle. Those parties include the construction sector, building owners and occupants, financial institutions, and public authorities

[10]. DBLs were introduced in 2020 within the EU Renovation Wave Strategy [6] and given a formal definition in the 2024 EPBD recast (Directive (EU) 2024/1275, Art. 2(41)) [4].

A BRP, in turn, is a tailored roadmap for the deep renovation of a specific building in a maximum number of steps (Art. 2(19)), intended to draw on the building data that a DBL is meant to hold. BRPs were introduced in 2024 through the EPBD recast (Article 12) as a voluntary scheme that Member States must make available by May 29, 2026, and may also make mandatory at the national level [4].

The DBL and the BRP are designed to complement, not replace, the EPC. The DBL extends the EPC by holding EPCs, BRPs, and building data in a single repository across the building's life cycle, addressing the EPC's lack of continuity over time. The BRP extends it forward in time, translating the EPC's static performance into a sequenced, customised renovation roadmap with information dependencies between successive stages made explicit, addressing the EPC's lack of a roadmap. The EPBD ties the three instruments together explicitly. A BRP must consider the EPC's information as its starting point (Annex VIII §3), and when issued jointly with the EPC it substitutes the EPC's standalone renovation recommendations (Art. 19(6)). The BRP is to be stored in or accessible via the DBL where one is available (Art. 12(8)) [4]. The added value of combining the three instruments is therefore not a new certificate but a continuous record of building information. That record supports decisions across the multi-year, multi-stage renovation process the EPC alone cannot describe.

1.2. Research gap

To support the introduction of these two concepts, the EU has funded research initiatives under the Horizon 2020 and Horizon Europe frameworks aimed at improving data transparency, accessibility, and decision-making throughout a building's life cycle [11]. These initiatives vary in scope (DBLs, BRPs, or both) and application domain (residential, non-residential, or both). Individual EU member states and organisations have also developed their own DBL/BRP data models and tools. Since DBLs are proposed as the common repository for all relevant building data, each of these initiatives proposes a data model that defines and stores what it counts as 'relevant'. For example, in Gómez-Gil et al. [12], four DBL initiatives were compared, which shows that what counts as relevant building data varies substantially between them.

Despite these extensive EU-funded and member-state efforts, the data models developed within the resulting initiatives are typically closed-source, not publicly accessible, or only partially published. That limits reusability and makes it difficult for researchers and practitioners to test, validate, and build on previous work. Many of the published data models have also been developed in, and are intended to be used as, semi-structured Excel spreadsheets rather than as formal data models. Excel is non-relational and cannot store complex relations between elements. It lacks proper version control and is often not centrally stored, which makes duplicate and conflicting versions likely. It is also prone to errors during manual data entry and manipulation, and lacks a programmatic interface for integration with other systems. The format therefore constrains what a published model can express and how reliably it can be reused.

Without well-documented, openly available, and formally specified data-model definitions, questions such as "does this data model fulfil a given set of data needs?" cannot be answered. The current proposals are difficult to compare in terms of coverage and completeness, and identifying which model best serves which use case, or where the gaps lie, becomes impractical. The absence of a common, standardised model means that each new implementation effectively starts from scratch in data modelling rather than building on established work.

An open, formally specified geospatial data model for urban energy modelling already exists for purposes adjacent to BRPs. The Open Geospatial Consortium (OGC) City Geography Markup Language (CityGML), paired with its Energy Application Domain Extension (Energy ADE), has been openly maintained and developed for more than a decade. Whether this established pairing is sufficient as a data model for BRP data requirements is an open empirical question that has not been systematically tested. This thesis addresses that gap.

1.3. Objective and motivation

Given this gap, this thesis sets out to do two things. First, the data models of existing (or proposed) initiatives identified across the European literature are compared, and the recurring data fields are distilled into a shared minimum set of attributes and properties: the Minimum Set of Required Data (MSRD). Second, CityGML 2.0 + Energy ADE 3.0 (beta 8) is assessed as the data model for BRP data requirements, with targeted extensions[1] proposed where the existing schema falls short. This second task is an evaluation, not the construction of a new data model. CityGML is a long-established open standard maintained by the OGC, while the Energy ADE is a community-developed extension to it, currently revised through an active development effort.

The kind of data model this thesis tests is open, formally specified, and geospatial. Bespoke DBL/BRP schemas and the proprietary data layers of commercial products do not offer reuse across implementations. Excel-based proposals do not formally specify their semantics, which makes coverage and completeness impossible to assess. An open, formally specified data model, by contrast, supports machine-readable conformance, a documented extensibility mechanism, and reuse across implementations.

The specific pairing this thesis tests is CityGML 2.0 + Energy ADE 3.0 (beta 8). The choice does not amount to a claim that this pairing is the optimal data model, only that it is a credible established starting point worth testing. A negative result, whether a field the schema cannot cover or real-world data it cannot cleanly represent, is itself a contribution to the standardisation effort. It identifies where Energy ADE 3.0 needs incremental development to serve the BRP use case.

1.4. Research questions

Resulting from this gap and objective, the following main research question and three sub-questions were formulated.

1.4.1. Main research question

To what extent does CityGML 2.0 + Energy ADE 3.0 (beta 8) constitute a meaningful starting point for a Building Renovation Passport data model, and what targeted extensions are required to close the gaps?

1.4.2. Sub-questions

1. Which data fields constitute the MSRD for Building Renovation Passports?
2. To what extent does the CityGML 2.0 + Energy ADE 3.0 (beta 8) data model cover the MSRD?
3. What does testing CityGML 2.0 + Energy ADE 3.0 (beta 8) at per-building and city scales, using real Dutch building-stock data, reveal about its adequacy and gaps?

[1]Throughout this thesis, "extension(s)" denotes a proposed addition to the data model that closes an MSRD gap. This is distinct from the Application Domain Extension (ADE), CityGML's formal mechanism for extending the standard, from which the Energy ADE takes its name.

1.5. Scope

The data model tested in this thesis is CityGML 2.0 paired with Energy ADE 3.0 (beta 8). CityGML 3.0 is not targeted directly: Energy ADE 3.0 (beta 8) currently extends CityGML 2.0, though it is designed for relatively easy adaptation to CityGML 3.0 in the near future.

The thesis evaluates this data model and identifies the targeted extensions needed where it falls short of the MSRD. Implementing and validating those extensions in the schema lies outside its scope; they are offered as proposals to the further development of the Energy ADE.

The initiative comparison covers 14 European initiatives, spanning DBL, BRP, and EPC-integration focuses and both residential and non-residential typologies; the selection criteria are set out in Chapter 3.

The data-model evaluation is EU-broad; the Netherlands serves as the test case because of its open-data coverage. The two scale tests set out in Section 1.3 are bounded to one owner-occupier dwelling for the audit-depth per-building test (Section 5.2) and one Dutch municipality for the city-scale test (Section 5.3).

1.6. Relevance

1.6.1. Scientific contribution

The scientific contribution of this thesis is twofold. First, it consolidates the data requirements of 14 European initiatives into the MSRD, an open requirement set for a BRP in a field where the underlying data models are often closed-source or only partially documented. Second, it tests an established open data model, CityGML 2.0 + Energy ADE 3.0 (beta 8), against that requirement set. It then reports, field by field, where the schema already covers the MSRD and where it does not, proposing targeted extensions for the gaps.

The evaluation runs at two levels. At the schema level it asks whether the data model offers a place for each MSRD field. At the field level it maps Dutch open-data sources onto the schema and records what can and cannot be populated. This makes the data-quality patterns in those registers visible and tractable within a single integrated model. The result is an open, reproducible evaluation that future researchers and practitioners can build on, critique, and extend.

The toolkit `CityGML2.0-EnergyADE3.0_creator` is released open-source. It bundles per-building and city-scale pipelines, JavaScript Object Notation (JSON) input schemas, end-to-end tests, and deterministic Geography Markup Language (GML) output that validates offline against the bundled XML Schema Definition (XSD) set.

1.6.2. Policy contribution

The 2024 EPBD recast obliges Member States to make BRPs available and recommends DBLs, but it leaves the underlying data model unspecified. This thesis shows that an existing open, international geospatial data model can serve as that data foundation, rather than each Member State commissioning a bespoke model that is often closed or specified only as a spreadsheet. Two results speak to policy. The open MSRD gives a vendor-neutral baseline of the data a passport must hold, against which national implementations can be checked. The coverage test grounded in Dutch open data then shows concretely which of those requirements public registers already meet and which they do not. The Dutch grounding is one worked instance of an approach that can be repeated in other Member State contexts.

1.6.3. Research-project contribution

This thesis contributes to RenoDAT (Accelerating building RENOvation and decarbonisation through DATa integration) [13], a research project funded by the *Nederlandse Organisatie voor Wetenschappelijk Onderzoek* (NWO, Dutch Research Council) and led by TU Delft (2025-2029). The project develops the data infrastructure for Building Renovation Passports. The data-model evaluation, the proposed extensions, and the open-source `CityGML2.0-EnergyADE3.0_creator` toolkit developed in this thesis are intended as a starting point for the project's wider work on data integration, scaling, and tooling.

1.6.4. Societal contribution

By evaluating an open, interoperable data model, this thesis addresses the information barriers in renovation decision-making. Building owners, energy advisors, financial institutions, and contractors often operate with non-interoperable systems and rely on manual data re-entry and translation between tools. This reliance increases costs, creates opportunities for error, and slows decision-making. An interoperable data model enables better information flows and reduces transaction costs. A well-designed data model also supports the generation of BRPs, since these are intended to draw on the data that a DBL holds.

1.7. The parallel MBE thesis

This research is conducted alongside a parallel Management in the Built Environment (MBE) MSc thesis at TU Delft. Both studies examine the same problem, the building data a BRP needs in the European context, worked through a Dutch implementation case, but from different perspectives and with different outputs. This thesis takes the data-modelling perspective, and evaluates the CityGML + Energy ADE data model for the data fields a BRP draws on. The parallel MBE thesis takes the practice perspective, and identifies the building-data needs and BRP expectations of the practitioners who advise Dutch owner-occupiers on energy renovation towards an emission-free home.

Each thesis stands on its own evidence. This thesis draws on the systematic comparison of Chapter 4 and the two implementation tests of Chapter 6. The parallel MBE thesis draws on 15 semi-structured interviews with 17 respondents across 9 stakeholder categories, such as energy advisors and coaches, contractors and installers, and one-stop shops. The interviews produce a practitioner-grounded view of which building data these stakeholders actually consult, struggle to find, or wish were standardised across the staged renovation process. They also capture the expectations and concerns these stakeholders would raise about a Dutch BRP.

The two studies are linked in both directions. A populated instance of the CityGML 2.0 + Energy ADE 3.0 (beta 8) data model, filled with real Dutch building-stock data, was used as a concrete prompt during the interviews conducted in the parallel MBE thesis. The practitioners' building-data needs identified in those interviews feed back into this thesis as one of the inputs that help determine the relevance of each MSRD feature in Chapter 4.

1.8. Thesis outline

Figure 1.1 gives an overview of the research design; the remainder of this section summarises each chapter in turn.

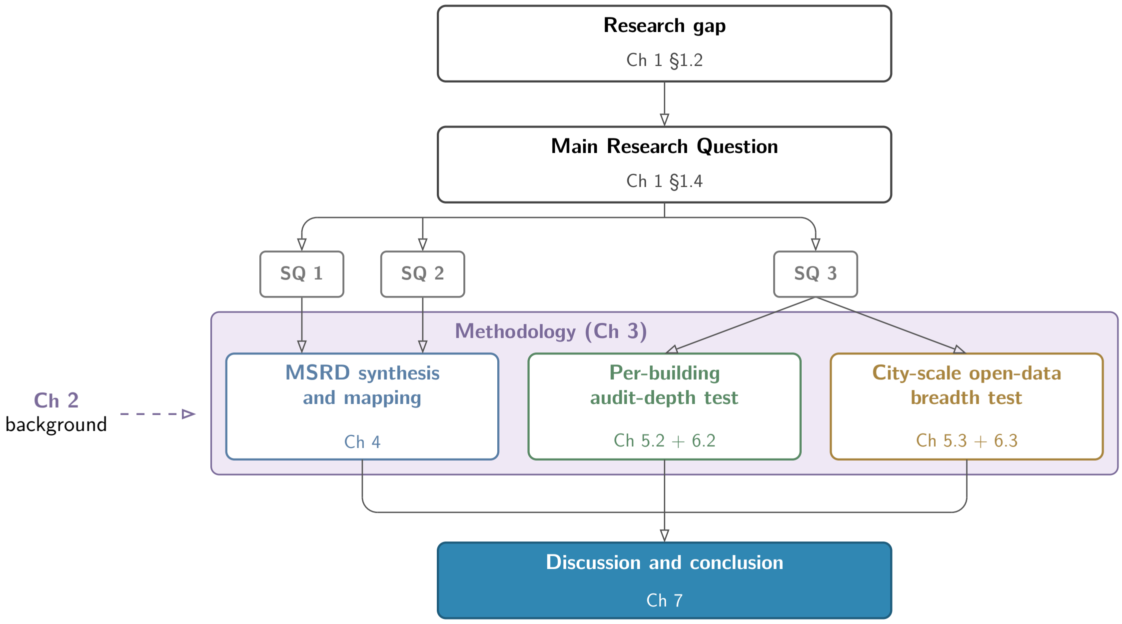


Figure 1.1: Overview of the research design, linking the main research question and its three sub-questions (SQ) to the chapters that answer them. Own work.

Chapter 2 establishes the working definitions of the EPC, the DBL, and the BRP, and introduces the 14 compared initiatives. It then makes the case for CityGML 2.0 + Energy ADE 3.0 (beta 8) as the candidate data model, situating Building Information Modelling (BIM), the Industry Foundation Classes (IFC), and CityJSON against that choice.

Chapter 3 sets out the comparison design for the 14 initiatives, the relevance filter behind the MSRD, the mapping procedure, and the two scale tests.

Chapter 4 is the core chapter. It compares the initiatives module by module, distils the recurring fields into the MSRD, maps the MSRD onto the data model, and locates where the schema cannot cover an MSRD field. The responses to those gaps are consolidated in Chapter 7.

Chapter 5 puts the data model to work in two pipelines, naming the dataset, design, and mapping choices of each. The per-building pipeline models one owner-occupier reference building at audit depth. The city-scale pipeline ingests the open Dutch registers, walked through on a small area in Emmer-Compascuum and also run on Delft, Groningen, and Zwolle as comparators.

Chapter 6 reports the produced artefacts, the audit-depth schema-fit findings from the per-building run, the data-quality findings drawn from the four full city-scale runs, and what the integrated model enables that the source datasets on their own do not.

Chapter 7 weighs the findings against the literature and the parallel MBE thesis, answers the research questions, and consolidates the proposed CityGML 2.0 + Energy ADE 3.0 (beta 8) extensions. It closes with implications, future work, limitations, and reflection.

2. Related Work and Background

This chapter sets out the related work and background the rest of the thesis builds on, moving from concept to candidate data model in three steps. It first introduces the Energy Performance Certificate, clarifies how the literature positions Digital Building Logbooks and Building Renovation Passports, adopts the working definitions used in this thesis, and situates how the Netherlands implements them. It then introduces the 14 European initiatives whose data fields are compared in Chapter 4, and closes with a brief introduction to the candidate data model, CityGML 2.0 + Energy ADE 3.0 (beta 8), at the level needed to evaluate it as a BRP data model.

2.1. Definitions and interrelationships of EPCs, DBLs, and BRPs

2.1.1. The Energy Performance Certificate

The Energy Performance Certificate is the European Union's principal instrument for disclosing a building's energy performance, introduced through the original Energy Performance of Buildings Directive in 2002 [8]. It classifies a building's modelled energy performance on a comparable letter scale and is issued at construction, sale, or letting, so that prospective buyers and tenants can compare dwellings [14].

For a data model, the decisive property of the EPC is that the label is a national construct. Member States set their own class boundaries, and even their own number of classes, so the same letter denotes very different levels of energy use across borders, as shown in Figure 2.1.

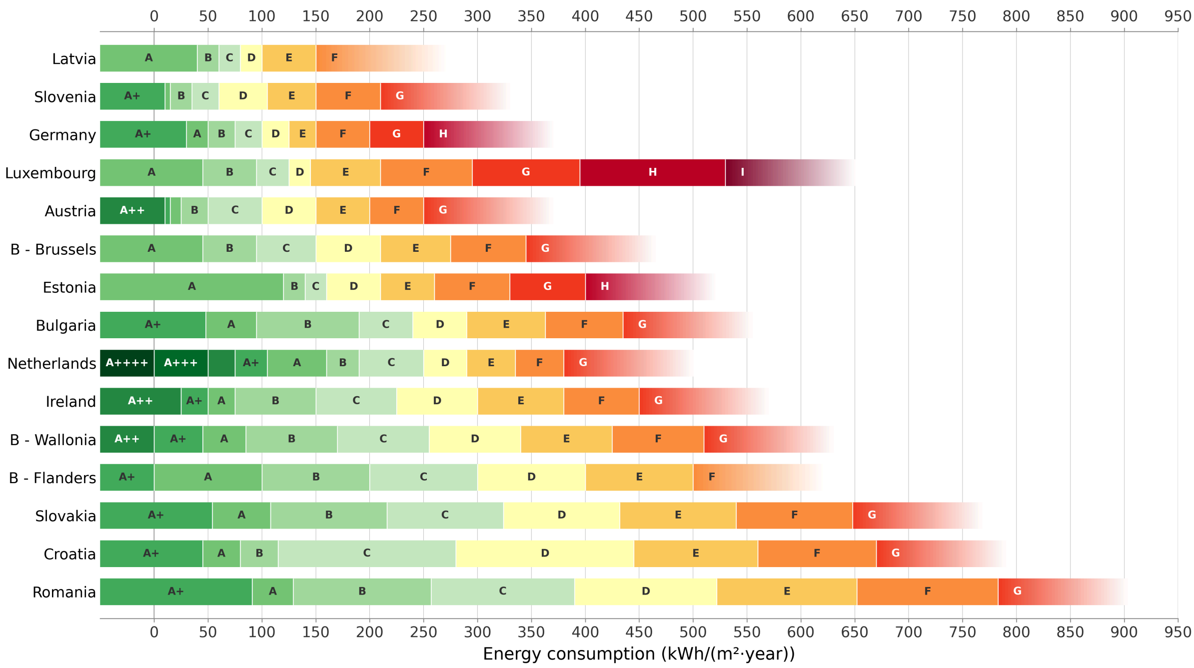


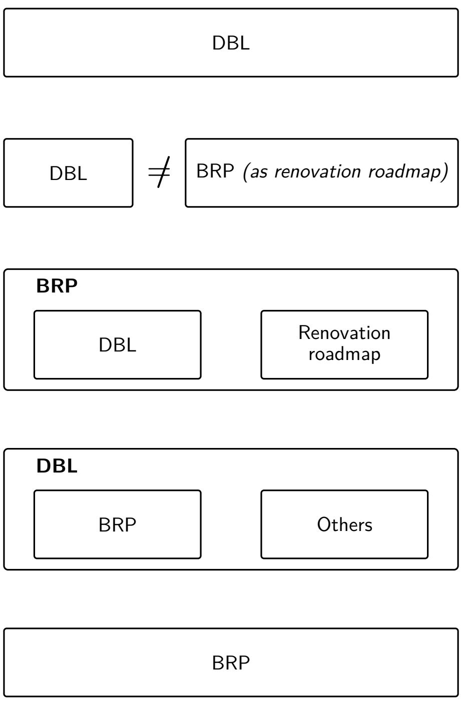
Figure 2.1: Energy-use ranges (in kWh/m^2/year) that define each energy-performance class for single-family houses across a sample of EU Member States. Own work; data derived from G. Ruggieri, et al. [15].

For example, a dwelling using 140 kWh/m^2/year is rated E in Latvia but A in the Netherlands. The number of classes also varies, from the A-to-F scale used in Latvia up to 9 bands in Luxembourg (ending at I) and 11 in the Netherlands (A++++ through G). The letter is therefore not comparable between countries. What is comparable, and machine-interpretable, is the underlying energy-use value carried together with its unit. This is a property that recurs throughout the thesis. A data model for building energy data must therefore record typed, unit-tagged values rather than nationally-scoped labels. Section 2.3 returns to this requirement as semantic interoperability.

In the Netherlands, for example, the label runs from A++++ (most efficient) to G (least efficient), and is issued by a licensed Energy Performance (EP) advisor who records numbers describing a dwelling's geometry (such as floor area and volume), its envelope, and its installations on site [14]. Those inputs are run through the prescribed NTA 8800 methodology to compute a predicted primary fossil-energy use in kWh/m²/year, which is then translated into the label.

2.1.2. Positioning DBLs and BRPs in the literature

The EPC's limitations as a single-moment certificate motivate the two instruments this thesis is concerned with: the Digital Building Logbook and the Building Renovation Passport. These terms are used across European policy and academic literature with varying, and sometimes conflicting, definitions. A recent systematic review of the field confirms that these instruments still lack settled definitions and that renovation passports, logbooks, and material passports are routinely conflated [16]. A further complication is the parallel use of Building Passport (BP) as a terminology variant for the DBL: sources that equate BP with DBL are not equating the BRP with the DBL, despite the partial overlap in the names. The following sections classify the reviewed literature into five categories, illustrated in Figure 2.2, based on how each source positions the two concepts and their interrelationship.



A. Engages with the Digital Building Logbook (or Building Logbook); the BRP, if mentioned, appears only as an unelaborated data input.

B. Treats the DBL and the BRP as separate, complementary tools, often following the EPBD IV definitions; the BRP is essentially a renovation roadmap.

C. Positions the BRP as the overarching tool, composed of two parts: a logbook (DBL) and a renovation roadmap.

D. Positions the DBL as the overarching repository within which BRPs are stored or accessible, alongside other building data.

E. Discusses only the BRP and does not engage with the DBL concept.

Figure 2.2: Five identified categories of how the literature positions the relationship between DBLs and BRPs. Categories C and D reflect a chronological shift, from BRP-as-overarching (early research projects, e.g. the Individual Building Renovation Roadmaps (iBRoad) and ALliance for Deep RENovation in buildings (ALDREN) projects) to DBL-as-overarching (recent EU policy framing). Own work.

A: Sources discussing only the concept of DBLs

In Toth et al. [17], a report from the X-tendo project (extending energy-performance certification schemes via a modular approach; EU Horizon 2020, 2019-2022), BRPs appear as one of six tiles labelled as data inputs to the DBL. The other five are the EPC, the land registry, financial data, the SRI, and links to one-stop shops and third parties. The BRP is shown only on the cover diagram, with no textual definition of what it contains. In Maia et al. [18], another X-tendo deliverable, BRPs are mentioned in a single paragraph as one of the data sources that the EU Renovation Wave strategy proposed to integrate into DBLs, again without further explanation. Both sources therefore position BRPs as data inputs to a DBL.

The X-tendo reports define a DBL as a common digital repository that stores all relevant building-related data throughout a building's life cycle. It integrates information from sources such as EPCs, BRPs, and SRIs across data types including technical systems, envelope elements, energy consumption, maintenance, and administrative records. This integration supports transparency, informed decision-making, and information sharing among stakeholders. The X-tendo project emphasises that the DBL should be interoperable with existing databases, user-friendly, and continuously updated, supporting energy efficiency improvements and the transition to a decarbonised building stock.

A similar pattern, framed around terminology rather than data flows, appears in Karami et al. [19]. In a semantic-mapping comparison of seven building-data models, Digital Building Logbook and Digital Building Passport are used as interchangeable terms (DBL/DBP) for a single repository of static as-built data and dynamic Key Performance Indicators across the building life cycle. The authors observe that the term Building Passport has by now replaced the older Building Logbook terminology. Renovation passports (such as the ALDREN BRP) are included among the building-data models compared, but the paper does not articulate an architectural relationship between the BRP and the DBL: it treats them as comparable data-model instances within a broader BL/BP family, without positioning one as containing or feeding the other.

B: Sources distinguishing DBLs and BRPs as separate tools

Several sources distinguish between DBLs and BRPs as separate instruments, following the definitions established in the recast EPBD [4]. There, the BRP is defined as *"a tailored roadmap for the deep renovation of a specific building in a maximum number of steps that will significantly improve its energy performance"* (Art. 2(19)). The DBL is defined as *"a common repository for all relevant building data, including data related to energy performance such as energy performance certificates, renovation passports and smart readiness indicators"* (Art. 2(41)), which facilitates informed decision-making and information sharing within the construction sector.

These definitions are adopted directly in Barbosa and Almeida [20], treating the DBL as a data repository and the BRP as a renovation roadmap, without further analysis of how the two relate to each other. Similarly, in Dorizas et al. [21], the DBL is described as a data repository that integrates all building-related data from BRPs, SRIs, Level(s), and EPCs to ensure compatibility and integration throughout the renovation process, with emphasis on its purpose as a user-friendly dashboard. BRPs are noted as contributing to energy savings and carbon emission reductions as one of their main benefits.

The DBL and BRP are also treated as separate but complementary instruments in Zsak et al. [22], where the DBL is described as a gateway that integrates datasets on energy, materials, and building performance, reinforcing BRPs as instruments for both sustainability monitoring and policy alignment.

C: Sources describing BRPs as the overarching tool, consisting of a logbook and roadmap

A substantial body of literature, particularly from the Buildings Performance Institute Europe (BPIE), iBRoad, and ALDREN research projects, positions the BRP as the overarching tool, composed of two main elements: a data repository (or logbook) and a renovation roadmap.

The BRP concept was introduced in Fabbri et al. [7] as a document, in electronic or paper format, that outlines a long-term (up to 15 or 20 years) step-by-step renovation roadmap for a specific building, resulting from an on-site energy audit. This definition notes that the BRP can include a digital logbook as a repository for building data, financing options, energy bills, and maintenance records alongside the renovation roadmap. An analysis of three national BRP initiatives [7, 9] showed that a logbook component was integrated in the Flemish Woningpas (housing passport), while the French *Passeport Efficacité Énergétique* was not itself a logbook but contributed to a separate government-mandated digital logbook. The German *individueller Sanierungsfahrplan* (iSFP, individual renovation roadmap) did not foresee a logbook component at all.

This two-part structure was further developed within the iBRoad project. Within this project, the BRP was described as comprising both an individual renovation roadmap and a building logbook [23], referred to respectively as the iBRoad-Plan and the iBRoad-Log [9]. The logbook component is further elaborated in Monteiro et al. [24] as a repository for all building-related information, with 21 proposed functionalities organised into 7 categories. These cover building data storage, diagnosis, displaying the renovation roadmap, alerts, sharing, benchmarking, and links to external services.

The ALDREN project adopted the same architecture for non-residential buildings. In Salvalai et al. [25], the BRP structure is explicitly defined as composed of two main elements: a data repository, referred to as the logbook, and a renovation roadmap, implemented as the ALDREN BuildLog and ALDREN RenoMap respectively. A four-level data granularity structure is described in Zirngibl et al. [26], in which data at Level 2 populates the Logbook, while Level 3 represents the core data appearing on the BRP cover. Multiple publications from this project [27, 28] confirm this structure, with the DIKW (Data-Information-Knowledge-Wisdom) hierarchy further applied in Sesana et al. [28] to describe how building data flows from raw inputs through the BuildLog to actionable renovation recommendations in the RenoMap.

This position is synthesised most concisely in Gómez-Gil et al. [12], which describes the DBL as one of two fundamental parts of the BRP, alongside a renovation roadmap, and notes that public administrations and research groups working on its definition agree on these two components. Historical context is provided in Gómez-Gil et al. [29], which observes that the DBL concept had already begun to take shape in academia, where it was associated with a renovation roadmap to form what became known as the building renovation passport.

D: Sources describing DBLs as the overarching tool, containing BRPs

A contrasting view, which emerged more recently in the policy literature, positions the DBL as the overarching framework within which BRPs are stored or accessible. This framing originates from the recast EPBD itself, which states in Article 12(8) that Member States must ensure the renovation passport is stored in, or can be accessed via, the digital building logbook where available [4, 30].

In the report by the European Commission's Executive Agency for Small and Medium-sized Enterprises (EASME) [10], the DBL is defined as a common repository for all relevant building data. The BRP is positioned as one of several functionalities of the DBL, listed alongside features such as document storage, material traceability, and Building Information Modelling (BIM) integration. In this framework, the BRP generates data (such as building-specific renovation recommendations) that feeds into the DBL's data fields.

The same framing is followed in Alonso et al. [31], where the BRP is treated as one of several data sources, alongside the Smart Readiness Indicator, Level(s), and Digital Product Passports, that feed into the DBL. The EPBD recast definition of the DBL is cited as a common repository for all relevant building data, including renovation passports. A similar position is taken in Karami et al. [32], citing both the EPBD and Global Alliance for Buildings and Construction (GlobalABC) definitions that list the renovation passport as one of several data types housed within the DBL, and concluding that the overarching concept is to develop a single repository, the DBL, that holds all building-related data for a building's entire life cycle.

In Gyuris et al. [33], an EUB SuperHub project deliverable, the DBL is structured as eight modules covering administrative, general, element, operational, performance, smart-readiness, financial, and BIM-documentation data. Renovation passports are not one of the modules; following the December 2021 EPBD recast proposal, the authors instead frame them as one of several data types the DBL holds or links to, alongside EPCs and Smart Readiness Indicators. The proposal's renovation-passport definition (a tailored roadmap for renovating a specific building in several steps) is quoted by the report. A separate literature-review chapter describes the iBRoad and ALDREN BRP-as-overarching architectures (category C above) at length. For its own data-structure analysis, however, the report treats the iBRoad-Log and ALDREN BuildLog (the logbook components of those BRPs) as DBL data structures comparable to the European Commission's Study EU DBL and the X-tendo logbook. The iBRoad and ALDREN BRP framing is therefore acknowledged but not adopted.

Two further sources reach the same overarching framing under different terminology, equating Building Passport with the DBL while still positioning BRPs as separate, narrower instruments whose data feeds into the broader repository. In Hartenberger et al. [11], the GlobalABC guideline, a BP is defined as a whole-life-cycle repository of building information, and BP, DBL, and Electronic Building File are explicitly treated as interchangeable terms. Renovation passports, alongside material passports, EPCs, and sustainability certifications, are described as narrower instruments whose data can be directly added to the BP as readable documents or digitally tagged to it via a unique building identifier. In Buchholz and Lützkendorf [34], the same conclusion is reached via a structured comparison of BP and DBL definitions in the literature: although different terms are used, the underlying definitions converge on essentially the same set of features, so that BPs and DBLs can be treated as a single tool. Renovation passports, material passports, BIM, and digital twins are distinguished as separate building-information-management tools, and a job-sharing approach is proposed with BPs at the forefront, in which renovation roadmaps are implemented alongside the BP/DBL rather than independently.

The ambiguity between categories C and D is noted in Koronen et al. [30], which recommends that the Commission must distinguish between the definitions and clarify the relationship between BRPs and DBLs to avoid perceived conflict or overlap.

E: Sources discussing only the concept of BRPs

Some sources discuss BRPs without reference to DBLs. In Lundgren [35], a thesis on Swedish BRP implementation, the BPIE definition of a BRP as a long-term step-by-step renovation roadmap is adopted, but the concept of a Digital Building Logbook is not mentioned. Similarly, in Plebankiewicz and Grącki [36], the BRP is described as a tool designed to encourage cost-effective renovations through a step-by-step roadmap, and the lack of a universally accepted definition is noted, but DBLs are not discussed.

2.1.3. Adopted definition of a BRP

The reviewed literature is split between two framings. Earlier research projects positioned the BRP as the overarching tool containing a logbook and roadmap (category C), while more recent EU policy instruments position the DBL as the overarching repository that stores renovation passports among other data (category D).

Following the recast EPBD and the most recent policy framing (category D), this thesis adopts the following definition: a **Building Renovation Passport** is a building-specific, long-term renovation roadmap, consisting of a sequence of energy efficiency renovations, which draws on and is stored in or accessible via a DBL. The BRP therefore only needs a subset of the data a DBL would hold, and its renovation recommendations are one of several outputs that such a repository can support.

For differentiation: a **Digital Building Logbook** is a central repository for all relevant building data throughout a building's life cycle; it provides the data foundation on which a BRP's personalised renovation recommendations are built. The DBL is invoked in this thesis only insofar as it informs the BRP definition and the data that a BRP draws upon; it is not itself the object of study. The empirical work, the research questions, and the rest of this thesis narrow to the BRP.

2.1.4. Mandatory content of a BRP under the EPBD

Beyond defining the instrument, the 2024 EPBD recast also specifies what a renovation passport must contain. Under Article 12 and Annex VIII §1, a BRP must include the following [4]:

- the building's current energy performance and the applicable national renovation requirements, such as minimum energy performance standards and any fossil-fuel phase-out dates;
- a staged renovation roadmap, presented graphically, with an explanation of the order in which the steps should be carried out;
- for each step, an estimate of the energy savings, the reduction in operational greenhouse-gas emissions, the energy-bill savings, and the energy-performance class reached afterwards;
- the share of renewable energy that could be generated and self-consumed after renovation, including any potential connection to district heating or cooling;
- wider information covering construction-product circularity, whole-life-cycle emissions, health, comfort, indoor environmental quality, and climate-adaptation capacity; and
- pointers to available financial support and to one-stop-shop advisory services.

A Dutch BRP, like that of any other Member State, must meet these minimum requirements. The mandated items, together with the building data needed to derive them, define what a BRP draws on.

2.1.5. The Dutch interpretation: the LVG and the *gebouwrenovatiepaspoort*

The Netherlands implements these definitions on two tracks, a passport track and a data track. On the passport track, a voluntary *gebouwrenovatiepaspoort* (building renovation passport) becomes available on May 29, 2026, implemented as a designation on the existing *maatwerkadvies*, the certified, building-specific renovation advice issued by a licensed advisor, and registered in the national energy-label database [37, 38]. The Dutch BRP is therefore not a new instrument built from scratch but an extension of an advisory product that already exists.

On the data track, the *Landelijke Voorziening Gebouwgegevens* (LVG, National Building-Data Service) is the Dutch operationalisation of a Digital Building Logbook. In the Kadaster scoping study commissioned by the Dutch Ministry of the Interior, the LVG is defined as a set of tools and agreements that make building data from multiple government sources accessible in a federated manner through a single portal [39]. It is a connecting service rather than a primary source, following the *Federatief Datastelsel* (FDS, Federated Data System) principle of *decentraal wat kan, centraal wat moet* ("decentralised where possible, centralised where necessary") [39, 40]. Its planned first release draws on four sources, the *Basisregistratie Adressen en Gebouwen* (BAG, Key Register of Addresses and Buildings), the national geo-data platform PDOK (*Publieke Dienstverlening Op de Kaart*, Public Services on the Map), the energy-label register EP-Online (operated by the *Rijksdienst voor Ondernemend Nederland*, RVO), and the renewable-energy subsidy register ISDE. The scoping study recommends making this data accessible to homeowners through the existing *MijnOverheid* portal, secured with DigiD. It notes, though, that the portal is not yet set up to present such building data coherently [39].

The LVG, as scoped in 2024, makes existing public building data coherently accessible, but its planned scope does not yet include several categories a staged renovation roadmap depends on. In particular, it omits a building's renovation history, its post-renovation performance, and envelope and material detail at component level [39].

2.2. Overview of the assessed initiatives

Table 3 lists the assessed initiatives with their aim, type, target building stock, active years, and geographic scope. Most are Digital Building Logbook or Building Renovation Passport proposals and implementations; the others are related tools that consume building data without proposing a data model of their own, adding a data-consumer perspective on what that data is for.

2.2. Overview of the assessed initiatives

ID	Initiative	Aim	Type	Target stock	Year(s)	Geographic Scope	Source
I1	EUB SuperHub DBL	Development of DBL structure for all types of buildings	Data model proposal	Entire stock	June 2021 to Dec. 2024	Transnational (7 countries)	[33]
I2	ALDREN	DBL/BRP development for deep renovation of non-residential buildings	Data model proposal	Non-residential	Nov. 2017 to Sep. 2020	Transnational (8 countries)	[25]
I3	Gómez-Gil et al.	Academic proposal for DBL data structure	Data model proposal	Entire stock	Oct. 2024	European (comparative analysis)	[41]
I4	iBRoad	BRP development for residential buildings, later integrated with EPC schemes and extended to multi-family and public buildings	Data model proposal including roadmap	Residential	June 2017 to Aug. 2024	Transnational (7 countries)	[42]
I5	Woningpas	Digital building passport and renovation decision-making support tool	Implementation	Entire stock	Dec. 2018 to ongoing	Regional (Flanders, Belgium)	[43]
I6	X-tendo	Next-generation EPC schemes toolbox	Data model proposal	Entire stock	Sep. 2019 to Aug. 2022	Transnational (10 countries)	[44]
I7	EU DBL (by Ecorys)	EU Framework for Digital Building Logbooks	Framework study	Entire stock	Nov. 2023	European	[45]
I8	BUILDCHAIN	Blockchain-based DBL for trustworthy building lifecycle knowledge	Data model proposal	Entire stock	Jan. 2023 to June 2026	Transnational (6 countries)	[46]
I9	OneClickRENO	Automatically generated, customisable BRPs via web tools	Data model + tool	Entire stock	Nov. 2023 to Oct. 2026	Transnational (5 countries)	[47]
I10	EPA (by Vitec Vabi)	Software for energy auditors to calculate energy usage and generate EPC scores	EPC software	Entire stock	Since 2008	National (Netherlands)	[48]
I11	BuurtWarmteWijzer	Digital tool for residents to explore district heating options and assess collective heat network feasibility	Decision-support tool	Residential	Since 2020	National (Netherlands)	[49]
I12	CLÉA	Digital building logbook for housing information management, maintenance tracking, and energy renovation support	Implementation	Residential	Since 2020	National (France)	[50]
I13	iSFP	Individual Building Renovation Roadmap (Germany's national BRP)	Implementation	Residential	Since July 2017	National (Germany)	[51]
I14	Hoomdossier	Digital building dossier used by energy coaches to gather building data and support residents with renovation advice	Implementation	Residential	Since 2018	National (Netherlands)	[52]

Table 3: Overview of Digital Building Logbook and Building Renovation Passport initiatives. The ID column (I1-I14) is used throughout the rest of this thesis to refer to these initiatives. The Source column cites where each initiative's data model was obtained, from published PDF deliverables and papers to proprietary software and licensed web platforms cited by their product website. Own work.

The 14 initiatives are deliberately heterogeneous. Three are official government initiatives at national or regional level, the German iSFP, the Flemish Woningpas, and the French CLÉA. Six are EU-funded research-project data-model proposals, iBRoad, ALDREN, X-tendo, EUB SuperHub, BUILDCHAIN, and OneClickRENO. Two are academic or framework-level studies, Gómez-Gil et al. and the Ecorys EU DBL framework. The remaining three are Dutch operational tools that consume building data without being national BRPs themselves, Hoomdossier, the Vitec Vabi EPA software, and BuurtWarmteWijzer. Earlier comparative work is narrower in scope. Gómez-Gil et al. set four Digital Building Logbook proposals side by side [12, 41], and Karami et al. semantically mapped seven building-data models [19, 32]. A recent review of the digital-building-logbook field likewise reports the absence of a common data model across implementations [53]. The dedicated BRP/DBL data models that come closest are recent and sharpen this gap rather than close it. Gómez-Gil et al. [54] propose a relational logbook model, and OneClickRENO delivers an EPBD-aligned passport schema in Extensible Markup Language (XML), but both are standalone tabular or relational models, without geospatial grounding or a link to open 3D building stock. The choice to include this broader set, rather than only BRP-titled initiatives, makes the MSRD synthesis in Chapter 4 a comparison across data-perspective categories rather than a literature review of BRPs alone.

2.3. CityGML and the Energy ADE as the candidate data model

This section introduces the candidate data model, CityGML paired with the Energy ADE, then weighs it against the alternatives a reader is likely to raise. Building Information Modelling, carried by the IFC schema, and the Infrastructure for Spatial Information in Europe (INSPIRE) Buildings theme lie at the finer and coarser ends of a spectrum of territorial scales on which CityGML occupies the middle (Figure 2.3).

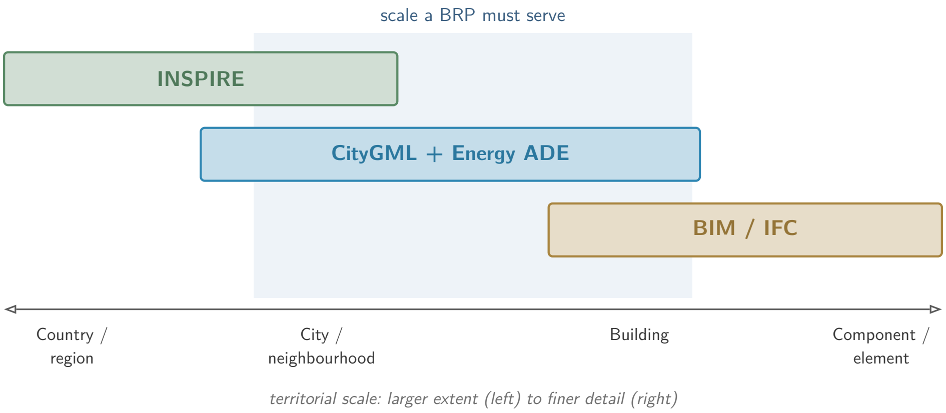


Figure 2.3: Spatial-scale spectrum of the data models a Building Renovation Passport might draw on. INSPIRE standardises building data at the territorial scale, CityGML with Energy ADE at the city-to-building scale, and BIM/IFC at the building-to-component scale. A renovation passport must cover a whole municipality at the resolution of the individual building (or dwelling, depending on the EU regulation), the scale at which CityGML and Energy ADE operate. Own work; the qualitative scale relationship follows Agugiaro et al. [55].

The DBL/BRP concept does not in itself prescribe a data model: it prescribes a set of properties a building should have on file. To turn that requirement into something machines can store, validate, and exchange, an underlying schema is needed. Two properties decide whether a candidate schema is fit for that role:

- its *coverage* of the required fields, namely whether, for each field, the schema offers a class, attribute, or relationship in which it can be recorded, a binary verdict of covered or absent; and
- its support for *semantic interoperability*, the guarantee that a value such as a U-value or an annual energy demand carries an unambiguous, machine-checkable meaning across systems, rather than a bare number whose unit and definition must be inferred.

Coverage is the field-level test taken up in Chapter 4. Whether a covered field is also modelled adequately, onto a structured class rather than a loose generic attribute, is a matter of degree, examined when the schema is exercised on real building data. These two properties are the working criteria against which this chapter and Chapter 4 judge the candidate data model.

Earlier studies have compared building-data models at the level of broad categories rather than testing one schema for field-level coverage against a consolidated requirement set (Section 2.2); that field-level assessment is the task of Chapter 4. Distilling such a consolidated requirement set, a minimum or core profile of the fields that matter, is itself established practice in building-data standardisation. The INSPIRE Buildings theme defines a Core profile of the minimum attributes required for EU-wide reporting [56], and the European Level(s) framework distils building sustainability assessment to a set of common core indicators [57]. The MSRD applies the same approach to the DBL/BRP data requirements.

Most of what a passport records is not geometry but attribute data, such as the building's age, its energy label, element U-values, and the dates of past and planned interventions. A geospatial data model nevertheless fits, because of the coupling between geometry and semantics introduced below. Every attribute attaches to an ontologically typed building object. Through that object the passport inherits a stable object identity, spatial aggregation from dwelling to building to neighbourhood, and a single, consistent system of units of measure, rather than having to organise each of these itself. This thesis takes the position that such a foundation is provided by the international open standard CityGML and its extension, the Energy ADE.

2.3.1. CityGML

CityGML is an open standard maintained by the OGC for the representation, storage, and exchange of semantic 3D city and landscape models. It defines a conceptual model expressed in the Unified Modeling Language (UML) and built on the ISO 191xx geographic information series [58, 59]. The current major version, CityGML 3.0, was published as an OGC Standard in September 2021 [60]. CityGML 3.0 keeps this technology-neutral conceptual model (Part 1) separate from its physical encodings, with the GML/XML encoding defined in Part 2 [61]. The earlier CityGML 2.0 did not make this split: its conceptual model and XML encoding were specified together. The standard originated in 2002 within the Special Interest Group 3D (SIG 3D) and since 2008 has been maintained jointly by the OGC CityGML Standards Working Group and SIG 3D [59].

A defining feature of CityGML is the coupling between geometry and semantics: a wall is at once a polygon (or a set of polygonal geometries) and a semantic `WallSurface` that belongs to the ontology of building elements. The standard has a modular architecture. A Core module defines the basic abstractions and is extended by thematic modules; this thesis uses the Building module [59]. Although 3.0 is the current release, this thesis targets CityGML 2.0, because the Energy ADE 3.0 (beta 8) it pairs with extends CityGML version 2.0.

Three further mechanisms make CityGML directly relevant to a DBL/BRP data model:

- *Application Domain Extensions (ADEs)* allow new classes and properties to be added to the schema without breaking core conformance [62]. This is the mechanism by which Energy ADE attaches energy-related semantics to the building model.
- *ExternalReferences* attach URIs or identifiers from external information systems (cadastre, ALKIS, INSPIRE) to any `CityObject`, supporting the cross-reference behaviour a DBL/BRP needs.
- *Units of measure* are inherited from GML, of which CityGML is an application schema: every measured quantity is typed as a GML measure (`gml:MeasureType` and its specialisations `gml:AreaType`, `gml:VolumeType`, and `gml:LengthType`) carrying an explicit `uom` attribute, so that an opaque-surface area or a U-value is unambiguous across implementations [61].

2.3.2. The Energy Application Domain Extension (Energy ADE)

The Energy ADE is an open extension that enriches CityGML with the data needed for urban building energy modelling. It builds upon a standardised way of extending CityGML and complies with its rules, but is not yet an official standard. Energy ADE 1.0 was released in March 2018 as an XSD extending CityGML 2.0, originating within the Energy ADE working group [55]. Development of the current Energy ADE 3.0 started in 2024 within the EU project

DigiTwins4PEDs[2] and is still going on as an international collaborative effort originally started by TU Delft and HFT Stuttgart [63].

The latest public draft, *Energy ADE 3.0 beta 8* (XSD dated May 14, 2026), is the implementation target of this thesis [63, 64][3].

Despite the name, *Energy ADE 3.0 beta 8 is an extension of CityGML 2.0* rather than CityGML 3.0: its target XML namespace `http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0` and its imported schemas reference CityGML 2.0 / GML 3.1.1 modules [64]. A formal port of the Energy ADE 1.0 conceptual model to CityGML 3.0 has been investigated as a model-driven mapping exercise [65], but no production-ready CityGML 3.0 + Energy ADE 3.0 pairing exists at present. This thesis therefore targets the currently implementable pairing *CityGML 2.0 + Energy ADE 3.0 beta 8*, which preserves the conceptual structure of the most recent Energy ADE.

Conceptually, Energy ADE 3.0 is organised into a set of UML-defined modules (Figure 2.4) [64]; the modules most relevant to a DBL/BRP are:

- a *Core* module that adds energy-related attributes and shared abstract base classes to `CityObject`, and defines the cross-object classes most relevant to a renovation passport, including `Intervention` (a past or planned renovation, with its type, action, and start and end dates) and `UtilityNetworkConnection` (a building's actual or planned connection to a utility network such as gas, district heating or cooling, electricity, water, waste water, or data);
- a *Building* module that extends `AbstractBuilding` with energy-relevant attributes such as building type, ownership, and the thermal status of the attic and basement, and models the thermal hull through zones (`Zone`, `ZonePart`) bounded by surfaces and openings; boundary surfaces carry total and opaque surface area, thickness, heat capacity, azimuth, and inclination, while surfaces and openings can carry a layered construction through the `layeredConstruction` relation available on any `CityObject`, whose `uValue` records the thermal transmittance; it represents the individual dwelling through the `BuildingUnit` class, which records per-unit floor location, number of rooms, ownership, address, and its own energy performance certificate; and it also holds the `EnergyPerformanceCertificate` and `Occupants` classes;
- a *Devices* module covering energy-conversion, distribution, and storage systems (e.g. boilers, heat pumps, photovoltaic and solar-thermal collectors, and electric-vehicle (EV) charging stations);
- a *Material and Layered Construction* module describing constructions, their layers, and the materials these refer to in a separate library, including thermal and embodied-carbon properties;
- a *Resources* module modelling energy, water, and other resources demanded, produced, or stored, together with the associated time series; and
- an *Urban Function Areas* module that aggregates building-level values to larger spatial units such as blocks, neighbourhoods, districts, or statistical areas.

[2] digitwins4peds.eu.

[3] This peer-reviewed description of the revision refers to it as Energy ADE 2.0; the project subsequently renamed it 3.0, the designation and beta 8 version pinned throughout this thesis.

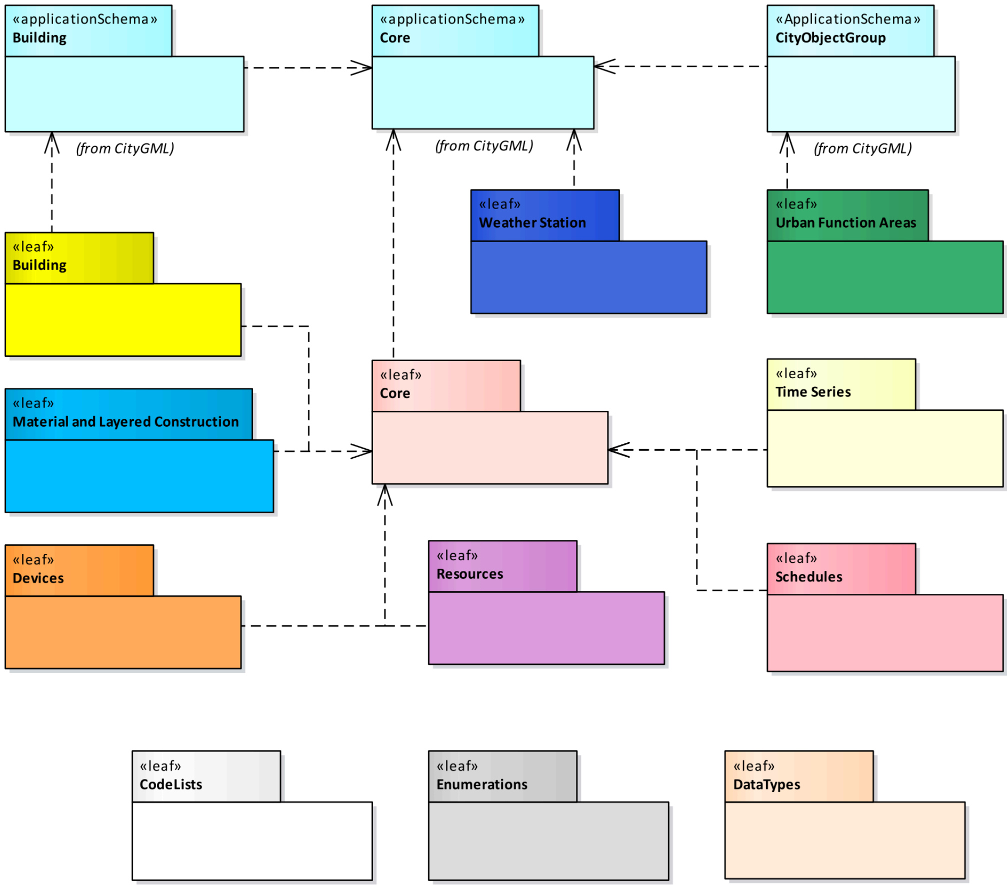


Figure 2.4: Package overview of the CityGML 2.0 + Energy ADE 3.0 (beta 8) data model, showing the Energy ADE leaf packages and the CityGML application schemas they specialise. Reproduced from the Energy ADE 3.0 (beta 8) UML documentation [64].

The remaining modules (time series, schedules, weather station, and the shared data types) are complementary shared classes used by the above-mentioned modules.

CityGML with Energy ADE has a decade-long track record in the purpose it was designed for, urban building energy modelling. It was designed as a common exchange format between urban energy simulators. SimStadt is built on CityGML and uses the `citygml4j` library to load, process, and store CityGML together with the Energy ADE [66], and gateways to other tools such as CitySim have been demonstrated [67]. It has supported city-scale analyses of heating demand, solar and photovoltaic potential, and long-term refurbishment scenarios [55]. The current revision is being tested in four European cities within the DigiTwins4PEDs project [63, 64]. That work, like the decade of urban-energy-modelling applications before it, targets energy simulation rather than the renovation-passport use case. The most relevant properties a renovation passport seems to need are therefore already present in the schema. What has not been tested is whether they cover the data a BRP must hold (Chapter 4), field by field, and whether that coverage holds on real open building-stock data. That coverage test is the question this thesis takes up.

2.3.3. Why CityGML rather than CityJSON

CityJSON is a lossy JSON encoding of a subset of the CityGML data model, developed by the 3D Geoinformation group at TU Delft and adopted as an OGC Community Standard in 2021 [68]. It is designed for ease of use by developers, dropping XML namespaces, compressing files by roughly a factor of six, and aiming to be friendly for web and mobile use [68]. The most fundamental limitation is that the Energy ADE is a CityGML Application Domain Extension, and CityJSON does not support ADEs. The CityJSON Extension mechanism is deliberately simpler and explicitly not conformant with CityGML ADEs, dropping inheritance and namespaces and allowing less customisation [69]. The Energy ADE therefore has no native CityJSON form and would have to be re-implemented as a separate, less expressive Extension. A more specific limitation, decisive for an energy-focused data model, is that CityJSON does not natively encode units of measure on attributes. Where CityGML inherits `gml:MeasureType` from GML so that a U-value or an annual energy demand carries its unit as a typed attribute, CityJSON requires an Extension defining a `{"value", "uom"}` object pattern to do the same [69]. An exploratory CityJSON energy extension exists [70], but it maps only a small portion of the Energy ADE 1.0 KIT Profile and was built to probe the limits of the encoding rather than to port the Energy ADE; it is far from a full porting. For a DBL/BRP, where the schema must normatively enforce typed, unit-tagged values to guarantee interoperability between energy-performance datasets, this is decisive; a CityGML-defined schema can still be serialised to CityJSON for delivery, but CityGML is the appropriate basis for the normative schema definition.

2.3.4. Why CityGML rather than BIM/IFC

The substantive counter-question lies at the fine end of the scale in Figure 2.3, whether Building Information Modelling, and specifically the Industry Foundation Classes (IFC) schema, would not be a more natural fit. IFC is an open, vendor-neutral specification maintained by buildingSMART International and standardised as ISO 16739 (most recently ISO 16739-1:2024, which formalises IFC 4.3) [71]. It is a deliberately exhaustive schema: version 4.3 alone defines over 1,300 entities and data types covering structural, mechanical-electrical-plumbing (MEP), spatial, scheduling, and cost concerns from initial design through facility management.

The argument against IFC for a generic DBL/BRP is not technical but economic and demographic. CityGML and IFC are designed for different scales. CityGML is city-scale and applies semantic generalisation, modelling building interiors only at its highest Level of Detail (LoD), which in CityGML 2.0 is LoD4. IFC, by contrast, is building-scale and construction-oriented, capturing interior detail down to individual cables and pipes [72]. Even an automated IFC-to-CityGML conversion is non-trivial, precisely because the two formats encode different intents. Full, interior-detailed CityGML building models, at LoD3 and above, rarely exist in practice, because constructing them requires multiple acquisition technologies and substantial manual work [72]. CityGML 3.0 removes the separate LoD4 and no longer confines interior modelling to a single level of detail [59], and dedicated IFC-to-CityGML 3.0 conversion tools are beginning to appear.[4] The OGC GeoBIM benchmark [73] confirms that IFC-to-CityGML interoperability is feasible but lossy, and is best understood as integration between two complementary scales rather than substitution.

For a BRP targeting the existing residential stock the asymmetry is decisive. About 75% of EU buildings are energy-inefficient under current standards and roughly 35% are over 50 years old [6]; almost none exist as native IFC models. Producing one retroactively typically requires *scan-to-BIM* workflows that combine laser scanning with extensive manual semantic remodelling, which remains labour-intensive and costly, and whose cost-benefit case for existing buildings is poorly documented [74]. Asking homeowners to fund a full as-built model on top of existing certification paperwork is unrealistic, particularly when the same money would buy actual renovation measures. The 2024 EPBD recast reflects this reality: Article 12 and Annex VIII

[4]Emerging IFC-to-CityGML 3.0 conversion tools include github.com/tum-gis/ifc-to-citygml3.

define the renovation passport in technology-neutral terms and do not mandate any particular data-acquisition technology, BIM and Geographic Information Systems (GIS) included [4].

CityGML, by contrast, aligns with what is realistically obtainable at scale. The Dutch 3DBAG provides automatically generated LoD1.2/LoD1.3/LoD2.2 models for all roughly 10 million buildings in the Netherlands, derived from BAG building footprints and the airborne LiDAR point cloud of the *Actueel Hoogtebestand Nederland* (AHN, the national elevation dataset). It is released as open data [75]. Such data can be combined with EPC audits, address-level cadastral records, and oblique aerial imagery to populate a renovation-passport data model at marginal cost per dwelling. This open 3D data covers only part of what a complete passport needs, but it provides that part at far lower cost than commissioning a full BIM model for each building.

This is not an argument against IFC, but a matter of using the right tool at the right scale. Where a maintained individual-building digital twin already exists, typically in publicly owned portfolios or recent constructions, IFC is the natural BRP carrier; Ugliotti and Stradiotto [76] demonstrate this by mapping EPC content into openBIM property sets for an Italian DBL case study. For the much larger residual stock, where such models do not exist and homeowner willingness to pay is limited, a CityGML-anchored data model draws on public 3D building data already produced for other purposes, keeping the data-acquisition footprint of the BRP in proportion to what owners and Member States can actually deliver.

3. Methodology

3.1. Research design overview

The objective of this research is to determine whether CityGML 2.0 + Energy ADE 3.0 (beta 8), an open geospatial data model, can serve as the data model for a Building Renovation Passport, and to propose targeted extensions where it cannot. Reaching that objective means first establishing what data such a passport must hold, distilled from existing initiatives into the MSRD, then testing this data model against that requirement both conceptually and on real Dutch building-stock data.

This research is organised as a conceptual analysis followed by two implementation tests, as shown in Figure 3.1. The conceptual analysis distilled the MSRD from the 14 surveyed initiatives and mapped it onto the candidate data model (Chapter 4). The first implementation test exercised the resulting mapping at audit depth on one owner-occupier reference building. The second tested it for breadth on a city-scale ingestion of the open Dutch registers. The findings come together as the answer to the main research question in Chapter 7.

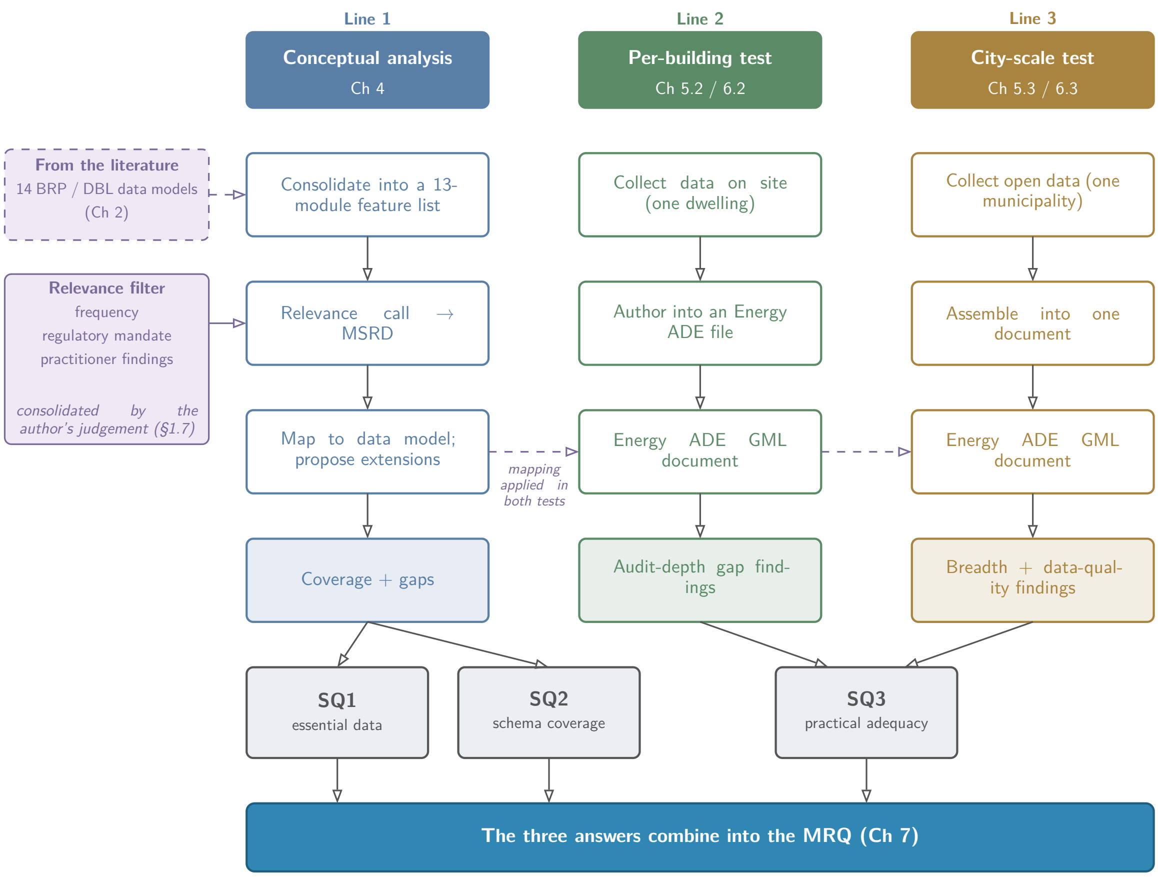


Figure 3.1: Methodology overview: three research lines, each from input through method to the sub-question (SQ) it answers, combining into the main research question. Own work.

The audit-depth test determines whether the schema can represent a full assessment of a single dwelling. The city-scale test determines whether the schema can be populated from real open data across a municipality. In both tests the criterion is the same. A concrete gap is recorded when the audit-depth test finds a field the schema cannot represent, or when the city-scale pipeline can map an open-data field only with loss or an ad hoc workaround. A field the schema can represent in more than one defensible way, where the right modelling choice is not yet settled, is recorded not as a binary gap but as an open design question for the standardisation effort to resolve (Section 7.5.2).

3.2. Methods

3.2.1. Establishing the core concepts

Objective. Establish operationalised definitions of Energy Performance Certificates (EPCs), Digital Building Logbooks (DBLs), and Building Renovation Passports (BRPs), including their interrelationships.

Approach. The analysis started from EU legislation and policy documents (EPBD recast, the Renovation Wave Strategy) to establish definitions of EPCs, DBLs, and BRPs. Academic literature was then reviewed to contextualise these definitions and to record how the concepts are interpreted and applied in practice. Sources were examined to identify recurring patterns in how DBLs and BRPs are related (overlapping, hierarchical, complementary), and these patterns were classified into a five-category framework that consolidates the conceptual picture (Section 2.1).

3.2.2. Gathering the proposed data models

Objective. Collect and document the data models from existing DBL/BRP proposals and implementations, including adjacent tools with related scopes (e.g. EPC-calculation tools, collective-heating decision-support tools).

Approach. Candidate initiatives were found through a literature search, the public deliverables of EU Horizon 2020 and Horizon Europe projects, pointers from colleagues at the faculty, and broad web searches. From these, initiatives were selected for analysis on four inclusion criteria: (1) relevance to the European policy context, (2) accessibility of documentation, (3) diversity in scope and approach (residential vs. non-residential, DBL focus vs. BRP focus, EPC integration), and (4) coverage of different building typologies. Only initiatives whose documentation was public or licensable were retained, since a closed model cannot be compared on coverage.

Data collection proceeded through document analysis of technical reports, project deliverables, data-model specifications, and public documentation of EU-funded projects. Google Scholar and Scopus were consulted to find additional DBL/BRP data-model proposals. The software interfaces and, where available, the documentation of operational tools were also assessed.

For each initiative, the data model was documented by recording the data fields, their definitions, data types, units of measure, and semantic context. As anticipated, this often involved extracting descriptive specifications, Excel templates, or fields implied by the software user interface, since many initiatives lack a formally specified schema.

3.2.3. Comparing the models and synthesising the MSRD

Objective. Synthesise the diverse data models into the MSRD, the essential data requirements for DBLs/BRPs (SQ1).

Approach. The comparative analysis followed a structured, bottom-up procedure. Every attribute from every initiative was first laid out side by side, then clustered by semantic meaning rather than by label, so that fields with different names but equivalent meaning aligned. For example, 'number of floors' and 'amount of floors' merged into a single theme.

To keep the comparison manageable and organised, the fields were grouped into semantic modules. The module boundaries were based on two of the most fully specified proposals. The

EUB SuperHub Digital Building Logbook supplied the category naming, and Gómez-Gil et al. supplied the finer separation of construction, systems, and renovation advice. Both were cross-checked against X-tendo and BUILDCHAIN. The result was reconciled into a single scheme and refined as the remaining initiatives were brought into the comparison, with individual fields moved between modules where a cleaner home emerged. The granularity was tuned to keep the comparison readable. Where only one initiative split a theme into finer fields, such as breaking a single address into separate street, house number, and town fields, those finer fields were collapsed into one line.

The resulting clusters were organised into 13 high-level modules (identification and administrative details; general building characteristics; envelope, construction and materials; technical systems; attachable documents; dimensions; operation and use; legal and finance; ancillary data and context; energy performance; indoor environmental quality; smart readiness; renovation advice). In the comparison of Chapter 4 these 13 modules are grouped into 3 conceptual layers along a dependency chain, repository, assessment, and functional. What each layer covers, and which modules belong to it, is set out where the layers organise that comparison (see Section 4.2.2). A building cannot be assessed without the repository data, and a roadmap cannot be advised without both the data and the assessment, which is the dependency the layering captures.

The module structure is a guideline, a deliberate middle ground between a field list too specific to compare across initiatives and one too generic to be informative. This taxonomy was built from the initiatives alone, independently of the target data model; the alignment noted in Chapter 4 between the three layers and distinct regions of the schema is therefore a finding about the schema's organisation, not an input to the module design. For each module, a matrix recorded which initiatives included which themes, and a descriptive summary captured how the included initiatives populated each theme.

The promotion of each module-level theme into the MSRD applied a discretionary relevance filter. The filter draws on three named inputs:

1. frequency of inclusion across the 14 surveyed initiatives, as a relative signal rather than a hard threshold;
2. regulatory mandate in EPBD Annex VIII; and
3. practitioner findings from the parallel MBE thesis, which interviewed 17 respondents across 9 stakeholder categories on which Dutch building-data sources they actually consult and trust.

These three inputs do not vote. They are consolidated by the author's discretionary judgement on BRP applicability, formed over the course of the thesis. The filter is therefore non-tiered: no single input automatically determines inclusion, and the relevance designation per field is the author's reasoned call on where the three inputs converge or diverge. To keep that call legible, the reasoning is written out alongside the notable and contested fields in the per-module comparison of Section 4.2.

This is a deliberate methodological trade-off. A stricter formula, such as promoting any theme that appears in more than half the initiatives, or a weighted score, would have been more reproducible, but it would have lost the contextual reasoning that the discretionary judgement carries.

3.2.4. Mapping onto the data model and proposing targeted extensions

Objective. Determine whether CityGML 2.0 + Energy ADE 3.0 (beta 8) can cover the MSRD data fields (SQ2), identify the gaps, and propose targeted extensions for the fields it does not cover directly.

Approach - mapping. The technical documentation for CityGML 2.0 + Energy ADE 3.0 (beta 8) (Section 2.3) was reviewed to map its structure, semantics, and extensibility mechanisms. A systematic mapping exercise was then conducted between the MSRD specification and the schema's UML model. For each MSRD field, the analysis recorded whether the field could be represented in the existing schema, and if so, which specific class, attribute, association, or relationship covered it. Each field was then assigned to one of three coverage outcomes. A field is covered directly when the existing schema already has a place for it, coverable through a proposed extension when it does not but a targeted addition would, and out of scope when it does not belong in a geospatial data model at all. The principal measure for SQ2 is the share of relevance-filtered MSRD fields that fall in each outcome.

Where the schema did not cover a field directly, the gap was classified by kind. The kinds are an absent class, a missing attribute on an existing class, insufficient semantic specificity, an incompatible data type, a missing relationship, and a structural or cardinality limitation. A structural or cardinality limitation might be a value the schema cannot reference, or an attribute that admits only one value where several with separate provenance are needed. A limitation of the last kind is often recorded as an open design question rather than as a single missing class or attribute. These six kinds classify every gap the thesis records, whether it was found in the per-module mapping of Chapter 4 or later in the audit-depth test (Section 6.2), so both sets of findings can be read in the same terms.

Energy ADE 3.0 extends CityGML 2.0 rather than CityGML 3.0 (see Section 2.3); a port of its conceptual model to CityGML 3.0 is flagged as future work in Section 7.5. A scenario-storage separation was kept explicit throughout: the schema should hold the inputs and outputs of a scenario evaluation, but not implement the energy-calculation algorithm itself (NTA 8800 or equivalent). The latter is functional processing beyond the scope of a data-model evaluation.

Approach - targeted extensions. Where the mapping revealed a gap, an extension was proposed following the UML-based, model-driven approach to CityGML Application Domain Extension (ADE) development set out by van den Brink, Stoter, and Zlatanova [77], which is also the approach the Energy ADE itself follows [63]. For each gap, the extension proposed one or more of the following, as the gap required:

- new classes, with definition, attributes, and inheritance;
- new attributes on existing classes, with name, data type, multiplicity, and semantic definition;
- new associations between existing or new classes; and
- new code lists for enumerated values that need standardisation.

The extensions are framed as proposed sketches and input to the Energy ADE development effort, not as finished artefacts. Where the right direction is not yet clear, the case is documented as an open question for future work. The consolidated set of proposed extensions, including additional proposals responding to the audit-depth findings of Section 6.2, is presented in the discussion (Section 7.3).

The first supervisor of this thesis is heavily involved in the development of the Energy ADE 3.0 [63]. Some refinements identified during the mapping and audit work were taken up in the schema before the beta 8 freeze, and are reported separately as a contribution of the thesis (Section 7.2.3). To keep the evaluation independent of that supervisory role, it is pinned to the resulting fixed baseline, the beta 8 XSD dated May 14, 2026. The extensions this thesis proposes go beyond that baseline and are not yet adopted into it.

3.2.5. Testing at two scales

Objective. Test the practical adequacy of the mapping by populating the schema with real Dutch building-stock data at two complementary scales, audit depth and city-scale breadth (SQ3).

Because neither pipeline implements the proposed extensions, both scale tests exercise the base schema rather than the extensions.

Approach - per-building test. The audit-depth test took one owner-occupier dwelling in Delft as its case. An owner-occupier home was chosen for two reasons. The Dutch *gebouwrenovatiepaspoort* (building renovation passport) is being developed as an extension of the *maatwerkadvies* (building-specific renovation advice) that energy-performance advisors deliver to exactly this group, so the case matches the instrument the thesis targets. A fully documented dwelling also lets the test exercise most of the Energy ADE schema at audit depth.

The building data were collected with reference to the ISSO 82.1 intake protocol [78], the checklist Dutch energy-performance advisors work through, so that the recorded data reflect what a realistic BRP-style audit gathers. The checklist was used to make sure no thematic area was overlooked, not as the sole source, since building plans, detail drawings, the existing energy label, and conversations with the resident also fed the model. The intake deliberately stayed within realistic limits. The dwelling was visited once, the roof was not climbed, and no specialised equipment was used, mirroring what an energy-performance advisor's intake actually collects. Fields that could not be populated under these conditions are therefore reported as what such an intake misses, not as data unknowable in principle. The collected data were authored into a GML document under the schema, covering the dwelling's zones, schedules, devices, layered constructions, and a material library.

Approach - city-scale test. The city-scale test populated the same schema from open data across a whole municipality. A second scale was needed because many renovation decisions cannot be taken at the level of a single dwelling. A connection to district heating, neighbourhood-scale planning, and the aggregated statistics published only at postcode level all lie above the individual building, so a city-scale model reaches a category of information the per-building test cannot.

The pipeline took a configuration naming a Dutch municipality and assembled one document from BAG, 3DBAG, EP-Online, the *Basisregistratie Grootschalige Topografie* (BGT, Key Register of Large-Scale Topography), and *Centraal Bureau voor de Statistiek* (CBS, Statistics Netherlands) Postcode-6 statistics. The pipeline also adds solar-panel polygons [79] and individual trees (CFTree) [80][5]. The pipeline was run on a small area of Emmer-Compascuum, a village in the municipality of Emmen, chosen because the open solar-panel dataset and AHN6 elevation data both cover it. This let the solar-panel and tree layers be exercised alongside the core registers. Taking a small-area subset keeps the demonstration legible.

[5]The CFTree implementation is openly available at github.com/NoahAlting/CFTree (GPL-3.0); the AHN6-compatible fork used in this thesis is at github.com/DaanSchlosser/CFTree.

All city-scale sources are open Dutch government data or openly licensed research datasets, expressed in the Dutch national grid (`EPSG:28992`). Their provenance, vintage, and licences, together with which pipeline consumes each, are documented with the implementation in Chapter 5 and the reproducibility appendix (Appendix A). Using only open or licensable data keeps the breadth test reproducible, but it also bounds the result, since the sources are Dutch and the breadth findings transfer to other countries only where comparable open data exists.

The pipeline was also run on Delft, Groningen, and Zwolle. These additional runs do not carry the main evaluation, which rests on Emmer-Compascuum, but they widen the sample for a cross-source data-quality analysis. Because the integrated document brings BAG, 3DBAG, and EP-Online onto the same building, an attribute that several registers report independently, such as construction year or net floor area, can be compared directly. The analysis recorded the rate of cross-register agreement, detected default and placeholder values, and inspected rounding patterns. Throughout, these are treated as reconciliation targets that an integrated, semantically precise model makes tractable, not as criticism of any single source.

Approach - validation. Two kinds of evidence establish adequacy, and they demonstrate different things. Whether the schema semantically covers the MSRD, that is, whether it has a meaningful place for each field, is established by the mapping (Section 3.2.4) and, for a fully populated building, by the audit-depth test. Structural correctness of the produced documents is established separately. Each output file was validated against the bundled Energy ADE 3.0 (beta 8) XSDs, which confirms that the GML conforms to the schema but says nothing about whether the schema covers the MSRD. Structural inspection in the KITModelViewer was documentary, confirming that the expected parent-child nesting and populated Energy ADE classes appeared as designed. It let the structure be read and visualised, including geometries (wherever applicable), without parsing the XML by hand.

3.3. Research timeline

The research spans three TU Delft graduation quarters (Q6-Q8); Figure 3.2 shows the six work-streams and the four assessment milestones (A1-A4). A1 (January 27, 2026) was the formal kick-off from which the substantive comparative work began; the preceding period was directed at problem framing, background reading, and initial data-model documentation. The MSRD comparison and the CityGML 2.0 + Energy ADE 3.0 mapping ran sequentially from February through to early April. Schema-extension reasoning and implementation testing then ran in parallel from late March, the per-building pipeline preceding the city-scale one by about a month so that the fields it established at audit depth could inform the city-scale ingestion design. Writing ran continuously from mid-January, with revision passes in late May.

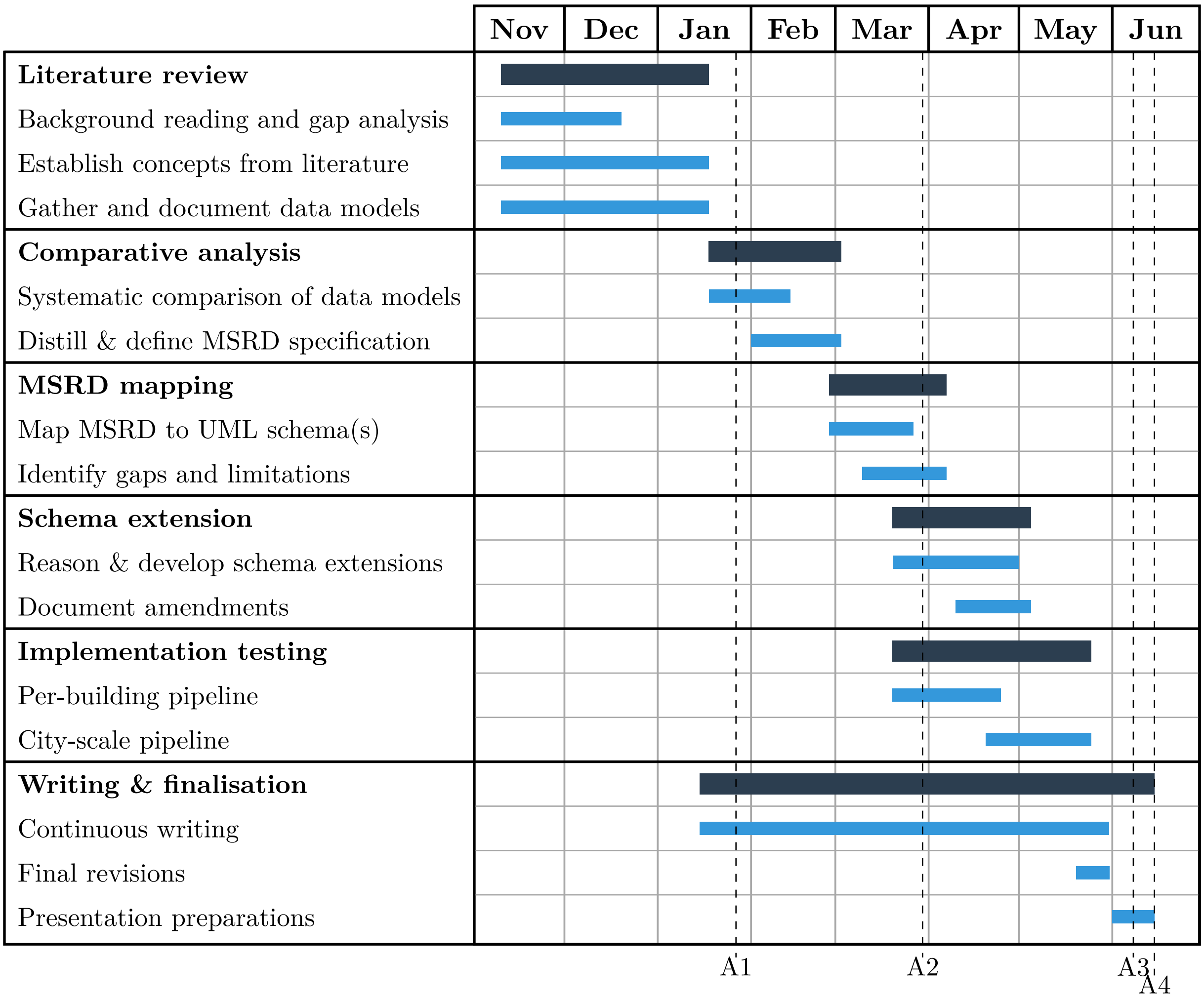


Figure 3.2: Thesis research timeline. Milestones: A1 kick-off (January 27, 2026), A2 midterm (March 30, 2026), A3 green light (June 8, 2026), A4 finalisation (June 15, 2026). Own work.

4. Conceptual Analysis

4.1. Introduction

This chapter delivers the conceptual contribution of the thesis. It compares the 14 reviewed initiatives, synthesises the resulting MSRD, and identifies where CityGML 2.0 + Energy ADE 3.0 (beta 8) does not cover the MSRD directly.

The chapter is organised in two parts. Section 4.2 compares the 14 initiatives at two levels. The top-level category layer shows how differently the initiatives organise the same content, while the per-module field layer works across 13 modules grouped into 3 layers (a repository layer, an assessment layer, and a functional layer). Each module is handled in its own sub-subsection, which compares the initiatives, decides which fields are relevant using the relevance filter from Section 3.2.3, and maps the relevant fields to the data model. Section 4.3 then assembles the cross-module summary and reports how well CityGML 2.0 + Energy ADE 3.0 (beta 8) covers the result.

4.1.1. Worked examples of relevance reasoning

The relevance call in this thesis is a judgement informed by three inputs (as discussed in the methodology). These are then weighed together, and the final call is made. The five examples below show how the inputs combine on individual fields, so the reasoning behind each per-module decision is clear before the per-module sweep in Section 4.2.

Example 1: Energy label (Module 10). The energy-performance label is included by almost every surveyed initiative, is explicitly required as part of a Building Renovation Passport by EPBD Annex VIII §1, and is named by practitioners across all stakeholder categories in the parallel MBE thesis as the single most-consulted building-data field. All three inputs converge. **Verdict: in the MSRD.**

Example 2: Building address (Module 1). The address is included by almost every initiative, is implicitly required as a building identifier by EPBD Annex VIII §1, and is named in the parallel MBE thesis as the primary key that practitioners use to link building data across registers (BAG, EP-Online, cadastre). All three inputs converge. **Verdict: in the MSRD.**

Example 3: Owner address (where different from building address) (Module 1). The owner's address is included by only a minority of initiatives, is not mentioned in EPBD Annex VIII §1, and is described by parallel-MBE practitioners as information that belongs to the cadastral or municipal administrative system rather than to a building-data instrument. The low frequency, the absence of regulatory mandate, and the practitioner framing of scope each point the same way: owner identity is an administrative concern adjacent to the data model rather than a property of the building itself. The connection to a specific owner can be carried by a stable building identifier resolved against an external administrative layer. **Verdict: not in the MSRD.**

Example 4: Expected building lifetime (Module 2). The field appears in barely any of the initiatives, is not named in EPBD Annex VIII §1, and is not raised by parallel-MBE practitioners as a field they consult. On the three inputs alone it would fall out. The renovation logic pulls the other way. Whether a renovation is worth undertaking depends on how much longer the building is expected to stand, and a building near the end of its life is a poor candidate for deep renovation. That decision relevance carries the field into the MSRD on the author's own judgement, against the three inputs. It maps onto the generic `validTo` attribute that every `_CityObject` already carries, so recording it costs no extra modelling effort and keeps the model future-proof. **Verdict: in the MSRD.**

Example 5: Identified damages (Module 3.1). Damage observations appear in only a minority of initiatives, but are named in EPBD Annex VIII §1 indirectly through the requirement that the BRP capture wider information related to building condition, and are repeatedly named in the parallel MBE thesis as the type of information practitioners need at inspection time and currently struggle to record in a structured way. Here the inputs diverge. Frequency is low, but the regulatory mandate and the practitioner pull both point to inclusion, and together they carry the field. **Verdict: in the MSRD.**

These five examples show the kind of reasoning that has been performed across the 13 modules, for each individual field. The reasoning is written out for the notable and contested fields. The resulting verdict, in or out of the MSRD, is recorded for every field in its module's mapping table.

4.2. Structural comparison of the assessed initiatives

4.2.1. Overview and organisation

The 14 initiatives are not a like-for-like set. As Table 3 has shown, they range from data-model proposals (EUB SuperHub, X-tendo, BUILDCHAIN), through national implementations (Woningpas, CLÉA, iSFP), to tools that only consume building data (Vitec Vabi's EPA software, BuurtWarmteWijzer, Hoomdossier). They also target different building stock, from the entire stock down to residential-only, and operate at scales from the single building to the neighbourhood. These differences shape what each initiative records and how it organises that record, so placing them on a common footing is the first task of this section.

Beyond purpose and scope, the initiatives also differ in breadth and depth of coverage, and in how they organise and frame their data fields. They distinguish different groupings, name those groupings differently, and attach a different semantic scope to each name. These differences are flattened by the module-by-module comparison in the following sections, which re-expresses every initiative in a single shared set of categories that this thesis synthesised for this comparison (Section 3.2.3).

Read side by side, the initiatives' own structures reveal several recurring patterns in how they divide and label the same content. The five most prominent are set out below.

Naming divergence for equivalent content. Initiatives often label the same conceptual area very differently. For example, what this thesis calls "Identification & administrative details" is labelled "Administrative information" in EUB SuperHub, X-tendo, and BUILDCHAIN; "1.1 Administrative data" (a sub-section inside the wider "B1 Building Picture" module) in ALDREN; "A. General and administrative information" in iBRoad; "*Données générales*" in CLÉA; "*Woninggegevens*" in Hoomdossier; and "1. Building data & geometry" in iSFP (where it is merged with the geometry module).

How themes are merged, or split. EUB SuperHub places both the envelope/construction data and the technical building systems under a single umbrella labelled "Building element information", with no structural distinction between the two. iBRoad does the same under "B. Building construction information". X-tendo and Gómez-Gil, by contrast, give these two areas separate categories ("Building description & characteristics" plus "Building material inventory" for X-tendo; "Construction and materials" plus "Technical systems" for Gómez-Gil). ALDREN is different again. All four themes (envelope, systems, general building characteristics, and dimensions) are sub-sections of the same top-level module “B1 Building Picture”, differentiated only by a section number (1.x, 2.x, 3.x, 4.x).

Calculation-chain organisation versus building-part organisation. Most initiatives organise categories around physical parts of the building (envelope, systems, etc.). iSFP breaks with this completely, structuring its categories around the energy calculation chain, moving from geometry input and physics parameters through energy metrics, building components, system technology, and financials to environmental impact and user influence. The result is a category named “2. Calculation parameters & physics” with no counterpart in any other initiative. Vitec Vabi’s EPA software does something similar (implicitly, organised around the NTA 8800 calculation norm), as do BuurtWarmteWijzer’s database tables (“scenarios”, “data_3d_var”) which represent calculation scenarios rather than building parts.

Resident-centred framing. Hoomdossier inverts the structure entirely. Where all other initiatives start from the building’s physical attributes, Hoomdossier starts from the resident: their motivations (“*Woondroom / Drijfveer*”), their wishes (“*Woonwensen*”), and their behaviour (“*Kleine maatregelen & gedrag*”). The building’s physical status (“*Woningstatus*”) appears only as one of seven categories, subordinate to the resident’s perspective. No other initiative in this comparison has structured its data this way.

Absent categories. Some initiatives lack certain data categories. For example, finance and legal data is completely absent in BuurtWarmteWijzer (perhaps since its main purpose is a scenario calculation tool) and largely absent in Hoomdossier (centred on the resident rather than property valuation). Smart readiness and indoor environmental quality are absent in Hoomdossier and CLÉA, and only marginally present in Woningpas and iSFP.

Because the initiatives divide the same content so differently, comparing them at all required normalising onto a single neutral scheme. The 13 modules used throughout this chapter, and the 3 layers they group into, are that scheme, synthesised from the initiatives rather than adopted from any one of them (see Section 3.2.3 for the full rationale). Figure 4.1 records each initiative’s own category structure directly, before this flattening, placing them side by side for comparison.

Figure 4.1: Top-level data structure of each assessed initiative, in its own order and naming. Module names and groupings follow each initiative's own documentation. Where an initiative names many very specific sub-categories, these are collapsed onto the single module this thesis condensed them into. Own work.

4.2.2. Table layout and module layers

The per-module comparisons that follow all share the same table shape, shown first for Module 1 in Table 5. They all follow the same structure:

- The **Feature** column names a data field that recurs across the initiatives;
- The % column gives how many of the 14 initiatives include it;
- The **MSRD** column gives the relevance-filter verdict, that is, whether the field is taken into the Minimum Set of Required Data;
- The remaining columns give where the field maps in the data model, by module, class, attribute, and type.

For a field taken into the MSRD, a mapping target in these columns means the existing schema covers it, while a cross (✗) means no faithful target exists and a targeted extension is required. Coverage here also includes a generic free-text attribute where the field is itself given as an unstructured note. It does not extend to fields whose faithful use would need structure the schema lacks, such as a dedicated class, an enumerated type, or a way to sequence the field. The same shape recurs in every per-module mapping table in the sections that follow.

Per-initiative inclusion matrices for modules 2-13 are reproduced in Appendix B to keep the body compact; each module section below shows the field-to-CityGML / Energy ADE mapping table only. Module 1 retains both the inclusion matrix and the mapping table as a demonstrator.

- The **repository layer** (Modules 1-9) carries the raw building data the passport stores, physical and administrative: identification, general characteristics, envelope and materials, technical systems, attachable documents, dimensions, operation and use, legal and finance, and ancillary or environmental context.
- The **assessment layer** (Modules 10-12) carries the building's performance and quality characterisations, whether measured or computed: energy performance, indoor environmental quality, and smart readiness.
- The **functional layer** (Module 13) carries the renovation-passport output itself, which a passport can only produce once the repository data and its assessment are in place.

The layers map roughly onto distinct parts of the CityGML 2.0 + Energy ADE 3.0 (beta 8) schema (the repository layer to CityGML Core, Energy ADE Building Physics, Devices, and Layered Construction; the assessment layer to Energy ADE Resources and additional attributes; the functional layer to the schema area where extensions are most likely required).

4.2.3. Repository layer (Modules 1-9)

Identification & administrative details

Module 1 covers the identification and administrative details of the building. Most DBL proposals start with these details, such as address fields and geospatial coordinates, often accompanied by a building identifier. Ownership and occupancy details are also frequently included.

Environmental and contextual fields such as climate and soil are not included in this module, since they are not administrative information; see Module 9 (ancillary data and context) for these fields.

Table 4 shows an overview of the data fields proposed/used in the 14 assessed initiatives.

Feature	**I1**	**I2**	**I3**	**I4**	**I5**	**I6**	**I7**	**I8**	**I9**	**I10**	**I11**	**I12**	**I13**	**I14**	**Total**	**%**
Building address details	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	14	100%
Building identification (Cadastral/INSPIRE)	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			11	79%
Ownership details and occupancy details	✓	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓	✓	12	86%
Geospatial Coordinates (latitude, longitude, altitude)	✓	✓	✓	✓		✓	✓				✓				7	50%
DBL author/ assessor qualifications and information	✓	✓		✓	✓	✓		✓	✓	✓			✓	✓	10	71%
Details on the building with building-unit relation			✓	✓	✓		✓		✓	✓	✓				7	50%
Timestamps on collection, provision or modification**			✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		10	71%
Building owner address details			✓							✓		✓	✓	✓	5	36%

Table 4: Overview of the features of module 1: Identification & administrative details. Initiative IDs (I1-I14) are defined in Table 3. Own work.

Some of the initiatives only describe the need for an address field. Yet, most proposals give concrete data fields that belong to an address, using varying semantics (e.g. street, ThoroughfareName, 'address', thoroughfare, all to indicate the street name), and include various levels of administrative units, such as country, region, municipality, street name, number, number extension(s), postcode, PO box, and occasionally the building name.

Most initiatives propose to include some sort of unique building identification, without going into further detail. Some are more specific and explicitly refer to the local cadastral ID, and others even suggest also including the INSPIRE ID. Table 5 shows the mapping.

Feature	**%**	**MSRD**	**Module**	**Class**	**Attribute**	**Type**
Building address details	100%	Yes	Core*	Address	Multiple	Multiple
Building identification (Cadastral/INSPIRE)	79%	Yes	Core	_CityObject	identifier	Code [0..1]
Ownership details and occupancy details	86%	Yes	Building Building	_AbstractBuilding _AbstractBuilding	bdgOwnerName bdgOwnershipType	CharacterString [0..1] OwnershipTypeValue [0..1]
Geospatial Coordinates (latitude, longitude, altitude)	50%	Yes	Core	_CityObject	referencePoint	GM_Point [0..1]
DBL author/ assessor qualifications and information	71%	Yes	DataTypes	Metadata	Multiple	Multiple
Details on the building with building-unit relation	50%	Yes	Building	BuildingUnit	N/A (done by composition)	
Timestamps on collection, provision or modification**	71%	Yes	Core* Core*	_CityObject _CityObject	creationDate terminationDate	Date [0..1] Date [0..1]
Building owner address details	36%	No	✗			

Table 5: Overview how each feature of module 1 maps onto the CityGML Core and/or the Energy ADE. Column **%** gives the feature's frequency across the 14 initiatives; column **MSRD** gives the relevance-filter call (per the relevance filter of Section 3.2.3). An asterisk (*) denotes a CityGML Core module attribute; no asterisk denotes an Energy ADE attribute. **Besides the Energy ADE attributes, 3DCityDB instances have additional administrative database fields for all `CityObject`s. Own work.

Module 1 is already almost fully covered by the data model as is, except for the address details of the building owner where these differ from the building's address. A DBL or BRP describes the physical characteristics of a building, and owner details not tied to the building itself raise privacy concerns, which likely explains why only a minority of initiatives included them. The owner identity should be maintained in an external administrative system and linked via the building's stable unique identifier. Login or system credentials are treated the same way; they are an implementation concern rather than a property of the building, and belong in a separate authentication layer, not in the data model.

Regarding the building identification, `ExternalReferences` could also be used if there is a desire to store both a national and an INSPIRE cadastral ID at once. Whether a (Dutch) BRP requires both is a decision for the ministry. What matters is that either one is a unique identifier that stays stable for the whole lifecycle of a building.

General building characteristics

Module 2 collects the characteristics that describe the building as a whole, separate from its envelope (Module 3) or its technical systems (Module 4). These run from the year of construction, the use and building type and the number of floors and units through to the roof type and the status indicators (building state, conservation status, protected-monument status) that condition any renovation. They are the descriptors most initiatives record first, and the ones the energy and renovation analysis downstream treats as fixed inputs. Table 6 shows the mapping.

Feature	%	MSRD	Module	Class	Attribute	Type
Year of building construction	100%	Yes	Building	_AbstractBuilding	yearOfConstruction	xs::gYear [0..1]
Date of demolition	7%	No	Building	_AbstractBuilding	yearOfDemolition	xs::gYear [0..1]
Number of floors	86%	Yes	Building	_AbstractBuilding	storeysAboveGround	xs::nonNegativeInteger [0..1]
			Building	_AbstractBuilding	storeysBelowGround	xs::nonNegativeInteger [0..1]
Year of last (major) renovation, and description	57%	Yes	Core	Intervention	interventionStartDate	Date [0..1]
			Core	Intervention	interventionEndDate	Date [0..1]
			Core	Intervention	type	InterventionTypeValue
			Core	Intervention	action	InterventionActionValue [0..1]
Building use/function	79%	Yes	Building	_AbstractBuilding	function	BuildingFunctionType [0..*]
			Building	_AbstractBuilding	usage	BuildingUsageType [0..*]
Building type (MFH, SFH, office, etc.)	86%	Yes	Building	_AbstractBuilding	bdgType	BuildingTypeValue [0..1]
Building name (or project name)	71%	Yes	Core	AbstractFeature	name	CodeType [0..*]
Number of dwelling units	50%	Yes	Building	_AbstractBuilding	bdgNumberOfBuildingUnits	Integer [0..1]
Number of total units (or as linked to)	29%	Yes	Building	_AbstractBuilding	bdgNumberOfBuildingUnits	Integer [0..1]
Type of roof (flat, gabled, hipped)	43%	Yes	Building	_AbstractBuilding	roofType	RoofTypeType [0..1]
Number of (specific type/ total) rooms	29%	Yes	Building	BuildingUnit	numberOfRooms	Integer [0..1]
Main orientation the building faces	29%	Yes	Building	_BoundarySurface	bdgBdrySurfAzimuth	Angle [0..1]
Details on barrier-free design (e.g. ramps)	21%	No	Building	BuildingInstallation	class	BuildingInstallationClassType [0..1]
Existence of elevators	21%	Yes	Building	BuildingInstallation	class	BuildingInstallationClassType [0..1]
Building state (new, in-design, existing, etc.)	36%	Yes	Core	_CityObject	status	StatusValue [0..1]
The floor of the unit	21%	Yes	Building	BuildingUnit	floorNumberFrom	Decimal [0..1]
			Building	BuildingUnit	floorNumberTo	Decimal [0..1]
Overall building conservation status (bad, good, etc.)	21%	Yes	Core	_CityObject	indicator	Indicator [0..*]
Number of (disabled) car parking spaces	14%	No	Transportation	TrafficArea	function	TrafficAreaFunctionType [0..*]
Whether the building has any sort of historical status	43%	Yes	Building	_AbstractBuilding	bdgIsProtected	Boolean [0..1]
Is the topmost floor heated?	29%	Yes	Building	_AbstractBuilding	bdgAtticThermalStatus	ThermalStatusValue [0..1]
Whether the basement floor(s) is/are heated	21%	Yes	Building	_AbstractBuilding	bdgBasementThermalStatus	ThermalStatusValue [0..1]
Expected building lifetime	14%	Yes	Core	_CityObject	validTo	DateTime [0..1]
If there are thermally (un)conditioned sport facilities	14%	No	Building	AbstractZone	type	CurrentUseValue
			Building	AbstractZone	isHeated	Boolean [0..1]
			Building	AbstractZone	isCooled	Boolean [0..1]
Number of swimming pools, elevators, balconies	7%	No	Devices	AbstractDevice	numberOfDevices	Integer [0..1]

Table 6: Overview how each feature of module 2 maps onto the CityGML Core and/or the Energy ADE. An asterisk (*) denotes a CityGML Core module attribute; no asterisk denotes an Energy ADE attribute. Own work.

Module 2 is fully covered by the data model as is. The number of dwelling or total units, if building-unit objects are explicitly modelled, can simply be classified by function and counted. However, if available a better proxy for simulation is the qualified floor area split by residential / non-residential, rather than a raw unit count.

The overall building conservation status, and other such descriptive and subjective attributes, are best treated as a derived description, e.g. from an inspection, rather than a direct input attribute. Such an attribute could help prioritise renovation works, but its granularity and subjectivity make it unusable as input for objective analysis and simulation.

Several fields are left out of the MSRD as out of scope for a renovation passport. The date of demolition marks the end of a building's life rather than its renovation, and a handful of accessibility and amenity details recorded by only one or two initiatives do not bear on the renovation or energy assessment. Several of these excluded fields nonetheless keep a mapping target in Table 6: where a native CityGML or Energy ADE attribute already exists for them, the mapping is recorded at no extra cost, which leaves the model ready for them should a later use emerge.

Lastly, the 'Expected building lifetime' is taken into the MSRD on the reasoning of Section 4.1.1, and maps onto the generic `validTo` attribute on `_CityObject`, set to the expected end-of-life date. This is distinct from the demolition date above, which records an actual end-of-life event rather than a forward-looking expectation that bears on whether a renovation is worth undertaking.

Envelope, construction & materials

Module 3 covers the building envelope and the materials it is built from. It is split into two parts: part I treats the high-level construction, the thermal-envelope performance, and the openings; part II treats the layer build-up and the material library. Table 7 and Table 8 show the mapping.

Some initiatives have narrowly targeted data fields for narrowly targeted questions, such as what the finish of the external walls is, or whether an envelope element is insulated, recorded as a checkbox or boolean value. While these can be useful, an actual layer build-up is far more versatile, and can also answer these questions, for example by checking whether the build-up has an insulation layer or what the material or description of the last layer is.

Feature	%	MSRD	Module	Class	Attribute	Type
High-level envelope & construction						
The high-level type of construction	29%	Yes	Layered construction	LayeredConstruction	type	LayeredConstructionTypeValue [0..1]
The high-level facade type (glass, steel, etc.)	36%	Yes	Layered construction	LayeredConstruction	type	LayeredConstructionTypeValue [0..1]
The main structure of the building	36%	Yes	Building	_AbstractBuilding	bdgConstructionWeight	ConstructionWeightValue [0..1]
Identified damages (cracks, degradation, etc.)	14%	Yes	✗			
Identified post-catastrophic damages	7%	Yes	✗			
Details on thermal bridges	43%	Yes	Building	_BoundarySurface	bdgBdrySurfAdditionalThermal-BridgeUValue	Measure [0..1]
Internal heat capacity per m²	29%	Yes	Building	AbstractZone	heatCapacity	Measure [0..1]
Infiltration rate (1/h)	36%	Yes	Building	AbstractZone	infiltrationRate	Measure [0..1]
Openings (Windows, Skylights, Doors)						
Only description of the necessity of describing openings	7%	N/A	N/A			
Indication what kind of opening it is	57%	Yes	Building	AbstractZoneOpening	N/A (done by composition)	
Total area of the opening (m²)	50%	Yes	Building	_Opening	bdgOpnArea	Area [0..1]
g-value of the opening	43%	Yes	Layered construction	LayeredConstruction	gValue	Scale [0..1]
Type of the window glazing (single, double, triple, etc.)	64%	Yes	Layered construction	LayeredConstruction	type	LayeredConstructionTypeValue [0..1]
The type of sun shading (e.g. no shading, external, etc.)	36%	Yes	Devices	MovableShadingDevice	type	ShadingDeviceTypeValue
Frame to glass proportion/ percentage indication	36%	Yes	Layered construction	LayeredConstruction	glazingRatio	Scale [0..1]
The materials of the opening, like frame, glazing, etc.	36%	Yes	Layered construction	SolidMaterial	type	SolidMaterialTypeValue [0..1]
Frame U-value (W/m²K)	36%	Yes	Layered construction	LayeredConstruction	uValue	Measure [0..1]
Glazing U-value (W/m²K)	29%	Yes	Layered construction	LayeredConstruction	uValue	Measure [0..1]
Total U-value of the opening (W/m²K)	71%	Yes	Layered construction	LayeredConstruction	uValue	Measure [0..1]
Orientation of the opening	29%	Yes	Building	_Opening	bdgOpnAzimuth	Angle [0..1]
Light Transmission (LT) factor	14%	Yes	Layered construction	LayeredConstruction	transmittance	Transmittance [0..*]
Producer/ Brand	14%	Yes	Core*	_CityObject	externalReference	ExternalReference [0..*]
Model number	14%	Yes	Core*	_CityObject	externalReference	ExternalReference [0..*]
Airtightness class	14%	Yes	✗			
Total height & total width	21%	Yes	Building	_Opening	geometry	lod3MultiSurface
Digital Product Passport	7%	No	Core*	_CityObject	externalReference	ExternalReference [0..*]
Specific mention of images/photographs of the opening	7%	No	Core*	_CityObject	externalReference	ExternalReference [0..*]
Quantity of identical openings	7%	Yes	✗			
Source used (e.g. by inspection or by specifications)	7%	Yes	DataTypes	Metadata	source	CharacterString [0..1]
Description of the state of the opening (e.g. leaky)	14%	Yes	Core	_CityObject	status	StatusValue [0..1]

Table 7: Overview how each feature of module 3, part I maps onto the CityGML Core and/or the Energy ADE. An asterisk (*) denotes a CityGML Core module attribute; no asterisk denotes an Energy ADE attribute. Own work.

The initiatives that have included a high-level type of construction and facade type have added this as a dedicated attribute, yet actually no dedicated attribute is needed. This could (and should) be modelled by attaching one representative `LayeredConstruction` to the building directly, with a single-layer proxy, e.g. concrete. This is consistent with how walls reference constructions, here just applied at the building level. Additionally, 'Facade' in the data model means all exterior vertical surfaces touching outside air.

Identified damages and identified post-catastrophic damages are both relevant to a renovation passport, since a damaged element is a natural opportunity to renovate rather than merely repair. Neither can be modelled directly. The schema has no class that records a dated, located, and severity-rated observation of a defect, which is an absent-class gap. The same shape recurs in the condition-related fields of Modules 2 and 4, so a single condition-observation pattern that responds to it is proposed in Section 7.3. The point made by several initiatives still holds: such an observation is only useful if it is clear and measurable.

The airtightness class of an opening has no direct mapping. It does not quite reduce to an infiltration rate of zero, as one might assume, since a perfectly airtight dwelling is uninhabitable and its air must still be changed. Two quantities sit behind the term: the unintended leakage of a poorly sealed envelope, which the infiltration rate on `AbstractZone` already carries at zone level, and the deliberate air changes a dwelling needs, modelled separately through ventilation. The simulation-relevant behaviour is therefore covered without the class. What is left unmapped is the per-opening airtightness label itself, which several initiatives record without attaching a defined meaning to it, a minor missing attribute rather than a structural gap, noted in Section 7.3.

The quantity of identical openings has no dedicated count attribute, a minor missing-attribute gap noted in Section 7.3. Where the individual openings are not modelled or drawn geometrically, the total surface area and opaque area can be stored and used as a proxy, and a bare count says little on its own without the U-value or size of the opening.

A free-text quality description of the state of an opening is carried, loosely, by a generic string attribute on any `_CityObject`, the same mechanism used for other unstructured notes in this chapter. It serves inspection workflows, though only as an unstructured note. A formally structured condition rating, by contrast, would need the same condition-observation pattern proposed for the damage fields.

Feature	%	MSRD	Module	Class	Attribute	Type
Walls, Floor, Roof						
Wall orientation	43%	Yes	Building Building	_BoundarySurface _BoundarySurface	bdgBdrySurfAzimuth bdgBdrySurfInclination	Angle [0..1] Angle [0..1]
Wall U-value (W/m²K)	71%	Yes	Layered construction	LayeredConstruction	uValue	Measure [0..1]
Floor U-value (W/m²K)	71%	Yes	Layered construction	LayeredConstruction	uValue	Measure [0..1]
Roof U-value (W/m²K)	71%	Yes	Layered construction	LayeredConstruction	uValue	Measure [0..1]
Surface area(s) per type (m²)	43%	Yes	Building	_BoundarySurface	bdgBdrySurfTotalSurfaceArea	Area [0..1]
Ordered layers (materials, thickness, etc.)	36%	Yes	Layered construction	Layer	Multiple	Multiple
Installation/renovation date	50%	Yes	Core Core	Intervention Intervention	interventionStartDate interventionEndDate	Date [0..1] Date [0..1]
Layer details						
Material of the layer	36%	Yes	Layered construction Layered construction Layered construction	SolidMaterial Liquid Gas	type type type	SolidMaterialTypeValue [0..1] LiquidTypeValue [0..1] GasTypeValue [0..1]
Layer thickness	50%	Yes	Layered construction	Layer	thickness	Measure
Layer thermal capacity	14%	Yes	Layered construction	SolidMaterial	specificHeatCapacity	Measure [0..1]
Material weight (mass of each building element)	29%	Yes	Layered construction Building Layered construction	SolidMaterial _BoundarySurface Layer	density geometry thickness	Measure [0..1] lod3MultiSurface Measure
Layer volume per material	29%	No	Building Layered construction	_BoundarySurface Layer	geometry thickness	lod3MultiSurface Measure
Global Warming Potential (GWP) - embodied carbon	21%	No	Layered construction	SolidMaterial	embodiedCarbon	Measure [0..1]
Total Renewable Primary Energy (PERT)	7%	No	✗			
Total non-Renewable Primary Energy (PENRT)	7%	No	✗			
Embodied energy coefficient	8%	No	Layered construction	SolidMaterial	embodiedEnergy	Measure [0..1]
Material library						
No details on materials	43%	N/A	N/A			
Material type (& subtype)	50%	Yes	Layered construction	SolidMaterial	type	SolidMaterialTypeValue [0..1]
Life span expectancy of building material	29%	Yes	Core	_CityObject	validTo	DateTime [0..1]
Certificates, like a Environmental Product Declaration	29%	No	Core*	_CityObject	externalReference	ExternalReference [0..*]
Material thermal conductivity	21%	Yes	Layered construction	SolidMaterial	thermalConductivity	Measure [0..1]
Fire resistance class	21%	No	✗			
Waste category	21%	No	Resources	Waste	type	WasteTypeValue
Chemical declaration	21%	No	✗			
Global Trade Item Number (GTIN)	21%	No	Core*	_CityObject	externalReference	ExternalReference [0..*]
Material density	7%	Yes	Layered construction Layered construction	SolidMaterial SolidMaterial	density density	Measure [0..1] Measure [0..1]
Material vapour permeability	7%	Yes	Layered construction	SolidMaterial	permeance	Measure [0..1]
Reuse capacity description	7%	No	Resources	Waste	isRecyclable	Boolean [0..1]
Recycling capacity description	7%	No	Resources	Waste	isRecyclable	Boolean [0..1]
Heat capacity	0%	Yes	Layered construction	SolidMaterial	specificHeatCapacity	Measure [0..1]

Table 8: Overview how each feature of module 3, part II maps onto the CityGML Core and/or the Energy ADE. An asterisk (*) denotes a CityGML Core module attribute; no asterisk denotes an Energy ADE attribute. Own work.

The features missing from the data model in Table 8 are mainly used only in Life Cycle Assessment (LCA) and are of interest after demolition, making them primarily relevant to DBLs rather than BRPs. Combined with their low coverage across the assessed initiatives, these features are deemed not relevant to include. If they were, the most suitable place would be a few extra attributes on the material library.

Across its fields, Module 3 is well covered. The layered-construction model represents the envelope build-up, the U-values, the materials, and the openings directly, and the LCA-oriented material fields are deliberately left out as out of scope for a renovation passport. The coverage gaps are the two damage-observation fields, the opening-level airtightness class, and the missing count attribute for identical openings, all of which are forwarded to Section 7.3.

Technical systems

Module 4 covers the building's technical systems, the heating, domestic hot water, cooling, ventilation, lighting, shading, and building management. For each, the comparison records the system description, the performance parameters, the asset identity and lifecycle, and any metering or monitoring attached to it. Energy ADE was built around exactly this domain, so the inventory of devices and their carriers, efficiencies, capacities, and installation dates map onto the Devices module directly. Table 9 shows the mapping.

Feature	%	MSRD	Module	Class	Attribute	Type
System inventory (Heating / DHW / Cooling / Ventilation / Lighting / Shading / BMS)						
Presence indicatable per system?	100%	Yes	Devices	AbstractDevice	Multiple	Multiple
System category	100%	Yes	Core	DeviceOperation	type	DeviceOperationTypeValue
How grouped the system is (e.g. (de)centralised)	43%	Yes	Devices	ThermalDistribution	distributionPerimeter	DistributionPerimeterTypeValue [0..1]
Served area / served units	43%	Yes	DataTypes Devices	CityObjectRelation ThermalDistribution	relationType distributionPerimeter	RelationTypeValue DistributionPerimeterTypeValue [0..1]
System description field (e.g. its type)	71%	Yes	Core*	AbstractGMLType	gml:description	gml:StringOrRefType
System description						
Energy carrier / source	100%	Yes	Resources Resources	Energy Energy	energyCarrier source	EnergyCarrierValue [0..1] EnergySourceValue [0..1]
Technology / system type	79%	Yes	Devices	AbstractDevice	Multiple	Multiple
Distribution type / medium	43%	Yes	Devices	ThermalDistribution	medium	MediumTypeValue [0..1]
Performance parameters						
Efficiency metric (e.g. heat recovery COP)	50%	Yes	Devices	AbstractDevice	efficiencyIndicator	CharacterString [0..1]
Rated capacity (e.g. in kW)	58%	Yes	Devices	AbstractDevice	installedPower	Measure [0..1]
Recorded efficiency value	50%	Yes	Devices Core	AbstractDevice DeviceOperation	nominalEfficiency yearlyGlobalEfficiency	Measure [0..1] Decimal [0..1]
Control / automation class (manual, fully integrated, etc.)	33%	Yes	✗			
Renewable contribution indicator	92%	Yes	Resources	Energy	source	EnergySourceValue [0..1]
Emissions factor / CO_2 intensity available	50%	Yes	Resources	AbstractResource	co2Equivalent	Measure [0..1]
Asset identity & lifecycle						
Manufacturer / producer	33%	Yes	Core*	_CityObject	externalReference	ExternalReference [0..*]
Model name/number	25%	Yes	Devices	AbstractDevice	model	CharacterString [0..1]
Installation year	75%	Yes	Devices	AbstractDevice	yearOfInstallation	Integer [0..1]
Unique asset ID / serial number	8%	No	Core	_CityObject	identifier	Code [0..1]
Expected lifespan / end-of-life year	25%	Yes	Core	_CityObject	validTo	DateTime [0..1]
Condition / state rating	25%	Yes	Core	_CityObject	indicator	Indicator [0..*]
Maintenance record present	42%	Yes	Core	Intervention	type	InterventionTypeValue
Last maintenance / inspection date	25%	Yes	Core	Intervention	interventionStartDate	Date [0..1]
Metering, monitoring & evidence						
System-level sub-metering available	25%	Yes	Core	SensorData	type	SensorDataTypeValue
Annual energy use per system recorded	50%	Yes	Resources	AbstractResource	amount	Measure [0..1]
Operational data available	50%	Yes	Resources	AbstractResource	Multiple	Multiple
BMS/IoT integration link	25%	Yes	Time Series	SensorConnection	Multiple	Multiple
Documents attached for the system	33%	Yes	Core*	_CityObject	externalReference	ExternalReference [0..*]
Evidence/source type	42%	Yes	DataTypes	Metadata	acquisitionMethod	DataAcquisitionMethodValue [0..1]
Data collection date	25%	Yes	Time Series Time Series	RegularTimeSeries RegularTimeSeries	startTimestamp endTimestamp	DateTime DateTime
Recommended upgrade measure per system	42%	Yes	Core Core	Intervention Intervention	type action	InterventionTypeValue InterventionActionValue [0..1]

Table 9: Overview how each feature of module 4 maps onto the CityGML Core and/or the Energy ADE. An asterisk (*) denotes a CityGML Core module attribute; no asterisk denotes an Energy ADE attribute. Own work.

The data model does not have a served-area or served-units attribute field; instead the system is linked, using `CityObjectRelations`, to any building, zone, or unit to denote which areas it serves, so that a heating system is linked only to the living-room zone, for example.

There is currently no dedicated attribute to record the control or automation class of a system. It could be carried by the generic indicator attribute, but that is an open value rather than a formal, consistently-formatted enumeration, which is an insufficient-semantic-specificity gap. A single-attribute addition that responds to it is noted in Section 7.3; the same kind of information recurs in the smart-readiness fields of Module 12.

The ‘maintenance record present’ feature needs no dedicated attribute. Interventions in the data model include maintenance, so if that part of the model is filled out, a maintenance record is present; if not, it is not. The same mechanism stores and derives the last maintenance or inspection date, with multiple dated interventions representing a maintenance history.

Beyond the control-class attribute, Module 4 is fully covered. The served-area relationship, the system inventory and its performance parameters, and the maintenance history through interventions all have a place in the data model.

Attachable documents (file repository)

Module 5 concerns the building’s file repository, the documents, models, and images a DBL or BRP should be able to store and link, from EPCs and inspection reports to drawings, permits, and BIM or geometry files. The question for the data model is not which documents exist, but whether arbitrary files can be attached to the right object and moment in time, with enough metadata to be found and trusted later. Table 10 shows an overview of the document types proposed/used in the 14 assessed initiatives.

Feature	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14
EPCs, with potential attachments	✓	✓	✓	✓	✓							✓		
Reports regarding any type of inspection, e.g. technical systems	✓		✓	✓	✓		✓							
Contracts, e.g. on utility, tenancy & maintenance	✓		✓			✓		✓						
Building valuation report(s)	✓		✓			✓		✓						
Sustainability certificates (DGNB, BREEAM, LEED, etc.)	✓	✓	✓									✓		
Bills, e.g. on utility, construction, maintenance	✓	✓		✓										
Permits: Location, planning, building, construction, use, etc.	✓		✓	✓		✓		✓				✓		
Safety & user manuals of the technical systems	✓		✓			✓						✓		
Insurance documents	✓		✓			✓		✓						
Fire safety plans & reports	✓							✓						
Weather/climate files, for both current and 2050	✓			✓				✓						
Renovation advice document, e.g. as a roadmap file			✓		✓							✓		
Seismic resilience report	✓													
Life Cycle Analysis (LCA) report			✓											
Property information relevant in case of property transfer					✓									
Documents on environmental footprints, e.g. ozone depletion			✓					✓						
Architectural & technical drawings, e.g. floor plans, sections	✓		✓			✓		✓	✓			✓		
As-built construction documentation	✓											✓		
Maintenance & completed-works records	✓		✓	✓		✓		✓				✓		

Table 10: Overview of the discussed documents that a DBL/BRP should be able to store. Initiative IDs (I1-I14) are defined in Table 3. Own work.

The documents in Table 10 are diverse and differ considerably per initiative, yet they are all relatively simple, most likely PDFs. Several initiatives, in varying degrees, also propose a Key Performance Indicator (KPI) field derived from these documents; a valuation document, for example, is often accompanied by a ‘valuation amount’ field. This pattern opens an option in conceptual data modelling. A UML subclass could be defined for the commonly found document types, each accompanied by one or two KPI indicators relevant to that type and room for a descriptive text, for example to summarise the main findings. Table 11 shows the mapping.

Feature	%	MSRD	Module	Class	Attribute	Type
Proprietary and/or open BIM/GEO formats	57%	Yes	Core*	_CityObject	externalReference	ExternalReference [0..*]
Regular documents (like PDFs)	71%	Yes	Core*	_CityObject	externalReference	ExternalReference [0..*]
Metadata fields (e.g. issue date, issuer, document type)	57%	Yes	Core	_CityObject	metadata	Metadata [0..1]
Image files	43%	Yes	Core*	_CityObject	externalReference	ExternalReference [0..*]

Table 11: Overview how each feature of module 5 maps onto the CityGML Core and/or the Energy ADE. An asterisk (*) denotes a CityGML Core module attribute; no asterisk denotes an Energy ADE attribute. Own work.

Module 5 is fully covered. Any `_CityObject` in CityGML or the Energy ADE can carry any number of `ExternalReferences`, with accompanying metadata for the issue date, issuer, and document type, so the repository need is met without extension. The typed-document subclass sketched above, a small set of common document types each with one or two KPI fields and a free-text summary, is a modelling refinement an implementation may adopt, not a gap in coverage.

Dimensions

Module 6 covers the building's dimensions, from the floor areas (net, gross, heated, footprint) and the non-floor surface areas (envelope, walls, roof, glazing) through to the heights, volumes, and derived shape and compactness factors. These are the geometric quantities that energy calculations and system sizing depend on. Table 12 shows the mapping.

Feature	%	MSRD	Module	Class	Attribute	Type
Floor areas						
Net floor area (NFA)	93%	Yes	Building	_AbstractBuilding	bdgArea	QualifiedArea [0..*]
Heated/conditioned floor area	71%	Yes	Building	_AbstractBuilding	bdgArea	QualifiedArea [0..*]
Gross floor area (GFA)	57%	Yes	Building	_AbstractBuilding	bdgArea	QualifiedArea [0..*]
Cooled floor area	43%	Yes	Building	_AbstractBuilding	bdgArea	QualifiedArea [0..*]
Footprint (of ground floor) area	50%	Yes	Building	_AbstractBuilding	bdgArea	QualifiedArea [0..*]
Non-floor surface areas						
Total envelope surface area (derived sum)	64%	Yes	Building	_AbstractBuilding	bdgArea	QualifiedArea [0..*]
External wall area (total)	50%	Yes	Building Building	_AbstractBuilding _BoundarySurface	bdgArea bdgBdrySurfTotalSurfaceArea	QualifiedArea [0..*] Area [0..1]
Roof area (total)	50%	Yes	Building	_AbstractBuilding	bdgArea	QualifiedArea [0..*]
Window/glazing area (total)	43%	Yes	Building Building	_Opening _BoundarySurface	bdgOpnArea bdgBdrySurfTotalSurfaceArea	Area [0..1] Area [0..1]
Door area	21%	Yes	Building	_Opening	bdgOpnArea	Area [0..1]
Heights						
Height above/below terrain height	36%	Yes	Building Building	_AbstractBuilding _AbstractBuilding	measuredHeight bdgHeight	gml::LengthType [0..1] QualifiedHeight [0..*]
Room/ Ceiling height	21%	Yes	Building Building	_AbstractBuilding _AbstractBuilding	storeyHeightsAboveGround storeyHeightsBelowGround	gml::MeasureOrNullListType [0..1] gml::MeasureOrNullListType [0..1]
Base height of building (sometimes altitude)	29%	Yes	Building	_AbstractBuilding	bdgHeight	QualifiedHeight [0..*]
Volumes						
Heated/conditioned volume	57%	Yes	Building	_AbstractBuilding	bdgVolume	QualifiedVolume [0..*]
Gross volume	29%	Yes	Building	_AbstractBuilding	bdgVolume	QualifiedVolume [0..*]
Net volume	29%	Yes	Building	_AbstractBuilding	bdgVolume	QualifiedVolume [0..*]
Cooled volume	14%	Yes	Building	_AbstractBuilding	bdgVolume	QualifiedVolume [0..*]
Shape factor and compactness						
Shape factor (envelope area / gross volume)	29%	Yes	Building Building	_AbstractBuilding _AbstractBuilding	bdgArea bdgVolume	QualifiedArea [0..*] QualifiedVolume [0..*]
Compactness (envelope area / gross floor area)	14%	Yes	Building Building	_AbstractBuilding _AbstractBuilding	bdgArea bdgArea	QualifiedArea [0..*] QualifiedArea [0..*]

Table 12: Overview how each feature of module 6 maps onto the CityGML Core and/or the Energy ADE. An asterisk (*) denotes a CityGML Core module attribute; no asterisk denotes an Energy ADE attribute. Own work.

Module 6 is fully covered. CityGML 2.0 already carries the principal heights, areas, and volumes on the `AbstractBuilding` class, and the Energy ADE adds the conditioned-area and conditioned-volume distinctions that energy calculations need. The shape and compactness factors are derived from these quantities rather than stored as separate attributes.

Operation and use

Module 7 covers how the building is actually operated and used. This spans the occupancy and behavioural patterns, the number of occupants, the heating and cooling set points, the ventilation habits, and the usage intensities for heating, cooling, hot water, and electricity. These drive the demand side of any energy calculation. Table 13 shows the mapping.

The behavioural-pattern or user-profile field and the number of occupants are more nuanced: these can be either reported by the owner-occupier or tenant, or determined statistically, often because such factors cannot be taken into account in a fair comparison between buildings. Set points are also often standardised for calculations. What some initiatives propose is not entirely clear, because their data-field definitions are general and high-level.

Privacy is a second reason for the statistical route. Occupancy and behavioural patterns describe the household rather than the building, and tied to an address they count as personal data under the General Data Protection Regulation (GDPR). Beckel et al. [81] infer the number of occupants and other household characteristics from smart-meter data alone. In the Netherlands, the Senate rejected two smart-metering bills in 2009 over exactly this concern, that detailed consumption data reveals the patterns of personal life inside the home [82].

However, the other features are most likely proposed as actual behavioural insights from the owners, not statistically derived.

Feature	%	MSRD	Module	Class	Attribute	Type
Behavioural patterns/ user profile	71%	Yes	Building	AbstractZone	Multiple	Multiple
Number of occupants	57%	Yes	Building Building Building	Occupants Occupants Occupants	numberOfOccupants type occupancySchedule	Integer [0..1] OccupantsTypeValue AbstractSchedule [0..1]
Set points for heating and cooling	57%	Yes	Building Building	AbstractZone AbstractZone	heatingSchedule coolingSchedule	AbstractSchedule [0..1] AbstractSchedule [0..1]
Hot water usage intensity (low, medium, high)	36%	Yes	Resources Core	Energy _CityObject	amount indicator	Measure [0..1] Indicator [0..*]
Annual usage days	14%	Yes	Core	AbstractSchedule	temporalExtent	TM_IntervalLength [0..1]
Daily HVAC system operating hours	21%	Yes	Building Building Building	AbstractZone AbstractZone AbstractZone	heatingSchedule coolingSchedule mechanicalVentilationSchedule	AbstractSchedule [0..1] AbstractSchedule [0..1] AbstractSchedule [0..1]
Ventilation habits	29%	Yes	Building Building	AbstractZone AbstractZone	mechanicalVentilationSchedule isMechanicallyVentilated	AbstractSchedule [0..1] Boolean [0..1]
Room for auditor advice regarding usage habits	29%	Yes	✗			
Heating usage intensity (low, medium, high)	21%	Yes	Resources Core	Energy _CityObject	amount indicator	Measure [0..1] Indicator [0..*]
Cooling usage intensity (low, medium, high)	14%	Yes	Resources Core	Energy _CityObject	amount indicator	Measure [0..1] Indicator [0..*]
Electricity usage intensity (low, medium, high)	21%	Yes	Resources Core	Energy _CityObject	amount indicator	Measure [0..1] Indicator [0..*]
Owner satisfaction regarding room temperature	7%	No	✗			
The type of cooking (electric vs. gas)	21%	Yes	Core	DeviceOperation	type	DeviceOperationTypeValue

Table 13: Overview how each feature of module 7 maps onto the CityGML Core and/or the Energy ADE. An asterisk (*) denotes a CityGML Core module attribute; no asterisk denotes an Energy ADE attribute. Own work.

Regarding the four ‘intensity’ attributes, the preference is to store the actual measured values of per-resource usage or production. Stating an intensity level with such granularity is a simplified proxy that is hard to use in practice. Nevertheless, using the indicator attribute, the intensity can be denoted on such a scale.

The room for auditor advice is the one operation-and-use field with no place in the schema: there is no attribute for a free-text advisory note attached to the building’s use. It is a minor missing-attribute gap, noted in Section 7.3. The owner-satisfaction rating, by contrast, is a perception measure that moves into the consultancy area and is too subjective to carry as a structured input, so it is left out of the MSRD.

With that one exception, Module 7 is covered: occupancy, set points, schedules, and the measured usage values all map onto the Energy ADE's occupant and schedule classes.

Legal and finance

Module 8 covers the financial and legal context of a renovation. It spans the property valuations (the official tax value and the market value), the operational costs (maintenance, energy, and water), the renovation costs and any subsidies or funding programmes, and the metadata that records when and how a valuation was made. These fields frame the business case for renovating, which is part of what a BRP is meant to support. Table 14 shows the mapping.

Feature	%	MSRD	Module	Class	Attribute	Type
Property valuations						
Property tax valuation / Official value	50%	Yes	Core*	_CityObject	externalReference	ExternalReference [0..*]
Market value / Property value	50%	Yes	Core*	_CityObject	externalReference	ExternalReference [0..*]
Annual maintenance cost	43%	Yes	Resources	AbstractResource	expense	Measure [0..1]
Renewal / Renovation cost	43%	Yes	Resources	AbstractResource	expense	Measure [0..1]
Rental value / Annual rent	29%	Yes	Core*	_CityObject	externalReference	ExternalReference [0..*]
Property yield (%)	29%	Yes	Core	_CityObject	indicator	Indicator [0..*]
Lifecycle and maintenance costs		Yes	Resources	AbstractResource	expense	Measure [0..1]
Sales transaction value / Property price paid	7%	No	Core*	_CityObject	externalReference	ExternalReference [0..*]
Life Cycle Cost (LCC)	14%	Yes	Core	_CityObject	indicator	Indicator [0..*]
Valuation metadata						
Valuation date	36%	Yes	Core*	_CityObject	creationDate	Date [0..1]
Valuation method / approach	29%	Yes	DataTypes	Metadata	acquisitionMethod	DataAcquisitionMethodValue [0..1]
Valuation conducted by (name/contact)	29%	Yes	DataTypes	Metadata	author	CharacterString [0..1]
Valuation document (linked file)	21%	Yes	Core*	_CityObject	externalReference	ExternalReference [0..*]
Financial data collecting date / last update	14%	Yes	Core*	_CityObject	creationDate	Date [0..1]
Valuation purpose	7%	No	✗			
Valuation cost (€)	7%	No	✗			
Property selling date	7%	No	Core*	_CityObject	externalReference	ExternalReference [0..*]
Economic observation period (years)	14%	Yes	Resources	AbstractResource	referencePeriod	ReferencePeriodValue [0..1]
Operational energy costs						
Annual energy costs (total)	50%	Yes	Resources	Energy	expense	Measure [0..1]
Annual energy cost by carrier (electricity/ gas/ etc.)	57%	Yes	Resources	Energy	expense	Measure [0..1]
Annual water cost	29%	Yes	Resources	Water	expense	Measure [0..1]
Subsidies / Grants / Financial programs	36%	Yes	✗			
Annual energy cost by use (heating/ cooling/ etc.)	7%	Yes	Resources	Energy	expense	Measure [0..1]
Building insurance cost	7%	No	✗			
Certification costs (EPC/ BREEAM/ LEED/ etc.)	7%	No	✗			
Legal and property documents						
Tenancy agreement	36%	No	Core*	_CityObject	externalReference	ExternalReference [0..*]
Insurance policy / document	21%	No	Core*	_CityObject	externalReference	ExternalReference [0..*]
Clean soil statement	14%	Yes	Core*	_CityObject	externalReference	ExternalReference [0..*]
Permits and licenses						
Building / Construction / Use permits	50%	Yes	Core*	_CityObject	externalReference	ExternalReference [0..*]
Maintenance service contract / log	36%	Yes	Core*	_CityObject	externalReference	ExternalReference [0..*]
Utility contracts	29%	Yes	Core*	_CityObject	externalReference	ExternalReference [0..*]
Ownership information						
Owner information	43%	Yes	Building	_AbstractBuilding	bdgOwnerName	CharacterString [0..1]
Legal / Fiscal property registration	29%	Yes	Core*	_CityObject	externalReference	ExternalReference [0..*]
Tenant information	14%	No	✗			

Table 14: Overview how each feature of module 8 maps onto the CityGML Core and/or the Energy ADE. An asterisk (*) denotes a CityGML Core module attribute; no asterisk denotes an Energy ADE attribute. Own work.

Most of these values are not properties of the building's fabric but records held in external administrative and financial systems, so the data model links to them through `ExternalReferences` rather than storing them as native attributes. The official and market valuations are the clearest example. The values that do belong in the model, the operational and renovation costs and the energy and water costs, map onto the Energy ADE's resource classes through their expense attributes. Valuation metadata, such as the date, method, and author, reuses the same provenance attributes used across the rest of the chapter.

The fields left out of the MSRD fall outside what a renovation passport needs. The transaction-history fields, the sale value and the selling date, record market events rather than the building's condition and belong in the cadastral and conveyancing registers. Insurance and tenancy records (the building-insurance cost, the policy document, the tenancy agreement, and tenant information) are private contractual arrangements that belong in external administrative systems and raise the same privacy concerns as owner identity in Module 1. The remaining valuation and certification details, the valuation's purpose and cost and the cost of obtaining certificates, are administrative metadata about the process rather than inputs to the renovation business case.

Module 8 is covered for all but one of the fields taken into the MSRD. The operational and renovation costs are held by the resource classes as genuine resource flows, and the administrative and valuation records are best linked by reference to the external systems that own them, consistent with the treatment of owner identity in Module 1. The exception is the subsidies and funding programmes. A subsidy is not a flow of energy or material into or out of the building, so the resource classes' expense and revenue attributes do not fit it, and the same applies to the building-insurance and certification costs left out earlier. The cost and financing side of the Energy ADE is still minimally developed, and how best to model these monetary fields is an open question for its further development rather than a gap that a single new attribute closes.

Ancillary data & (environmental) context

Module 9 covers the ancillary and environmental context around the building, from its climate zone and the utility connections (district heating, drinking water, sewerage, gas) through to the associated cadastral parcel, any heritage protection on the building or its surroundings, and contextual factors such as soil contamination. Much of this is, by definition, less central to a renovation passport than the building's own fabric and systems. A large part of the environmental context is already provided by adjacent geospatial datasets rather than by a building-data model, which is why fewer than half of these fields are taken into the MSRD. Table 15 shows the mapping.

Cadastral parcel details can be linked via `ExternalReferences`. Similarly, if both a national and an INSPIRE cadastral ID need to be stored at the same time, two `ExternalReference` entries can be used. To reinforce this, any `_CityObject` in CityGML or the Energy ADE can carry any number of `ExternalReferences`, for example images.

Feature	%	MSRD	Module	Class	Attribute	Type
Climate zone	64%	Yes	Weather station Urban Function Area	WeatherStation UrbanFunctionArea	Multiple Multiple	Multiple Multiple
District heat network connection availability	50%	Yes	Core Core	UtilityNetworkConnection _CityObject	networkType status	NetworkTypeValue NetworkConnectionStatusValue [0..1]
Green-blue level / climate resilience	36%	Yes	Core	_CityObject	indicator	Indicator [0..*]
Associated cadastral parcel details	29%	Yes	Core*	_CityObject	externalReference	ExternalReference [0..*]
The type of soil/terrain	29%	No	Core	_CityObject	indicator	Indicator [0..*]
Textual description of the building's surroundings	14%	No	Core	Metadata	qualityDescription	CharacterString [0..1]
External noise pollution	14%	No	Core	SensorData	type	SensorDataTypeValue
Soil/ground cleanliness/ contamination details	14%	Yes	Core	_CityObject	indicator	Indicator [0..*]
Drinkwater connection availability	29%	Yes	Core	UtilityNetworkConnection	networkType	NetworkTypeValue
Flood susceptibility	21%	No	Core*	_CityObject	externalReference	ExternalReference [0..*]
Sewerage available & details on the current connection	29%	Yes	Core Core	UtilityNetworkConnection _CityObject	networkType status	NetworkTypeValue StatusValue [0..1]
Whether a building is (dis)connected to/from gas	29%	Yes	Core Core	UtilityNetworkConnection _CityObject	networkType status	NetworkTypeValue StatusValue [0..1]
Energy community access availability	7%	No	✗			
Groundwater well availability	7%	No	✗			
Heat stress	14%	No	✗			
Outdoor air quality	7%	No	Core	SensorData	type	SensorDataTypeValue
Mobility details, like public transport options	7%	No	✗			
Space & greenery details	7%	No	Core	_CityObject	indicator	Indicator [0..*]
Radiation (by wireless internet and telecom antennas)	0%	No	Core	SensorData	type	SensorDataTypeValue
Perceived light (pollution) at night	7%	No	Core	_CityObject	indicator	Indicator [0..*]
Spatial planning of own and surrounding plots	7%	No	Core*	_CityObject	externalReference	ExternalReference [0..*]
Immovable heritage of own and surrounding buildings	14%	Yes	Building	_AbstractBuilding	bdgIsProtected	Boolean [0..1]
Whether a building is, or can be connected to electricity	21%	Yes	Core Core	UtilityNetworkConnection _CityObject	networkType status	NetworkTypeValue StatusValue [0..1]
The communication types available/connected (e.g. 5G)	7%	No	Core Core	UtilityNetworkConnection _CityObject	networkType status	NetworkTypeValue StatusValue [0..1]
Regulations in force at the time of construction	7%	Yes	Core*	_CityObject	externalReference	ExternalReference [0..*]

Table 15: Overview how each feature of module 9 maps onto the CityGML Core and/or the Energy ADE. An asterisk (*) denotes a CityGML Core module attribute; no asterisk denotes an Energy ADE attribute. Own work.

The utility connections (district heating, drinking water, sewerage, and whether the building is or can be connected to a gas network) map onto the `UtilityNetworkConnection` class, which matters for the energy-carrier transition a renovation often involves. The climate zone maps onto the `WeatherStation` reference, and heritage protection reuses the protected-monument flag from Module 2. The contextual factors that are kept, such as soil contamination and green-blue resilience, use the generic indicator attribute.

Module 9 is fully covered for the fields taken into the MSRD. The fields left out, such as the soil type, external noise, flood susceptibility, and mobility options, are either outside the renovation scope or already provided by adjacent geospatial standards, so they are deliberately not carried by the building-data model.

4.2.4. Assessment layer (Modules 10-12)

Energy performance

Module 10 covers the building's energy performance. This spans the official EPC rating (the class, the numeric indicator, and the certification status), the energy consumption broken down by carrier and end use, and the on-site energy production. It is the assessment a renovation is meant to improve, and it is the domain the Energy ADE was originally built for. Table 16 shows the mapping.

Feature	%	MSRD	Module	Class	Attribute	Type
Official ratings and certification						
EPC class / label	100%	Yes	Building	EnergyPerformanceCertificate	label	CharacterString
Numeric indicator	79%	Yes	Building	EnergyPerformanceCertificate	value	Measure [0..1]
EPC rating basis (actual / potential)	86%	Yes	Building Building	EnergyPerformanceCertificate EnergyPerformanceCertificate	status certificationMethod	EPCStatusValue CharacterString [0..1]
Renovation target / status	64%	Yes	Core	Intervention	type	InterventionTypeValue
EPC document as PDF	43%	Yes	Core*	_CityObject	externalReference	ExternalReference [0..*]
Energy consumption						
Total source energy (including grid losses)	64%	Yes	Resources Resources	Energy Energy	type amount	EnergyTypeValue Measure [0..1]
Final / delivered energy	100%	Yes	Resources Resources	Energy Energy	type amount	EnergyTypeValue Measure [0..1]
Heating demand	71%	Yes	Resources Resources	Energy Energy	endUse amount	EnergyEndUseValue Measure [0..1]
Cooling demand	50%	Yes	Resources Resources	Energy Energy	endUse amount	EnergyEndUseValue Measure [0..1]
DHW (hot water) demand	57%	Yes	Resources Resources	Energy Energy	endUse amount	EnergyEndUseValue Measure [0..1]
Lighting and aux	57%	Yes	Resources Resources	Energy Energy	endUse amount	EnergyEndUseValue Measure [0..1]
Calculation type	79%	Yes	DataTypes	Metadata	acquisitionMethod	DataAcquisitionMethodValue [0..1]
Energy production						
Renewable energy production	86%	Yes	Resources Resources	Energy Energy	operationType source	ResourceOperationTypeValue EnergySourceValue [0..1]
Self-consumption ratio	21%	Yes	Core	_CityObject	indicator	Indicator [0..*]
Renewable energy share (%)	36%	Yes	Core	_CityObject	indicator	Indicator [0..*]
Calculation zones						
Area (or volume) per zone	7%	Yes	Core Core	AbstractCityObjectSpace AbstractCityObjectSpace	area volume	QualifiedArea [0..*] QualifiedVolume [0..*]
Surface area of envelope area per zone	7%	Yes	Building	_BoundarySurface	bdgBdrySurfTotalSurfaceArea	Area [0..1]

Table 16: Overview how each feature of module 10 maps onto the CityGML Core and/or the Energy ADE. An asterisk (*) denotes a CityGML Core module attribute; no asterisk denotes an Energy ADE attribute. Own work.

The EPC fields map directly onto the Energy ADE's `EnergyPerformanceCertificate` class, which carries the label, the numeric value, and the certification status, while the EPC document itself attaches as an `ExternalReference`. The consumption figures map onto the `Energy` class through its end-use distinctions (heating, cooling, domestic hot water, lighting, and auxiliary), and the calculation type that produced them is recorded as provenance metadata. That last point matters for data quality: a measured consumption value and a calculated one are not interchangeable, and recording which is which lets a later reader judge the figure. On-site production maps onto the same `Energy` class through its operation type, and the derived ratios (self-consumption, renewable share) use the generic indicator attribute.

Module 10 is fully covered. The energy-performance domain is exactly what the Energy ADE was designed to model, so every relevant field maps directly and no extension is required.

Indoor environmental quality (IEQ)

This module has been split in six parts/tables due to its size and categorisation.

Module 11 covers indoor environmental quality, the conditions a renovation should protect or improve. It spans thermal comfort, indoor air quality, visual comfort and lighting, health and well-being, and acoustic comfort, together with how each assessment was carried out. Because the field is broad it is split into six tables; together they show the mapping, and the pattern is consistent across them.

Thermal comfort

Feature	%	MSRD	Module	Class	Attribute	Type
Temperature assessment						
Air temperature (average)	29%	Yes	Core Core	SensorData SensorData	type yearlyValue	SensorDataTypeValue Measure [0..1]
Hours outside comfort range	14%	No	Core	_CityObject	indicator	Indicator [0..*]
Set point temperature	21%	Yes	Building Building	AbstractZone AbstractZone	heatingSchedule coolingSchedule	AbstractSchedule [0..1] AbstractSchedule [0..1]
Temperature variation	7%	Yes	Core Core	SensorData SensorData	type yearlyValue	SensorDataTypeValue Measure [0..1]
Humidity assessment						
Average indoor relative humidity	36%	Yes	Core Core	SensorData SensorData	type yearlyValue	SensorDataTypeValue Measure [0..1]
Time with RH outside 30–60% comfort range	7%	Yes	Core	_CityObject	indicator	Indicator [0..*]
PMV/PPD assessment						
Predicted mean vote (PMV)	7%	Yes	Core	_CityObject	indicator	Indicator [0..*]
Predicted percentage dissatisfied (PPD)	7%	Yes	Core	_CityObject	indicator	Indicator [0..*]
Hours with PPD above thresholds	7%	Yes	Core	_CityObject	indicator	Indicator [0..*]
Summer comfort / overheating						
Summer thermal discomfort	14%	No	Core	_CityObject	indicator	Indicator [0..*]
Climate resilience (2050)	14%	No	Core	_CityObject	indicator	Indicator [0..*]
Owner satisfaction	14%	No	Core	_CityObject	indicator	Indicator [0..*]

Table 17: Overview how each feature of module 11, Part I maps onto the CityGML Core and/or the Energy ADE. An asterisk (*) denotes a CityGML Core module attribute; no asterisk denotes an Energy ADE attribute. Own work.

Indoor air quality

Feature	%	MSRD	Module	Class	Attribute	Type
CO_2 concentration						
CO_2 concentration (average)	21%	Yes	Core Core	SensorData SensorData	type yearlyValue	SensorDataTypeValue Measure [0..1]
Hours with CO_2 above thresholds	7%	Yes	Core	_CityObject	indicator	Indicator [0..*]
Ventilation assessment						
Ventilation rate	14%	Yes	Building	AbstractZone	infiltrationRate	Measure [0..1]
Ventilation system type	71%	Yes	Building	AbstractZone	isMechanicallyVentilated	Boolean [0..1]
Heat recovery efficiency	29%	Yes	Devices	AbstractDevice	nominalEfficiency	Measure [0..1]
Air tightness (n50/q50)	29%	Yes	Building	AbstractZone	infiltrationRate	Measure [0..1]
Air quality indicator	14%	Yes	Core	_CityObject	indicator	Indicator [0..*]
Pollutant concentrations						
Total volatile organic compounds (VOCs)	7%	No	Core Core	SensorData SensorData	type yearlyValue	SensorDataTypeValue Measure [0..1]
CMR VOCs	7%	No	Core Core	SensorData SensorData	type yearlyValue	SensorDataTypeValue Measure [0..1]
Formaldehyde	7%	No	Core Core	SensorData SensorData	type yearlyValue	SensorDataTypeValue Measure [0..1]
PM2.5 / PM10	14%	No	Core Core	SensorData SensorData	type yearlyValue	SensorDataTypeValue Measure [0..1]
Radon	14%	Yes	Core Core	SensorData SensorData	type yearlyValue	SensorDataTypeValue Measure [0..1]
R-value (pollutant index)	7%	No	Core	_CityObject	indicator	Indicator [0..*]
Outdoor air quality context						
Outdoor air quality	7%	No	Core Core	SensorData SensorData	type yearlyValue	SensorDataTypeValue Measure [0..1]
Nitrogen dioxide (NO_2)	7%	No	Core Core	SensorData SensorData	type yearlyValue	SensorDataTypeValue Measure [0..1]

Table 18: Overview how each feature of module 11, Part II maps onto the CityGML Core and/or the Energy ADE. An asterisk (*) denotes a CityGML Core module attribute; no asterisk denotes an Energy ADE attribute. Own work.

Visual comfort / lighting

Feature	%	MSRD	Module	Class	Attribute	Type
Daylight assessment						
Daylight provision	14%	Yes	Core	_CityObject	indicator	Indicator [0..*]
Light (lux) level	14%	Yes	Core Core	SensorData SensorData	type yearlyValue	SensorDataTypeValue Measure [0..1]
Light pollution	7%	No	Core	_CityObject	indicator	Indicator [0..*]
Artificial lighting						
Lighting system type	50%	Yes	Devices	LightingDevice	model	CharacterString [0..1]
Installed lighting power density	7%	Yes	Devices	LightingDevice	installedPower	Measure [0..1]
Lighting control systems	7%	No	Core	DeviceOperation	type	DeviceOperationTypeValue

Table 19: Overview how each feature of module 11, Part III maps onto the CityGML Core and/or the Energy ADE. An asterisk (*) denotes a CityGML Core module attribute; no asterisk denotes an Energy ADE attribute. Own work.

Health & well-being indicators

Feature	%	MSRD	Module	Class	Attribute	Type
Material health						
Asbestos presence	7%	Yes	Core	_CityObject	indicator	Indicator [0..*]
Material chemical declaration	14%	No	Core*	_CityObject	externalReference	ExternalReference [0..*]
General health context						
Health comfort indicator	7%	No	Core	_CityObject	indicator	Indicator [0..*]
Flood sensitivity	14%	No	Core	_CityObject	indicator	Indicator [0..*]
Heat stress risk	14%	No	Core	_CityObject	indicator	Indicator [0..*]

Table 20: Overview how each feature of module 11, Part IV maps onto the CityGML Core and/or the Energy ADE. An asterisk (*) denotes a CityGML Core module attribute; no asterisk denotes an Energy ADE attribute. Own work.

Acoustic comfort

Feature	%	MSRD	Module	Class	Attribute	Type
Noise assessment						
Noise control (general)	14%	Yes	Core	_CityObject	indicator	Indicator [0..*]
Traffic noise exposure	7%	No	Core Core	SensorData SensorData	type yearlyValue	SensorDataTypeValue Measure [0..1]

Table 21: Overview how each feature of module 11, Part V maps onto the CityGML Core and/or the Energy ADE. An asterisk (*) denotes a CityGML Core module attribute; no asterisk denotes an Energy ADE attribute. Own work.

Assessment method characteristics

Feature	%	MSRD	Module	Class	Attribute	Type
Data collection approach						
Requires physical measurements	29%	Yes	Core	Metadata	acquisitionMethod	DataAcquisitionMethodValue [0..1]
Requires dynamic simulation	7%	Yes	Core	Metadata	acquisitionMethod	DataAcquisitionMethodValue [0..1]
Static data entry only	93%	Yes	Core	Metadata	acquisitionMethod	DataAcquisitionMethodValue [0..1]
Monitoring data integration	21%	Yes	Time Series	SensorConnection	connectionType	SensorConnectionTypeValue
Standard references						
EN 15251 / EN 16798	14%	No	Core*	_CityObject	externalReference	ExternalReference [0..*]
Sustainability certification link	21%	No	Core*	_CityObject	externalReference	ExternalReference [0..*]

Table 22: Overview how each feature of module 11, Part VI maps onto the CityGML Core and/or the Energy ADE. An asterisk (*) denotes a CityGML Core module attribute; no asterisk denotes an Energy ADE attribute. Own work.

Across the six dimensions the mapping follows two patterns. Measured quantities, such as the air temperature, the relative humidity, the carbon-dioxide concentration, and the illuminance, map onto the `SensorData` class. The composite or derived scores, such as a daylight-provision index, an air-quality index, or a thermal-comfort rating, use the generic indicator attribute. Ventilation and airtightness reuse the `AbstractZone` attributes already introduced in Module 3, and one health hazard with direct renovation consequences, the presence of asbestos, is carried as an indicator on the building. The fine-grained pollutant measurements (the individual volatile organic compounds, formaldehyde, particulates) and the subjective comfort scores are left out of the MSRD as too granular or too subjective to act on.

Module 11 is fully covered for the fields that are taken in; no extension is required.

Smart readiness indicator (SRI)

Module 12 covers the building's smart readiness, the SRI score and class, the readiness-related infrastructure (EV charging, on-site energy storage, building automation and controls), and the metering and connectivity that make a building responsive to its occupants and to the grid. Smart readiness is a recent EPBD addition, so coverage across the assessed initiatives is thin, but the EPBD names it explicitly. Split into two parts, Table 23 and Table 24 show the mapping.

Feature	%	MSRD	Module	Class	Attribute	Type
SRI core indicators						
SRI result / score	50%	Yes	Core	_CityObject	indicator	Indicator [0..*]
SRI class (A–F rating)	7%	Yes	Core	_CityObject	indicator	Indicator [0..*]
SRI weighting factors (KF1–KF3)	7%	Yes	Core	_CityObject	indicator	Indicator [0..*]
SRI report / document	7%	Yes	Core*	_CityObject	externalReference	ExternalReference [0..*]
E-mobility and EV charging						
EV charging infrastructure (yes / no)	29%	Yes	Devices	EVChargingStation	N/A (existence of instance)	
Number of EV charging points	21%	Yes	Devices	EVChargingStation	numberOfDevices	Integer [0..1]
Total parking spaces	7%	No	✗			
Pre-cabled recharging stations	7%	No	✗			
EV charging station types (private / public)	7%	Yes	Devices	EVChargingStation	accessType	EVChargingAccessTypeValue [0..1]
EV charging types (grid / non-grid / market)	7%	Yes	Devices	EVChargingStation	type	Code
EV charging capacity (kW)	7%	Yes	Devices Devices Devices	EVChargingStation EVChargingStation EVChargingStation	installedPower chargingSpeedLevel connectorType	Measure [0..1] EVChargingSpeedLevelValue [0..1] EVChargingConnectorTypeValue [0..1]
EV grid balancing	14%	Yes	Devices	EVChargingStation	hasLoadManagement	Boolean [0..1]
EV charging information and connectivity	14%	Yes	Devices	EVChargingStation	connectorType	EVChargingConnectorTypeValue [0..1]
Energy storage and load shifting						
Storage of locally generated energy	36%	Yes	Devices Devices	ElectricalStorageDevice ThermalStorageDevice	Multiple Multiple	Multiple Multiple
Electrical storage system	14%	Yes	Devices Devices	ElectricalStorageDevice ElectricalStorageDevice	batteryTechnology powerCapacity	BatteryTechnologyTypeValue [0..1] Measure [0..1]
Heating system thermal storage / shifting	21%	Yes	Devices	ThermalStorageDevice	medium	MediumTypeValue [0..1]
Cooling system thermal storage / shifting	7%	Yes	Devices	ThermalStorageDevice	medium	MediumTypeValue [0..1]
Control of DHW storage charging	7%	Yes	Core	DeviceOperation	type	DeviceOperationTypeValue
Optimising self-consumption	7%	Yes	Core	_CityObject	indicator	Indicator [0..*]
Grid integration and demand response						
Smart grid integration	7%	Yes	Core	UtilityNetworkConnection	networkType	NetworkTypeValue
Demand response potential	29%	Yes	Core	_CityObject	indicator	Indicator [0..*]
Occupant participation in DR events	7%	No	Core	_CityObject	indicator	Indicator [0..*]

Table 23: Overview how each feature of module 12, Part I maps onto the CityGML Core and/or the Energy ADE. An asterisk (*) denotes a CityGML Core module attribute; no asterisk denotes an Energy ADE attribute. Own work.

Feature	%	MSRD	Module	Class	Attribute	Type
Building automation and control (BACS)						
BACS description	14%	Yes	Core	_CityObject	indicator	Indicator [0..*]
Control system for heating (class)	7%	Yes	Core	DeviceOperation	type	DeviceOperationTypeValue
Control system for cooling (class)	14%	Yes	Core	DeviceOperation	type	DeviceOperationTypeValue
Emission control for TABS	14%	Yes	Core	_CityObject	indicator	Indicator [0..*]
Control of distribution heat temperature	14%	Yes	Devices	ThermalDistribution	supplyTemperature	Measure [0..1]
Control of distribution pumps	7%	Yes	Devices	ThermalDistribution	nominalFlow	Measure [0..1]
Intermittent control	7%	Yes	Core	DeviceOperation	schedule	AbstractSchedule [0..1]
CHP control	7%	Yes	Core	DeviceOperation	type	DeviceOperationTypeValue
Technical building management systems	7%	Yes	Time Series	SensorConnection	connectionType	SensorConnectionTypeValue
IoT sensors and monitoring						
Sensors for energy consumption (HVAC / lighting)	7%	Yes	Core	SensorData	type	SensorDataTypeValue
Sensors for air temperature / humidity / presence	7%	Yes	Core	SensorData	type	SensorDataTypeValue
IoT continuous vibration sensors	7%	Yes	Core	SensorData	type	SensorDataTypeValue
IoT weather station data	7%	Yes	Weather Station	WeatherData	type	WeatherDataTypeValue
Self-attentive sensing configuration	7%	No	Core	_CityObject	indicator	Indicator [0..*]
Fault detection and structural health						
Fault detection of sensors	7%	No	Core	_CityObject	indicator	Indicator [0..*]
Alerts / warnings for anomalies	7%	No	Core	_CityObject	indicator	Indicator [0..*]
SHM thresholds	7%	No	Core	_CityObject	indicator	Indicator [0..*]
District and external integration						
Smart district potential / indicators	36%	Yes	Core	_CityObject	indicator	Indicator [0..*]
Building energy model (BEM)	7%	Yes	Core*	_CityObject	externalReference	ExternalReference [0..*]
Climate and resilience						
Solar potential (roofs / facades)	29%	Yes	Weather Station	WeatherData	type	WeatherDataTypeValue
Climate resilience potential	14%	No	Core	_CityObject	indicator	Indicator [0..*]
Metering and data collection						
Digital energy meters	29%	Yes	Time series	SensorConnection	connectionType	SensorConnectionTypeValue
Data collection timestamp	21%	Yes	Core*	_CityObject	creationDate	Date [0..1]

Table 24: Overview how each feature of module 12, Part II maps onto the CityGML Core and/or the Energy ADE. An asterisk (*) denotes a CityGML Core module attribute; no asterisk denotes an Energy ADE attribute. Own work.

The SRI score, class and weighting factors map onto the generic indicator attribute, the same mechanism used for the other derived ratings in the chapter, while the readiness infrastructure has dedicated homes: EV charging on the `EVChargingStation` class, on-site storage on the electrical and thermal storage-device classes, and the automation and control functions on the device-operation classes. The metering and Internet-of-Things (IoT) connectivity map onto the sensor and connection classes. The control-class information here is the same kind flagged in Module 4, and the single attribute proposed there in Section 7.3 would serve both. The purely operational fields (fault detection, anomaly alerting, structural-health thresholds) are left out of the MSRD, since they concern running the building rather than advising on its renovation.

With those exclusions, Module 12 is fully covered; no extension specific to this module is required.

4.2.5. Functional layer (Module 13)

Renovation advice

Module 13 is the renovation-passport output itself: the sequenced roadmap of renovation steps that the data of Modules 1 to 12 informs. It is the BRP's defining deliverable. Several of the assessed initiatives (iBRoad, iSFP, OneClickRENO) produce this roadmap as their primary product rather than as one field among many. ALDREN names elementary renovation actions and a Nearly Zero-Energy Building (NZEB) roadmap as standalone modules. It is also the module where the existing schema is thinnest, which makes it the focus of the coverage analysis in Section 4.3. Table 25 shows the mapping.

Feature	%	MSRD	Module	Class	Attribute	Type
Only general recommendation to include renovation data	21%	N/A	N/A			
Administrative (step) information						
Renovation measure proposals on specific elements	71%	Yes	Core	Intervention	action	InterventionActionValue [0..1]
			Core	Intervention	type	InterventionTypeValue
			Core	Intervention	interventionStartDate	Date [0..1]
			Core	Intervention	interventionEndDate	Date [0..1]
Textual renovation (stage) description	64%	Yes	✗			
Year of this renovation/ stage	43%	Yes	Core	Intervention	interventionStartDate	Date [0..1]
Attachable documents which relate to the renovation	57%	Yes	Core*	_CityObject	externalReference	ExternalReference [0..*]
Achieved/ desired renovation depth (descriptive)	36%	Yes	✗			
Energy & resource consumption improvements						
Resource consumption (kWh) vs. pre-renovation	79%	Yes	Resources	Energy	amount	Measure [0..1]
Energy label before/after (letter or colour)	64%	Yes	Building	EnergyPerformanceCertificate	label	CharacterString
Resource demand (kW) vs. pre-renovation	43%	Yes	Resources	Energy	maximumLoad	Measure [0..1]
Energy efficiency before / after renovation	43%	Yes	Core	DeviceOperation	yearlyGlobalEfficiency	Decimal [0..1]
Finances						
Investment costs per measure/ step	71%	Yes	Resources	OtherResource	expense	Measure [0..1]
Current total energy costs per year	57%	Yes	Resources	AbstractResource	expense	Measure [0..1]
Business as usual costs (or if it can be derived)	50%	Yes	Resources	AbstractResource	revenue	Measure [0..1]
Public funding program details	50%	Yes	Resources	Energy	expense	Measure [0..1]
Public funding investment amount (available)	43%	Yes	Resources	AbstractResource	revenue	Measure [0..1]
Overall total investment costs (staged or all at once)	21%	Yes	Resources	OtherResource	expense	Measure [0..1]
Tax incentive (name)	14%	Yes	Core*	_CityObject	externalReference	ExternalReference [0..*]
Reasoning & timelining						
Renovation measure priority level	50%	Yes	✗			
Motivation on why this specific measure is necessary**	29%	Yes	✗			
Estimation of the renovation works time**	14%	Yes	✗			
The first/best opportunity to do this renovation**	14%	Yes	✗			
Ideal season for executing the renovation step**	14%	Yes	✗			
Non monetary benefits						
Indication of new thermal comfort**	43%	Yes	Core	_CityObject	indicator	Indicator [0..*]
Descriptive explanation of other non-monetary benefits**	36%	Yes	Core	_CityObject	indicator	Indicator [0..*]
Negatives						
Constraints that limit/block certain renovations	36%	Yes	Core	_CityObject	indicator	Indicator [0..*]
Estimation of users' disruption**	14%	Yes	Core	_CityObject	indicator	Indicator [0..*]
Renovation risks (e.g. mold growth if not done properly)	21%	Yes	Core	_CityObject	indicator	Indicator [0..*]

Table 25: Overview how each feature of module 13 maps onto the CityGML Core and/or the Energy ADE. An asterisk (*) denotes a CityGML Core module attribute; no asterisk denotes an Energy ADE attribute. Own work.

Much of the module does map. A single renovation measure is carried by the Energy ADE's `Intervention` class, with its action, type, and dates. The supporting documents attach as `ExternalReferences`, and the quantified effects of a step map onto classes introduced earlier: the energy label before and after onto the `EnergyPerformanceCertificate`, the consumption and demand deltas onto the `Energy` class, and the investment costs and public funding onto the resource classes. The descriptive non-monetary benefits, constraints, and risks of a step are carried, more loosely, by the generic indicator attribute.

What the schema does not provide is the roadmap as a roadmap. A BRP is a sequence of steps, each an object in its own right, with a textual description, an achieved or desired renovation depth, a priority level, and a motivation for why it is necessary. Energy ADE 3.0 (beta 8) models the single coarse intervention, not this sequenced, per-step descriptor, and the four narrative fields map only onto the generic indicator, which is an open value rather than a structured descriptor. This is an absent-class and insufficient-semantic-specificity gap. A second cluster concerns scheduling. The estimated duration of the works, the first or best opportunity to carry a step out, and the ideal season for it have no temporal-sequencing place at all, which is a missing-attribute gap. Together these are the seven fields that pull Module 13′s coverage down. They are the principal subject of the proposed responses in Section 7.3, where a sequenced roadmap layer over the existing `Intervention` construct, and its relation to the draft Scenario ADE [83], is weighed as an open design question.

Taken together, the per-module comparisons above give an overview of how completely each initiative populates each of the 13 modules. Figure 4.2 collects that result.

Figure 4.2: How completely each of the 14 assessed initiatives covers each of the 13 modules, grouped into the 3 conceptual layers. Each cell gives the share of that module's features the initiative includes, from red (none) through yellow (about half) to green (all). This is initiative coverage, how much of each module the initiatives populate, and is distinct from the schema's coverage of the MSRD reported in Figure 4.3. Initiative IDs (I1-I14) are defined in Table 3. Own work.

4.3. MSRD synthesis

4.3.1. The MSRD as derived

The Minimum Set of Required Data is what remains after every field of the 14 initiatives is read through the discretionary relevance filter of Section 3.2.3. For the per-field reasoning, Section 4.1.1 walks through five representative cases, and the MSRD column of each mapping table in Section 4.2 records the verdict for every field.

Table 26 collects the result across the 13 modules.

Module	Compared	In MSRD	Covered	Extension
1. Identification & administrative details	8	7	7	0
2. General building characteristics	24	19	19	0
3. Envelope, construction & materials	60	44	40	4
4. Technical systems	30	29	28	1
5. Attachable documents	4	4	4	0
6. Dimensions	19	19	19	0
7. Operation & use	13	12	11	1
8. Legal & finance	34	25	24	1
9. Ancillary data & context	25	11	11	0
10. Energy performance	17	17	17	0
11. Indoor environmental quality	46	26	26	0
12. Smart readiness	45	37	37	0
13. Renovation advice	27	26	19	7
Total	**352**	**276**	**262**	**14**

Table 26: The MSRD summarised across the 13 modules. **Compared** is the number of distinct fields drawn from the 14 initiatives; **In MSRD** is the number taken in by the relevance filter; **Covered** is the number of MSRD fields with a mapping target in CityGML 2.0 + Energy ADE 3.0 (beta 8); **Extension** is the number requiring a proposed extension (Section 7.3). Own work.

Of the 352 distinct fields compared across the initiatives, 276 are taken into the MSRD; the rest are left out as out of scope for a BRP, too granular to act on, or too subjective to record as structured data. The two right-hand columns anticipate the coverage analysis that follows: of the 276 MSRD fields, 262 map onto the existing schema and 14 require a proposed extension.

4.3.2. Coverage of CityGML 2.0 + Energy ADE 3.0 (beta 8) by the relevance-filtered MSRD

This brings the chapter to its central question: to what extent does CityGML 2.0 + Energy ADE 3.0 (beta 8) constitute a meaningful starting point for a Building Renovation Passport data model, and what targeted extensions are required to close the gaps? Across the relevance-filtered MSRD, the existing schema provides a mapping target for 262 of the 276 fields, roughly 95%. On this evidence it is a strong and near-complete starting point. The large majority of the data a BRP needs already has a place in an open, formally specified data model, and the gaps that remain are few and localised. Two qualifications bound the claim. The figure is coverage of the MSRD as this thesis defines it, through a discretionary filter, not of an external ground truth. A mapping target existing at the conceptual level does not guarantee that it is semantically adequate, which is a question the audit-depth test of Chapter 6 examines on a real building.

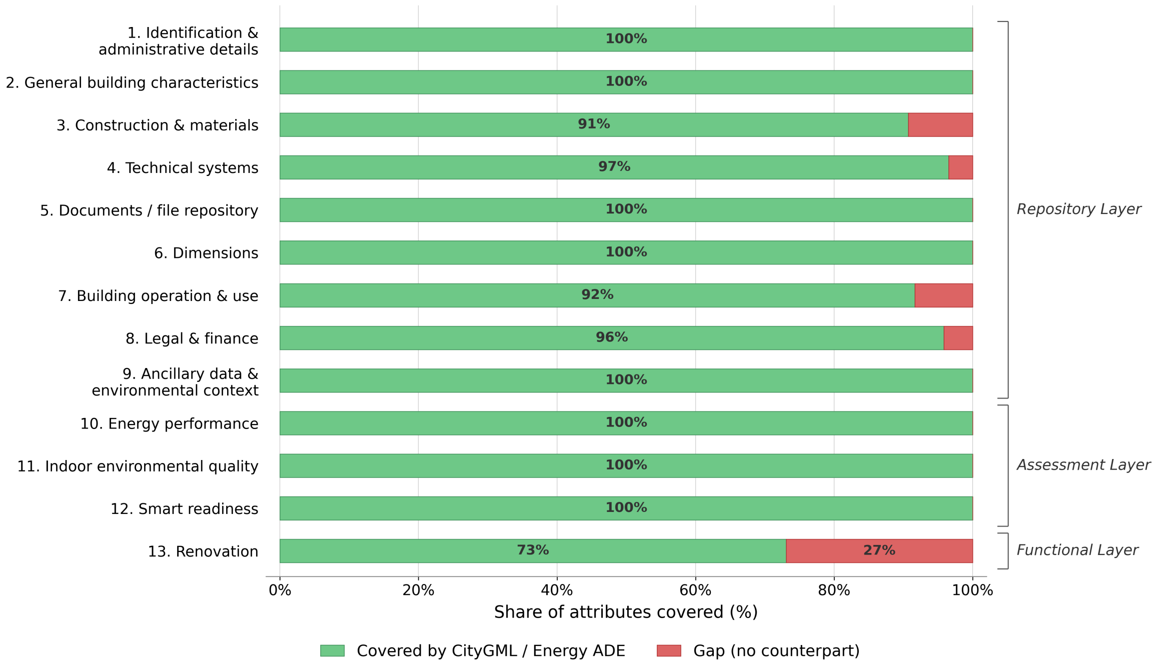


Figure 4.3: Coverage of the relevance-filtered MSRD by CityGML 2.0 + Energy ADE 3.0 (beta 8), per module, grouped into the three conceptual layers. Green is the share of MSRD fields with a mapping target in the existing schema; red is the share with no counterpart, forwarded as a proposed extension to Section 7.3. Own work.

Figure 4.3 shows where coverage is complete and where it is not. Once the filter has removed the fields a renovation passport does not need, coverage reaches 100% for 8 of the 13 modules, including the whole assessment layer (energy performance, indoor environmental quality, and smart readiness). This is unsurprising, since the energy domain is what the Energy ADE was built for. The schema is most complete in the assessment layer it was designed around, and its one substantial shortfall falls where the Building Renovation Passport concept is most novel. That gap is the staged renovation roadmap, the instrument's defining feature rather than a peripheral concern. The renovation-advice module that carries it stands at 73%. The schema records a single coarse intervention but not the sequenced, per-step roadmap with its narrative and scheduling descriptors, as set out in Section 4.2.5. The next gaps are the four envelope and opening fields of Module 3 (the two damage-observation fields, the opening-level airtightness class, and the missing count of identical openings, 91% covered). Two more are single attributes, the control or automation class in Module 4 and the free-text auditor advice in Module 7. The fourteenth sits apart from this renovation-advice cluster. It is the subsidies and funding programmes of Module 8, where the difficulty is not a missing attribute but that the Energy ADE's cost and financing model is not yet developed enough to hold them faithfully, which drops Module 8 to 96%. Together these make up the 14 fields of Table 26, the 7 of Module 13, these 6, and the Module 8 subsidies field. Thirteen of them are taken up as proposed responses in Section 7.3; the subsidies field is left as an open modelling question for the further development of the data model.

The mapping established here is the starting point for the two implementation tests of Chapter 6. How its fields are actually modelled, together with the cross-cutting design conventions for parent placement, units of measure, and cross-system references, is set out where it is first needed, at the start of Chapter 5.

5. Implementation

5.1. Introduction and design conventions

5.1.1. Testing at two scales

The MSRD-and-mapping proposal of Chapter 4 is tested in this chapter against real Dutch building-stock data, using two pipelines that emit CityGML 2.0 + Energy ADE 3.0 (beta 8) documents at different scales. The per-building pipeline (Section 5.2) exercises most of the Energy ADE vocabulary at audit depth on one owner-occupier reference building in Delft. Its inputs are a hand-authored feature-collection JSON and a Rhino STEP geometry covering zones, schedules, devices, layered constructions, and a material library. The city-scale pipeline (Section 5.3) takes a configuration that names a Dutch municipality and assembles one GML file by combining BAG and 3DBAG with EP-Online and BGT. Optional layers add solar-panel polygons [79] and individual trees (CFTree) [80]. It is walked through on a small area in Emmer-Compascuum (a village in the municipality of Emmen) and also run on Delft, Groningen, and Zwolle as comparators for the cross-cutting analysis in Section 6.4.

The validation is empirical, and its logic is set out in Section 3.1. The mapping is the theoretical contribution of Chapter 4, and this chapter exercises it against real data. The produced documents, and what they reveal about the data model, are reported in Chapter 6. This chapter records how.

The extent of what the two pipelines exercise is the base schema as it stands. The targeted extensions developed in Chapter 4, and consolidated in Section 7.3, are conceptual sketches that neither pipeline implements. What is put to the test is therefore how far the existing CityGML 2.0 + Energy ADE 3.0 (beta 8) covers the MSRD under real data, not the proposed additions.

The two pipelines are released as open-source artefacts (Appendix A). The architectural details are recorded in the public repository's `README` and `CONTEXT.md`. Each pipeline section below opens with a small data-flow diagram (input sources, mapping choices, GML output) so that the data lineage is inspectable at a glance.

5.1.2. Cross-cutting design conventions

Four design choices shape how the MSRD maps onto CityGML 2.0 + Energy ADE 3.0 (beta 8) in both pipelines. None is specific to one MSRD field; each informs the mapping across multiple modules and is referenced back from Section 5.2.2 and Section 5.3.2.

Scope-based parent placement

Energy ADE devices and physical features are parented according to the scope of the entity they describe. Devices serving a single dwelling (heat pumps, individual radiators, per-unit meters) parent to `nrg3:BuildingUnit`. Devices shared across a building (a rooftop photovoltaic array, a building-wide hot-water circulator) parent to `bldg:Building`. Addresses are modelled at `bldg:Building` level, with each `nrg3:BuildingUnit` carrying an `xlink:href` reference to the address. The full rule, including the edge cases that the pipelines encode, lives in the public repository's `CONTEXT.md` (see Appendix A for the repository link).

Units-of-measure discipline

Every quantitative attribute in the proposed schema inherits from `gml:MeasureType` and carries an explicit `uom` attribute, so a value such as a U-value or an energy figure is unambiguous across systems. What this discipline makes possible when one register reports the same quantity under incompatible regulatory regimes is shown on the EP-Online data in Section 6.3.

Cross-system linking via external identifiers

Identifiers from external registers are attached to CityObjects through `nrg3:identifier` elements, each carrying a `codeSpace` that names the register it comes from. The BAG *pand* and *verblijfsobject* identifiers attach this way, on the Building and the building unit respectively, under their BAG code spaces, and further register keys attach the same way where they apply. Where a value is derived from an external source rather than being an identifier, its provenance is recorded in an `nrg3:Metadata` block (`nrg3:source`) on the feature that carries the value. Together these support the cross-source linkage the city-scale pipeline relies on, the BAG-to-EP-Online join in particular, and let a downstream reader trace each value back to the register it came from.

Why CityGML 2.0 (and not CityGML 3.0)

Both pipelines target CityGML 2.0 because Energy ADE 3.0 (beta 8) extends it rather than CityGML 3.0; the technical reason is set out in Section 2.3, and the port to CityGML 3.0 is future work (Section 7.5).

5.2. Per-building pipeline

The per-building pipeline populates the schema at audit depth for the single owner-occupier reference building in Delft introduced in Section 3.1, whose case-selection rationale is given there. The extent it sets out to cover is one fully documented dwelling, reached across the building-physics, device, occupant, and energy-resource modules at once. The thermal zoning and its boundary surfaces, the layered constructions and their materials, the heating, hot-water, and photovoltaic devices, the occupants, and the measured energy resources are all populated together. Two parts of the vocabulary are left aside by design. Conditioning is carried as per-zone-part setpoint schedules rather than the Occupancy module's daily and seasonal patterns. Consumption is carried as measured energy resources rather than through the separate demand-and-supply classes, because the case has metered values directly. The inputs are LoD0-LoD3 geometry hand-authored in Rhino and exported to STEP, and a hand-authored feature-collection JSON. What this section records is how that data was instantiated; the produced document and its audit-depth findings are reported in Section 6.2.

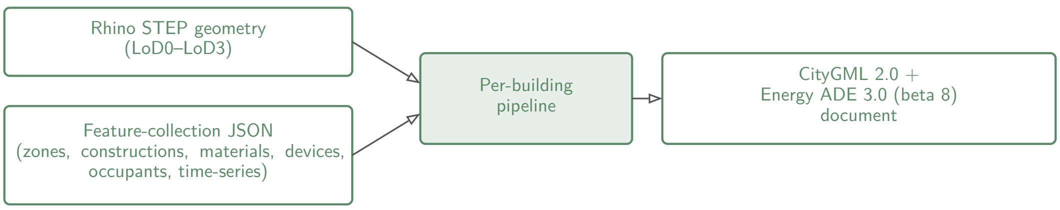


Figure 5.1: Per-building data flow: two hand-authored inputs are merged into one Energy ADE document. Own work.

5.2.1. Datasets and sources

The pipeline takes two hand-authored inputs and merges them into one CityGML 2.0 + Energy ADE 3.0 (beta 8) document, as Figure 5.1 shows. The geometry is authored in Rhino across four levels of detail and exported to STEP, giving an LoD0 footprint, an LoD1 massing, an LoD2 roof shape, and an LoD3 envelope that carries the window and door openings. The non-geometric building data are held in a feature-collection JSON that records the thermal zoning, the layered constructions with their material library, the rooftop photovoltaic array, the heating and domestic-hot-water devices, the occupants, and the measured energy time-series. The pipeline attaches the physics and the devices to the geometric shell and writes one XSD-valid GML file.

Both inputs are own work and ship as a sanitised fixture in the public repository (Appendix A), so no third-party licences or external identifiers apply at this scale. The intermediate feature-collection file and the geometry source are the instrument, not the object of study; the data model, not the pipeline, is what is evaluated.

5.2.2. Mapping choices

The per-module tables of Section 4.2 record which schema class covers each field. This section records how each feature group was actually instantiated in `NL-single-family-house.gml`. For each group that means the parent it was placed under, the way it references other features, and the modelling calls that the conceptual mapping leaves open. The produced file, its structural validation, and the audit-depth findings are reported in Section 6.2.

Building, building unit, and address

The dwelling is one `bldg:Building` holding one `nrg3:BuildingUnit` for the household. Following the scope-based placement rule of Section 5.1.2, the address is modelled once on the Building through `bldg:address`, and the building unit carries an `nrg3:address` reference to it by `xlink:href` rather than repeating it. The two *Basisregistratie Adressen en Gebouwen* (BAG, Key Register of Addresses and Buildings) identifiers attach where their scope applies, the *pand* identifier on the Building and the *verblijfsobject* identifier on the building unit, each in an `nrg3:identifier` element under the BAG code space. Keeping the *pand*-scope and *verblijfsobject*-scope facts separable is what the city-scale pipeline later depends on (Section 5.3.2).

Multi-LoD geometry and thematic surfaces

All four levels of detail attach to the same `bldg:Building`. The LoD0 footprint and LoD1 solid are held in `bldg:lod0FootPrint` and `bldg:lod1Solid`; the LoD2 and LoD3 representations are carried on thematic `bldg:WallSurface`, `bldg:RoofSurface`, and `bldg:GroundSurface` features, with the LoD3 walls nesting `bldg:Window` and `bldg:Door` openings through `bldg:opening`. Thematic surfaces are split per planar segment, rather than one surface per wall or one per orientation, because orientation is an attribute the schema records on the surface (its azimuth) rather than a grouping key. A per-segment split also lets disconnected parts and per-surface geometry coexist. The decision here is the granularity of the split and the LoD slot each representation occupies, not the class each element maps to.

Thermal zones and zone parts

The dwelling is one `nrg3:Zone`, which references its building unit by `xlink`, subdivided into `nrg3:ZonePart` instances per storey. The zone is not forced to coincide with the visible geometry: `nrg3:coincidesWithLod2Hull` and `nrg3:coincidesWithLod3Hull` are both false, so the thermal model and the geometric hull stay independent. Each zone part records whether it is heated, cooled, and mechanically ventilated, and carries its heating and cooling setpoints as `nrg3:ConstantValueSchedule` values in `uom="Cel"`. Splitting one zone into parts, rather than declaring one zone per storey, keeps a single thermal zone for the unit while still letting the conditioning differ between storeys.

Thermal boundaries and openings

Each planar envelope segment of a zone part is its own boundary surface, an `nrg3:ZoneWallSurface`, `nrg3:ZoneRoofSurface`, or `nrg3:ZoneGroundSurface` under `nrg3:zoneBoundary`, following the per-surface rule agreed with the Energy ADE developer. Every boundary carries its own physics, the inclination and azimuth in `uom="deg"`, the total and opaque surface areas in `uom="m2"`, the heat capacity in `uom="kJ/(K*m2)"`, and a thickness in `uom="m"`. Windows and doors attach to these boundaries as `nrg3:ZoneWindow` and `nrg3:ZoneDoor` openings under `nrg3:zoneOpening`, each with its own area, orientation, and a reference to its construction. The same physics is carried uniformly on the building-level thematic surfaces and on these zone-level boundaries, with an attribute left off only where it does not apply. A horizontal surface has no azimuth, and an opaque-area figure is recorded only where a surface carries openings.

Layered constructions and the material library

Every boundary and opening references its construction by identifier rather than restating the build-up, through an `nrg3:layeredConstruction xlink` to an `nrg3:LayeredConstruction` held in a shared `nrg3:LayeredConstructionLibrary`. Each construction lists its `nrg3:Layer` sequence, every layer giving a `nrg3:thickness` in `uom="m"` and an `xlink` to a material in a separate `nrg3:MaterialLibrary`. Materials are `nrg3:SolidMaterial` or `nrg3:Gas` instances carrying their thermal conductivity, density, and specific heat in their own units (`W/(K*m)`, `kg/m3`, and `J/(K*kg)`), so a material defined once is reused across constructions. Resolving every construction by its explicit identifier in this way keeps the file auditable.

The photovoltaic array

The rooftop array is one `nrg3:PhotovoltaicCollector` on the Building, placed there because a collective rooftop installation is a Building-scope device under the rule of Section 5.1.2. It is the dedicated photovoltaic class, not the generic `nrg3:GenericSolarCollector`, because the input carries full per-installation attribution, the installed power in `uom="W"`, the nominal efficiency in `uom="W/W"`, the module area in `uom="m2"`, and the azimuth and inclination in `uom="deg"`. The array states which roof surfaces it is installed on through `nrg3:CityObjectRelation` links of type `installedOn`, one per covered roof surface, and a further `serving` link to the building unit it supplies. The roof is represented at more than one level of detail, so the relation is repeated per representation: one link targets the LoD2 roof surface that hosts the array and two target the LoD3 surfaces it spans (Section 6.2). The city-scale case contrasts with this one by using the generic class where only roof-polygon extent is known (Section 5.3.2).

Heating, hot water, and appliances

The heating and hot-water devices parent to the `nrg3:BuildingUnit`, since they serve the single household. They are a ground-source `nrg3:HeatPump`, an `nrg3:ThermalDistribution` circuit, and an `nrg3:ThermalStorageDevice` for the hot-water buffer, each with its rated attributes in explicit units (installed power in `uom="W"`, temperatures in `uom="Cel"`, and the buffer volume in `uom="m3"`). Larger electrical loads and appliances are modelled the same way, an `nrg3:EVChargingStation` and several `nrg3:GenericElectricalDevice` instances. Each device carries its own consumption as a nested energy resource rather than through a separate connection graph, which keeps the device and its demand together.

Occupants and schedules

The household occupancy is modelled via one `nrg3:Occupants` instance under the building unit's `nrg3:occupiedBy`, recording the number of residents. The conditioning schedules are the per-zone-part setpoints described above, rather than separate occupancy patterns, because the case carries measured consumption directly. The schema's temporal validity attributes, `validFrom` and `validTo`, are available on city objects and are used here to date the charging-station installation. The same mechanism would record a change in occupancy over time, so historical changes are representable without an extension.

Energy demand and supply

Measured energy is what makes the file an audit-depth artefact rather than a static description. Whole-dwelling electricity consumption is an `nrg3:Energy` resource on the building unit, holding an `nrg3:MonthlyTimeSeries` whose `nrg3:valuesList` is in `uom="kWh"` with explicit start and end dates and an interpolation type; photovoltaic production is modelled the same way on the array. Where only an annual figure is known, the resource carries a scalar `nrg3:amount` with a reference period instead of a series. The Module 10 mapping of Section 4.2 covers which performance fields the schema holds; what is decided here is that measured and modelled quantities live side by side, each with its own provenance and unit.

A decision that recurs across these groups is how to record the same quantity from more than one source. The floor area, for instance, is kept as separate `nrg3:QualifiedArea` entries rather than reconciled to a single number, one registered in the BAG and one measured from the LoD3 geometry, each tagged with its `nrg3:source` and its area `nrg3:type`. Keeping both, with their provenance, is the pattern the city-scale pipeline generalises when independent registers disagree (Section 5.3.2); the disagreement itself is analysed in Section 6.4.

5.3. City-scale pipeline

The city-scale pipeline takes a configuration that names a Dutch municipality and an area of interest, and assembles one CityGML 2.0 + Energy ADE 3.0 (beta 8) document from the open Dutch building-stock data services. It is walked through here on a small area in Emmer-Compascuum (a village in the municipality of Emmen, approximately 41.5 ha, the reference example configuration is in the public repository) and was also run on Delft, Groningen, and Zwolle as comparators for the cross-cutting analysis in Section 6.4.

The extent this pipeline covers is the breadth of the stock rather than the depth of one dwelling. It reaches each building's geometry, its administrative identity, and its energy performance, together with the above-building context that a single dwelling cannot hold, all assembled from the open Dutch registers. It does not reach the interior building physics that the audit-depth pipeline populates. The open registers carry no thermal zoning, no layered constructions or materials, and no per-dwelling devices or occupants, so those modules stay empty here by design. For the same reason a detected roof installation maps to the generic solar collector class rather than the dedicated photovoltaic one (Section 5.3.2). That division of labour between the two pipelines is the depth-and-breadth design of Section 3.1.

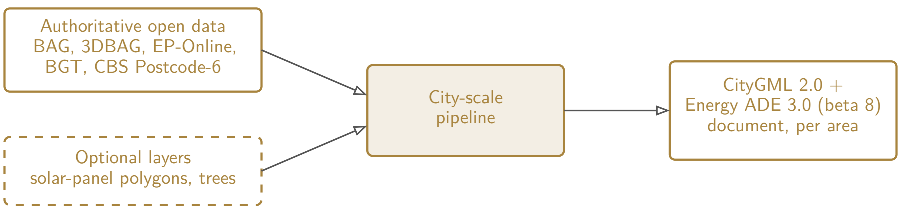


Figure 5.2: City-scale data flow: authoritative open data and optional layers are assembled into one Energy ADE document per configured area. Own work.

5.3.1. Datasets and sources

Figure 5.2 traces the flow, and Table 27 lists what each source provides and the role it plays. The test area is a small area of Emmer-Compascuum.

Source	Provides	Access	Role
BAG	Building outlines, dwelling units, addresses, construction year	Web Feature Service (WFS), via PDOK	identity and administrative anchor
3DBAG	Building geometry by level of detail	CityJSON tiles	geometry
EP-Online	Energy-performance figures per dwelling	RVO export	assessment input
BGT	Large-scale topography	WFS (PDOK)	vegetation cross-reference
CBS, Postcode-6	Neighbourhood dwelling-energy aggregates	open-data portal	above-building context
Solar-panel shapes [79]	Roof-panel extent	Zenodo (CC-BY-4.0)	solar-panel layer
CFTree [80], combined with municipal data	Tree locations, species, protection	algorithm and municipal export	vegetation layer

Table 27: City-scale data sources, what each provides, and its role in the model. Full provenance, vintage, and licences are in Appendix A. Own work.

The sources are joined on the BAG identifiers. Each *pand* is the geometric and administrative anchor for one building, and the *verblijfsobject* records under it become its building units. The 3DBAG geometry, the EP-Online figures, and the optional layers all attach to that anchor. EP-Online is matched to a *verblijfsobject* by its BAG identifier, with a normalised address key as a fallback where the identifier is missing. The match is the integration step, and how often it succeeds is reported in Section 6.4. Because every source is expressed on the Dutch national grid (`EPSG:28992` in the horizontal, with *Normaal Amsterdams Peil* (NAP) height), the layers combine without reprojection.

5.3.2. Mapping choices

As at audit depth, the class each field maps to is the per-module mapping of Section 4.2; this section records how the open data was instantiated and the decisions the conceptual mapping leaves open. The produced documents and their validation are reported in Section 6.3.

Buildings, units, and addresses

One BAG *pand* becomes one `bldg:Building`, with a `gml:id` of the form `pand_<identificatie>` and the *pand* identifier repeated in an `nrg3:identifier` element under the BAG code space. Each contained *verblijfsobject* becomes an `nrg3:BuildingUnit` (`bu_<identificatie>`) under that building, carrying its registered usable floor area as an `nrg3:QualifiedArea` in `uom="m2"`. The address is held on the building and each unit references it by `xlink`, the same scope-based placement used at audit depth (Section 5.2.2).

Linking EP-Online

EP-Online is the assessment input, and linking it is the decisive integration step of this pipeline. A certificate is matched to its *verblijfsobject* by the BAG identifier first, and by a normalised address key where that fails. A successful match attaches the certificate's energy figures to the building unit as an `nrg3:Energy` resource, with the EP-Online origin recorded in the resource's `nrg3:Metadata` and each figure keeping the explicit `uom` of its regulatory regime (Section 5.1.2). How often the match succeeds, and what that says about cross-register linkage, is a finding of Section 6.4.

Geometry from 3DBAG

3DBAG supplies the geometry, attached to the building at LoD0, LoD1, and LoD2 and keyed to the same *pand* identifier. 3DBAG is purely geometric, while identity and the legal-unit breakdown come from BAG, so the two are complementary rather than overlapping. This is the join that lets a 3D model carry the administrative and performance attributes the geometry alone cannot.

Solar panels from roof polygons

Where the optional solar layer is enabled, each detected roof-panel polygon becomes an `nrg3:GenericSolarCollector` on the building, with an `installedOn` relation to the roof. The generic class is used here, in contrast to the dedicated `nrg3:PhotovoltaicCollector` of the audit-depth case (Section 5.2.2), because the aerial source marks only a panel footprint. It does not establish whether a panel is photovoltaic or solar-thermal, let alone the per-installation power, efficiency, and orientation that the dedicated class expects. Modelling what is known, and no more, keeps the city-scale output faithful to its inputs, while not precluding future enrichment or refinement of the collected data.

Trees and the vegetation layer

Detected trees become `veg:SolitaryVegetationObject` features positioned by a reference point, carrying species and crown dimensions where the source provides them. The BGT and the Emmen export supply the species and protection context. The vegetation layer is optional and bears on shading and renovation context rather than on a building's own performance, which is why it lies outside the core building model. It is included in the test data nonetheless, as a reminder that CityGML stores not only building data, the core concern of this thesis, but also the most relevant surrounding urban objects.

Neighbourhood context from CBS

The CBS Postcode-6 dwelling-energy aggregates are modelled as `nrg3:UrbanFunctionArea` features, one per postcode area, set above the individual buildings. This is the one place the city-scale model reaches information that does not exist at the level of a single dwelling, which is the reason the second scale was needed (Section 3.1).

Conflicting sources and regulatory regimes

Bringing several registers onto one building makes disagreement explicit, and the pipeline records rather than resolves it. It uses the same dual-entry discipline as the audit-depth case (Section 5.2.2). Where two sources report the same quantity differently, for example the BAG usable floor area and the EP-Online thermal-zone area of the same building unit, both are kept as separate `nrg3:QualifiedArea` entries under the unit's `nrg3:area`, each tagged with its `nrg3:source`. The same discipline carries the two Dutch energy regimes. NTA 8800 and the legacy NEN 7120 express their results in different units, and because every quantity states its `uom`, the model holds both without conflating them. What these disagreements look like across the four tested areas is the cross-source analysis of Section 6.4.

5.4. Implementation summary

The two pipelines instantiate the Chapter 4 mapping against real Dutch building-stock data at complementary scales. The per-building pipeline (Section 5.2) populates the schema at audit depth from one hand-authored owner-occupier case, exercising the building-physics, device, occupant, and energy-resource modules together. The city-scale pipeline (Section 5.3) assembles one document per configured area from the open Dutch registers, joined on the BAG identifiers, and reaches the above-building context that a single dwelling cannot. The cross-cutting design conventions of Section 5.1.2, scope-based parent placement, explicit units of measure, and external-identifier linking, shape both.

What the populated documents reveal about the data model's adequacy, and how the four areas compare, is the subject of Chapter 6.

6. Results and Analysis

6.1. Introduction

This chapter reports the outputs of the two pipelines of Chapter 5 and the findings they expose. The pipelines test the data model at two scales. The per-building pipeline produces one owner-occupier CityGML 2.0 + Energy ADE 3.0 (beta 8) document at audit depth (Section 6.2). The city-scale pipeline produces five documents. One is a detailed multi-theme walk-through of a small area within Emmer-Compascuum. The other four are full-extent runs, the whole Emmer-Compascuum settlement together with the municipalities of Delft, Groningen, and Zwolle, that test the same mapping for breadth (Section 6.3).

Across the two scales the tests yield three types of finding. Schema-fit findings record where the schema holds the data but leaves a modelling decision under-specified. The per-building audit raised two such situations; one resolves into a modelling rule within the existing schema, and one stands as a finding (Section 6.2). Data-quality findings record cross-register disagreements that the integrated output makes systematically visible, and the four full runs reveal four (Section 6.4). The third type records what the integrated, semantically defined model makes possible that the source datasets, read apart, do not, and there are two of these (Section 6.4). The schema coverage gaps the tests also reveal are not a separate finding type here; they are carried forward and consolidated as proposed extensions in Section 7.3. Together these form the empirical answer to SQ3.

6.2. Per-building pipeline output and findings

The per-building pipeline of Section 5.2 produced a single CityGML 2.0 + Energy ADE 3.0 (beta 8) document for the owner-occupier reference building in Delft. This section reports that artefact in two parts. The first walks the populated feature tree and records the structural validation that confirms the document is valid against the schema. The second reports two points that populating a real building at audit depth brought to light, where the data model met a situation the mapping of Chapter 4 did not fully settle. One resolves into a modelling rule within the existing schema; the other stands as a finding, and the design response it motivates is consolidated with the coverage gaps of Section 4.3 in Section 7.3.

6.2.1. Produced artefact and structural validation

The pipeline emitted one document, `NL-single-family-house.gml`, which validates against the bundled schema set without error. The modelling rules behind each feature group are stated in Section 5.2.2 and the cross-cutting conventions in Section 5.1.2; this subsection reports what those rules produced. Figure 6.1 shows the building as the viewer renders it at LoD2 and LoD3.

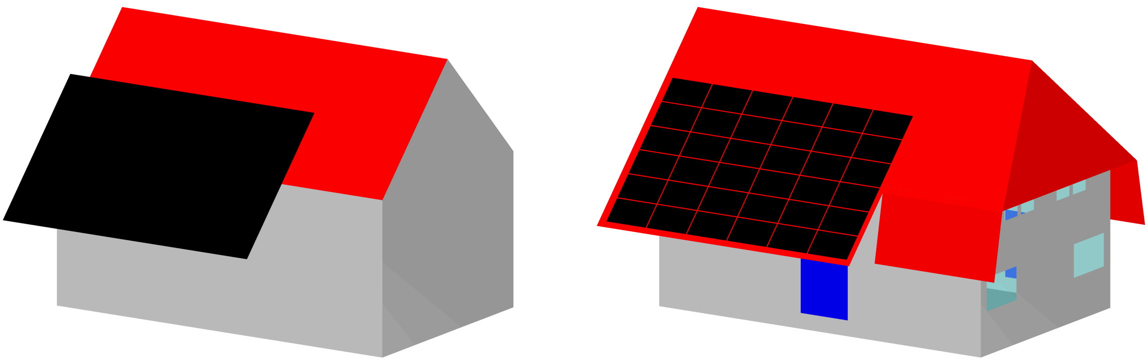


Figure 6.1: The owner-occupier reference building rendered from `NL-single-family-house.gml`, LoD2 (left) and LoD3 (right). Screenshot of KITModelViewer (KIT); model by the author.

The document carries one `bldg:Building` with one `nrg3:BuildingUnit` (a single `woonfunctie` dwelling), and the four exterior levels of detail, LoD0 through LoD3, are all present on that building: an `bldg:lod0FootPrint`, an `bldg:lod1Solid`, the LoD2 thematic surfaces, and the LoD3 surfaces with openings. The thermal model is one `nrg3:Zone` divided into two `nrg3:ZonePart` instances, one per heated storey (Figure 6.2), each carrying its heating and cooling setpoints as `nrg3:ConstantValueSchedule` values in degrees Celsius. Table 28 lists the populated feature tree as read in the viewer inspector.

Name	**Value**	**Description**
`bldg:Building`		owner-occupier dwelling; LoD0 to LoD3 all present
`├ bldg:boundedBy`	24	building-level thematic surfaces: 12 wall, 10 roof, 2 ground
`├ nrg3:zone → nrg3:Zone`	1	thermal zone
`│ └ nrg3:zonePart → nrg3:ZonePart`	2	one per heated storey
`├ nrg3:buildingUnit → nrg3:BuildingUnit`	1	single `woonfunctie` dwelling
`│ ├ nrg3:occupiedBy → nrg3:Occupants`	1	resident count
`│ ├ nrg3:device → nrg3:HeatPump`	1	ground-source
`│ ├ nrg3:device → nrg3:ThermalDistribution`	1	
`│ ├ nrg3:device → nrg3:ThermalStorageDevice`	1	
`│ ├ nrg3:device → nrg3:EVChargingStation`	1	
`│ └ nrg3:device → nrg3:GenericElectricalDevice`	5	
`└ nrg3:device → nrg3:PhotovoltaicCollector`	1	`installedOn` relations to the roof surfaces at LoD2 and LoD3

Table 28: Populated Energy ADE feature tree of the owner-occupier reference building, as read in the KITModelViewer inspector. Devices and occupants parent to the `nrg3:BuildingUnit`; the rooftop `nrg3:PhotovoltaicCollector` and the `nrg3:Zone` parent directly to the `bldg:Building`. Own work.

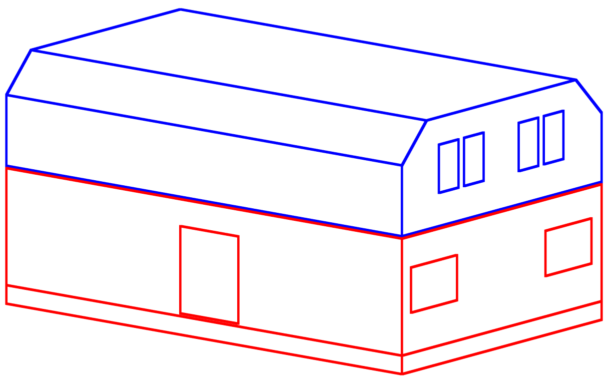


Figure 6.2: The owner-occupier LoD2 geometry as a wireframe; the two heated storeys the thermal model carries as two `nrg3:ZonePart` instances are shown in distinct colours (red and blue). Screenshot of KITModelViewer (KIT); model by the author.

The envelope is modelled per planar segment, following the design conventions of Section 5.1.2. The building carries 42 thematic boundary surfaces. Of these, 24 are at the building level (12 wall, 10 roof, and 2 ground surfaces) and 18 at the zone level (12 `nrg3:ZoneWallSurface`, 2 `nrg3:ZoneRoofSurface`, and 4 `nrg3:ZoneGroundSurface`), with 13 openings (8 windows and 5 doors) represented at both levels. Per-surface physics is populated uniformly across them. The `nrg3:bdgBdrySurfTotalSurfaceArea`, `nrg3:bdgBdrySurfInclination`, `nrg3:bdgBdrySurfThickness`, and `nrg3:bdgBdrySurfHeatCapacity` attributes are present on all 42 surfaces. `nrg3:bdgBdrySurfAzimuth` is carried on the 36 non-horizontal surfaces, since a horizontal floor has no meaningful azimuth, and `nrg3:bdgBdrySurfOpaqueSurfaceArea` on the 10 wall surfaces that carry openings. The thickness and heat-capacity values come from the layered constructions. The file resolves 12 `nrg3:LayeredConstruction` instances against a material library of 22 entries (20 `nrg3:SolidMaterial` and 2 `nrg3:Gas`), with the full layer-to-material chain resolving cleanly at validation time (Table 29).

Name	Value	Description
`nrg3:LayeredConstruction`		external wall (HSB timber frame, R_c=5.0), `uValue` 0.2 W/(K · m²)
├ `nrg3:layer 1 (inner)`	12 mm	Fermacell gypsum-fibre board → `nrg3:SolidMaterial`
├ `nrg3:layer 2`	0.15 mm	PE foil vapour barrier → `nrg3:SolidMaterial`
├ `nrg3:layer 3`	11 mm	chipboard V313 → `nrg3:SolidMaterial`
├ `nrg3:layer 4`	120 mm	Naturoll 032 mineral wool → `nrg3:SolidMaterial`
├ `nrg3:layer 5`	140 mm	Naturoll 032 mineral wool (same material) → `nrg3:SolidMaterial`
├ `nrg3:layer 6`	0.5 mm	Morgo-Vent breather membrane → `nrg3:SolidMaterial`
├ `nrg3:layer 7`	42 mm	ventilated cavity → `nrg3:Gas`
└ `nrg3:layer 8 (outer)`	22 mm	DCV cladding → `nrg3:SolidMaterial`

Table 29: One `nrg3:LayeredConstruction` (the external wall) resolving its ordered, inner-to-outer `nrg3:Layer` stack by reference into the project `nrg3:MaterialLibrary` (22 entries: 20 `nrg3:SolidMaterial` and 2 `nrg3:Gas`). Each `nrg3:Layer` carries its own thickness and points at a shared material, so the same mineral wool resolves for both insulation layers. Own work.

The technical systems and the renewable installation populate the device and resource vocabulary at the depth an audit makes available. The dwelling carries a ground-source `nrg3:HeatPump`, an `nrg3:ThermalDistribution`, an `nrg3:ThermalStorageDevice`, an `nrg3:EVChargingStation`, and five `nrg3:GenericElectricalDevice` instances, all parented to the building unit because they serve the single household. The rooftop array maps to one `nrg3:PhotovoltaicCollector`, the technology-specific class, chosen for the reasons given in Section 5.2.2. Table 30 reproduces its attributes as the viewer presents them.

Name	Value	Description
`GML Attributes`		
├ `gml:id`	pv_panel_1	
├ `gml:name`	PV collector (36x270 Wp)	
├ `nrg3:numberOfDevices`	36	
├ `nrg3:moduleArea`	59.4 m²	
├ `nrg3:azimuth`	235.65 deg	
├ `nrg3:inclination`	45.0 deg	
├ `nrg3:installedPower`	9720 W	
├ `nrg3:cellType`	unknown	codeSpace `CellTypeValue.xml`
└ `core:creationDate`	2026-04-04	
`nrg3:relatedTo`		
├ `nrg3:relationType`	installedOn	`xlink` to the LoD2 `bldg:RoofSurface` hosting the array
├ `nrg3:relationType`	installedOn	one `xlink` per covered LoD3 `bldg:RoofSurface`
└ `nrg3:relationType`	serving	`xlink` to the `nrg3:BuildingUnit` the array supplies

Table 30: Attributes of the `nrg3:PhotovoltaicCollector`, as read in the KITModelViewer inspector. Own work.

The dwelling's use and consumption complete the audit picture. One `nrg3:Occupants` instance records the resident count, and energy use is carried as `nrg3:Energy` resources with `nrg3:MonthlyTimeSeries` values. These are a metered house-consumption series, a metered photovoltaic-production series, and an independent NTA 8800 simulated production series that lets the measured generation be compared against a modelled estimate on the same building. The usable floor area is recorded from two sources that disagree; that case is the subject of the metadata finding below. With the artefact established, the next two subsections turn to what populating it revealed, first what the model covered cleanly, then the two points where it did not fully settle.

6.2.2. What the audit-depth model covered cleanly

Before the two findings, this subsection records what the audit-depth model covered cleanly, because the coverage is itself a result. Three things stand out.

The first is that one document holds the building across the full exterior level-of-detail range and at full audit depth at once. The same `bldg:Building` carries the LoD0 footprint, the LoD1 solid, the LoD2 thematic surfaces, and the LoD3 surfaces with their 13 openings. CityGML 2.0 reserves a fifth level, LoD4, for interior geometry such as rooms and furniture, which this file does not populate; the interior is instead carried thermally through the Energy ADE zone model (the `nrg3:Zone` and its `nrg3:ZonePart` instances) rather than as LoD4 room geometry. On top of that geometry, the thermal model, the 12 layered constructions resolving into a 22-entry material library, the technical systems, the occupants, and the energy resources all populate without conflict. A consumer does not have to choose between a coarse city-scale record and a detailed audit record, because the schema holds both on one feature.

The second is the energy resources, where the same file stores measured and modelled data side by side. The dwelling carries a metered house-consumption series and a metered photovoltaic-production series as `nrg3:MonthlyTimeSeries` values, and alongside them an independent NTA 8800 simulated production series for the same array. Because all three live on the same building in the same file, the measured generation can be read directly against the modelled estimate, as Figure 6.3 shows. Holding the real and the simulated series in one model is what makes that comparison a lookup rather than a join across separate datasets. It generalises to any measured-against-modelled check a renovation assessment wants to make. The two series end roughly 20% apart, which is the expected discrepancy between a calculation on standard reference weather and years of measured reality. The point of the exercise is the side-by-side comparison itself, not a validated simulation.

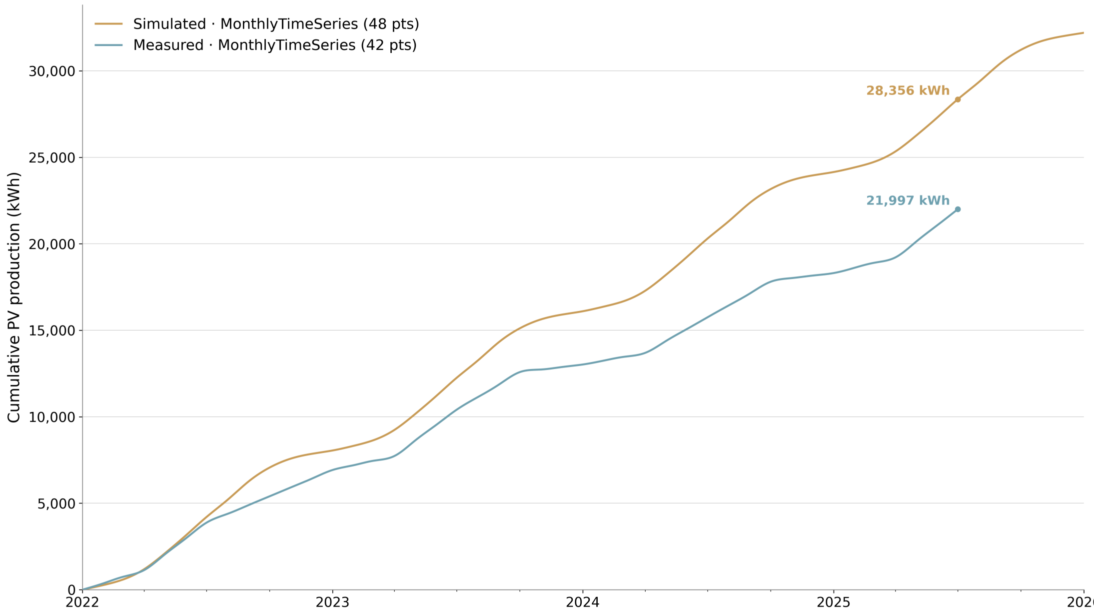


Figure 6.3: Cumulative metered photovoltaic production against the independent NTA 8800-simulated production for the owner-occupier array (2022 to 2025), both carried as `nrg3:MonthlyTimeSeries` resources in the same CityGML 2.0 + Energy ADE 3.0 (beta 8) document. Own work.

The third is time. Because `validFrom` and `validTo` are available on every city object, a system replaced over the building's life can be recorded as a dated state rather than overwriting the current one. The file exercises this once, dating the charging-station installation through `validFrom`, so the schema already has a place for the kind of history a renovation passport accumulates, even though a single audited snapshot gives it little to record.

6.2.3. Schema-fit findings at audit depth

Building the owner-occupier file end to end brought up two situations that needed a closer look. The first resolves within the schema once the relation vocabulary is used as intended, and is recorded here as a modelling rule. The second is a finding about the schema, and the design option it opens is weighed in Section 7.3.

Installation relations across levels of detail

The photovoltaic array is mounted on the roof, and the model records this with `installedOn` relations from the collector to the roof surfaces it covers (Listing 6.1). The roof is represented twice, at LoD2 and at LoD3, and the two representations are distinct surface objects with unrelated `gml:id` values, so a single relation can only ever point into one of them.

```
<nrg3:relatedTo>
  <nrg3:CityObjectRelation>
    <nrg3:relationType
        codeSpace=".../OtherRelationTypeValue.xml">installedOn</nrg3:relationType>
    <nrg3:relatedTo xlink:href="#id_building_1_RoofSurface2_7"/>
  </nrg3:CityObjectRelation>
</nrg3:relatedTo>
```

Listing 6.1: One of the `installedOn` relations from the `nrg3:PhotovoltaicCollector` to a `bldg:RoofSurface`, carried as an `nrg3:CityObjectRelation`. The relation is repeated for each roof surface the array covers.

The schema's answer is repetition rather than a level-of-detail discriminator: the relation is repeated per covered surface in each representation, so a consumer reading either view follows the relations that resolve within the surfaces that view draws. This is the modelling rule recommended by the Energy ADE developer, and it asks for no schema change. The owner-occupier file carries three such relations, one to the LoD2 roof surface that hosts the array and one to each of the two LoD3 surfaces it spans. The same pattern recurs in large numbers in the city-scale output, where the integrated scene carries hundreds of `installedOn` relations against thousands of roof surfaces (Section 6.3).

Whole-feature metadata cannot be referenced from an individual value

The finding concerns provenance when two sources disagree on the same quantity. The owner-occupier dwelling has a usable floor area of 122.0 m^2 in the BAG register and 104.2 m^2 measured from the LoD3 geometry. Both are typed `netFloorArea`, the closest entry the `AreaTypeValue` codelist offers for the Dutch usable-area definition, so the two values are directly comparable. Because the BAG records its `oppervlakte` per verblijfsobject rather than per Pand, both entries live on the `nrg3:BuildingUnit`; the building itself carries only the outer-envelope gross floor area of 119.6 m^2, typed `grossFloorArea`, a different quantity rather than a second opinion on the same one. The schema's native mechanism for the disagreement is the qualified-attribute pattern. The unit's `nrg3:area` repeats, and each `nrg3:QualifiedArea` carries its own `nrg3:source` string and its area `nrg3:type`, so the numbers stay in the file side by side and a consumer can choose which source to trust (Listing 6.2).

```xml
<nrg3:area>
  <nrg3:QualifiedArea>
    <nrg3:source>BAG (oppervlakteverblijfsobject, VBO 0000000000000002)</nrg3:source>
    <nrg3:value uom="m2">122.0</nrg3:value>
    <nrg3:type codeSpace=".../AreaTypeValue.xml">netFloorArea</nrg3:type>
  </nrg3:QualifiedArea>
</nrg3:area>
<nrg3:area>
  <nrg3:QualifiedArea>
    <nrg3:source>3D model (LOD3 STEP geometry)</nrg3:source>
    <nrg3:value uom="m2">104.2</nrg3:value>
    <nrg3:type codeSpace=".../AreaTypeValue.xml">netFloorArea</nrg3:type>
  </nrg3:QualifiedArea>
</nrg3:area>
```

Listing 6.2: The two-source usable floor area carried as repeated `nrg3:area` properties on the building unit, each wrapping a `nrg3:QualifiedArea` with its own free-text `nrg3:source` and its mandatory `nrg3:type`. Both values stay in the file side by side.

This works. The repeating qualified attribute is the schema's intended way to carry a multi-valued quantity with provenance, so the two-source area case is a coverage confirmation rather than a gap. The limit appears when richer provenance is wanted. A `nrg3:QualifiedArea` carries a free-text `source` string but no structured author, acquisition method, or owner per individual value. Structured provenance of that kind lives in the `nrg3:Metadata` block, but that block extends `gml:MetaDataPropertyType` and carries no `gml:id` (Listing 6.3).

```xml
<nrg3:Metadata>
  <nrg3:qualityDescription>Usable (net) floor area disagrees between the BAG
    register (122.0 m2) and the measured 3D model (104.2 m2); both values are
    retained as separate QualifiedArea entries ...</nrg3:qualityDescription>
  <nrg3:source>BAG + on-site measurement survey</nrg3:source>
</nrg3:Metadata>
```

Listing 6.3: The whole-feature `nrg3:Metadata` block carrying structured provenance, here on the building unit whose diverging area entries it describes. Because it extends `gml:MetaDataPropertyType` it has no `gml:id`, so it cannot be the target of an `xlink` from an individual `nrg3:QualifiedArea`.

Without a `gml:id`, the block cannot be the target of an `xlink`, so whole-feature metadata is written inline once per feature (the owner-occupier file carries one on the building, one on the building unit, and one on the simulated production `nrg3:Energy` resource) and cannot be attached to or referenced from a single `nrg3:QualifiedArea`. Carrying structured per-value provenance would therefore require an extension. The metadata model is, like the cost model, a deliberately small first iteration of that part of the data model, so this reads as a point where the model has room to mature rather than a flaw in its design. The prevalence of this kind of disagreement across the building stock is itself a result, reported as a data-quality finding in Section 6.4; the schema-side response is weighed in Section 7.3.

6.3. City-scale pipeline output

The city-scale pipeline of Section 5.3 assembled five CityGML 2.0 + Energy ADE 3.0 (beta 8) documents. One is a small, multi-theme area in Emmer-Compascuum (approximately 41.5 ha), built with every optional input and used here as the primary walk-through. The other four cover the full municipalities of Delft, Groningen, and Zwolle, plus the full Emmer-Compascuum settlement, each built at LoD0 with energy labels as the breadth runs that feed the cross-source analysis of Section 6.4. All five were produced without error and validate against the bundled Energy ADE 3.0 (beta 8) XSDs, at scales from roughly 950 buildings in the small area to about 94,000 in Groningen, so the mapping holds when it is driven by national open data rather than by a hand-authored file.

The rest of this section walks the small-area scene one data source at a time. The mapping decisions themselves, and the rationale behind them, are set out with the pipeline in Section 5.3.2; this section reports what those decisions produced in the output, field by field. For each source it states what the pipeline read from it, how those fields were mapped onto the data model, and what appears in the output, so the lineage from a register field to a populated Energy ADE element is inspectable end to end. Each source has its own mapping table that records this lineage one row per source field, including the fields the source ships that the pipeline does not use. BAG is shown as its two registers (*pand* and *verblijfsobject*) and the vegetation input as its three (CFTree, BGT, and the Emmen protected-tree register), one table each. The *How* column tags the mechanism: *Native* for a typed Energy ADE or CityGML slot, *GenericAttribute* for a `gen:*Attribute` fallback where no native slot fits, *Cross-ref* for a `core:externalReference` link back to the source, *Computed* for a value derived in the pipeline rather than read, *Filter-only* for a field read for joining or clipping but never written, *Latent* for a field read but not written that has a documented future home, and *Dropped* for a shipped field the pipeline ignores. The recurring presence of the *GenericAttribute* tag is itself a finding. It marks every point where a real Dutch field has no native home in an energy-focused schema yet can still be carried in a structured, queryable form, which is the practical case for the codelist and attribute extensions of Section 7.3. The source endpoints, vintages, and licences are listed in Section 5.3.1 and Appendix A. Figure 6.4 gives an overview of the small-area scene with the energy-label theme active.

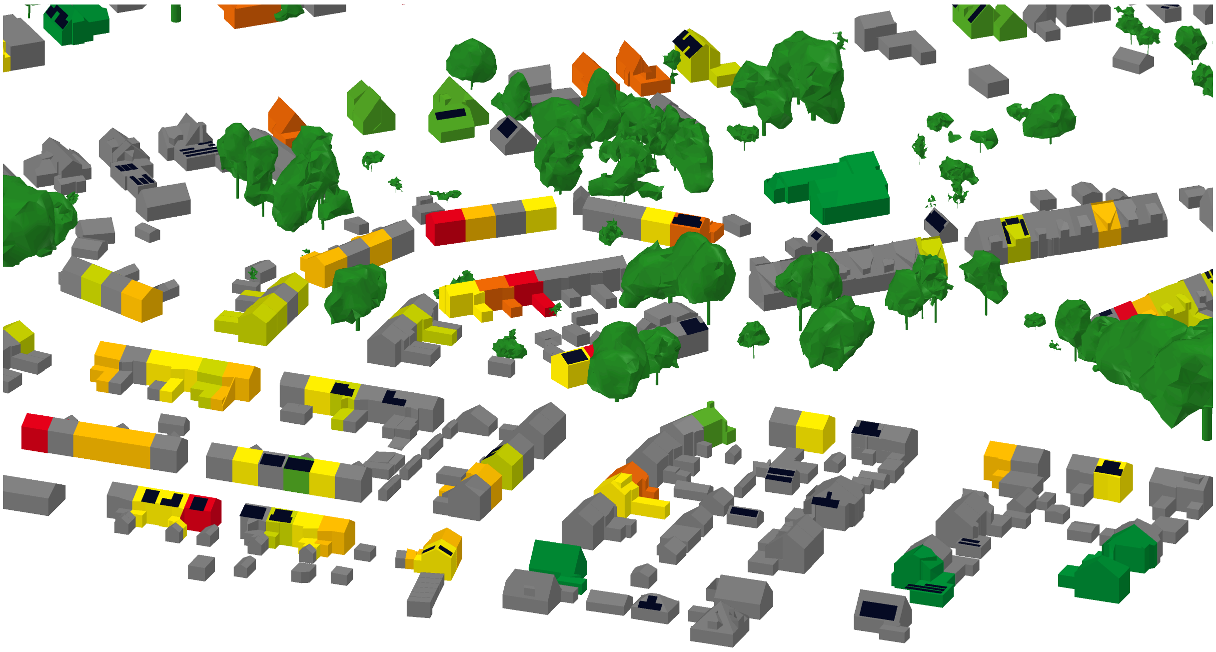


Figure 6.4: The integrated Emmer-Compascuum small-area scene, energy-label appearance theme active. Screenshot of KITModelViewer (KIT); model by the author.

6.3.1. Building identification and addresses (BAG)

The pipeline read building outlines and addressable units from the BAG through the national PDOK web feature service. From each `bag:pand` it took the stable identifier and the year of construction; from each `bag:verblijfsobject` it took the identifier, the use function, the floor area, the address-locating point, and the structured Dutch address components. The municipality outline and the 3DBAG tile index were also fetched, but only to set the bounding box and select tiles; neither emits a feature.

Each *pand* became one `bldg:Building` and each *verblijfsobject* one `nrg3:BuildingUnit` parented to its building, with the BAG identifiers attached as `nrg3:identifier` values under the BAG code space rather than overwriting the human-readable `gml:name` slot. The address was modelled once on the `bldg:Building` through the CityGML 2.0 composition slot and referenced from the unit by an `xlink`, which matches the Energy ADE association between a building unit and an address it does not own. The registered usable floor area, the BAG `oppervlakte` of the unit, entered as a `nrg3:QualifiedArea` tagged with its BAG source, leaving room for a second, differently-sourced area alongside it (a point that recurs under EP-Online below). In the small-area scene this produced 951 buildings and 603 building units; Table 31 shows one building expanded to its unit, address, and certificate.

Name	Value	Description
bldg:Building		
├ gml:id	pand_0114100000202794	
├ nrg3:identifier	0114100000202794	codeSpace BAG pand
├ bldg:yearOfConstruction	1926	
├ bldg:address (→ core:Address)		
│ ├ xAL:ThoroughfareName	Hoofdkanaal WZ	
│ ├ xAL:ThoroughfareNumber	38	
│ ├ xAL:PostalCodeNumber	7881AB	
│ └ xAL:LocalityName	Emmer-Compascuum	
└ nrg3:BuildingUnit		
├ gml:id	bu_0114010000280857	
├ nrg3:identifier	0114010000280857	codeSpace BAG verblijfsobject
├ nrg3:address (xlink to the core:Address above)		
└ nrg3:EnergyPerformanceCertificate		
├ nrg3:label	G	
├ nrg3:type	totalEnergyDemand	
└ nrg3:status	actual	

Table 31: One building expanded to show the core:Address modelled on it (its address components are xAL elements reached through core:xalAddress), the nrg3:BuildingUnit that references that address by xlink, and the unit's nrg3:EnergyPerformanceCertificate, as read in the KITModelViewer inspector. Own work.

Source field	Mapped to	How
identificatie	gml:id + nrg3:identifier (BAG pand code space)	Native
bouwjaar	bldg:yearOfConstruction + a nrg3:Metadata source block	Native
status	read but not written; no native lifecycle slot	Latent
geometry	(none); the 3DBAG geometry is used instead	Dropped
gebruiksdoel	(none); empty on the *pand* node	Dropped
aantal_verblijfsobjecten	(none)	Dropped
oppervlakte_min	(none); 3DBAG geometry is used instead	Dropped
oppervlakte_max	(none); 3DBAG geometry is used instead	Dropped
rdf_seealso	(none); implicit in the code space	Dropped

Table 32: BAG bag:pand to bldg:Building mapping (8 properties plus geometry shipped, 4 read). Every *pand* becomes one bldg:Building. Own work.

Source field	Mapped to	How
identificatie	gml:id + nrg3:identifier (BAG verblijfsobject code space); also the EP-Online join key	Native
gebruiksdoel	nrg3:type (Dutch term verbatim, own code space)	Native
oppervlakte	nrg3:QualifiedArea (type="netFloorArea", BAG source)	Native
geometry (point)	core:Address/core:multiPoint	Native
openbare_ruimte	xAL:ThoroughfareName	Native
huisnummer	xAL:ThoroughfareNumber	Native
huisletter	xAL:ThoroughfareNumberSuffix (typed huisletter)	Native
huisnummertoevoeging	xAL:ThoroughfareNumberSuffix (typed huisnummertoevoeging)	Native
postcode	xAL:PostalCodeNumber	Native
woonplaats	xAL:LocalityName	Native
pandidentificatie	groups the unit under its parent building	Filter-only
status	read but not written; no native lifecycle slot	Latent
bouwjaar	(none); the *pand* value is authoritative	Dropped
pandstatus	(none); redundant with the *pand* status	Dropped
rdf_seealso	(none); implicit in the code space	Dropped

Table 33: BAG bag:verblijfsobject to nrg3:BuildingUnit and core:Address mapping (14 properties plus geometry shipped, 11 read). Every *verblijfsobject* becomes one nrg3:BuildingUnit; its address is modelled once on the parent bldg:Building (CityGML 2.0 composition) and referenced from the unit by xlink, with the NL country wrapper emitted as a constant. Own work.

6.3.2. Building geometry (3DBAG)

The 3D geometry came from 3DBAG [75], which reconstructs the entire Dutch building stock from the BAG footprints and national airborne lidar. The pipeline read the CityJSON tiles and took 3 levels of detail and 8 of the roughly 62 building attributes the tiles carry. The LoD0 footprint, the LoD1.2 block, and the LoD2.2 surfaces[6] mapped onto `bldg:lod0FootPrint`, `bldg:lod1Solid`, and per-polygon `bldg:WallSurface`, `bldg:RoofSurface`, and `bldg:GroundSurface` thematic surfaces. The footprint vertices were lifted from the nominal zero height to the per-building terrain height so the LoD0 polygon aligns with the LoD1 ground face rather than floating.

Among the attributes, the maximum roof height minus the terrain height became a `nrg3:bdgHeight` qualified attribute, the LoD2.2 volume a `nrg3:bdgVolume`, the storey count `bldg:storeysAboveGround`, and the 3DBAG roof-type class was translated onto the SIG 3D `bldg:roofType` codelist. Each LoD2 surface also received the geometric subset of the per-surface physics it can support from geometry alone: total surface area, inclination, and, on non-horizontal faces, azimuth. The thickness and heat-capacity attributes that the per-building file carried (Section 6.2) are deliberately left empty here. The open registers provide no layered constructions, and inventing placeholder values would silently corrupt any downstream energy calculation. In the small-area scene the LoD2 geometry resolves to 13,519 wall, 2,995 roof, and 951 ground surfaces across the 951 buildings.

Source field	Mapped to	How
LoD0 surface	`bldg:lod0FootPrint` (vertices lifted to the terrain height)	Native
LoD1.2 solid	`bldg:lod1Solid`	Native
LoD2.2 face (wall semantics)	`bldg:WallSurface` (a specialised `bldg:_BoundarySurface`) under `bldg:boundedBy`, with its `bldg:lod2MultiSurface`	Native
LoD2.2 face (roof semantics)	`bldg:RoofSurface` under `bldg:boundedBy`, with its `bldg:lod2MultiSurface`	Native
LoD2.2 face (ground semantics)	`bldg:GroundSurface` under `bldg:boundedBy`, with its `bldg:lod2MultiSurface`	Native
(per LoD2 surface, from its geometry)	`nrg3:bdgBdrySurfTotalSurfaceArea` (m^2, holes subtracted)	Computed
(per LoD2 surface, from its geometry)	`nrg3:bdgBdrySurfInclination` (deg from the +Z axis)	Computed
(per non-horizontal LoD2 surface)	`nrg3:bdgBdrySurfAzimuth` (deg, compass bearing)	Computed
`identificatie`	join key back to the BAG *pand*	Filter-only
`oorspronkelijkbouwjaar`	`bldg:yearOfConstruction` (only when the BAG year is absent)	Native
`b3_h_dak_max`	`nrg3:bdgHeight` (`QualifiedHeight`, `type="maxHeightAboveGround"`): the maximum roof height	Native
`b3_h_maaiveld`	the terrain height: subtrahend of `nrg3:bdgHeight` and the LoD0 Z-lift	Native
`b3_volume_lod22`	`nrg3:bdgVolume` (`QualifiedVolume`)	Native
`b3_bouwlagen`	`bldg:storeysAboveGround`	Native
`b3_dak_type`	`bldg:roofType` (mapped to the SIG 3D roof-form codelist)	Native
`gebruiksdoel`	would map to `bldg:function`, but the 3DBAG *pand* node ships it empty, so none is emitted in this output	Dropped
`status`	read but not written; no native lifecycle slot	Latent

Table 34: 3DBAG CityJSON to CityGML mapping (around 62 attributes plus 3 LoD geometries shipped, 8 attributes plus 3 LoDs read). The height and volume use the Energy ADE qualified-attribute extensions, because `bldg:Building` has no native slot for them; per-surface thickness and heat capacity are left empty, because the open registers carry no layered constructions and inventing values would corrupt downstream energy calculations. The remaining around 54 attributes (reconstruction-quality statistics such as `b3_rmse_lod*`, `b3_val3dity_lod*`, and `b3_puntdichtheid_ahn*`, and 14 BAG-lifecycle duplicates) are out of scope and not mapped. Own work.

[6] 3DBAG publishes its geometry under the refined level-of-detail specification of [84], which subdivides the integer CityGML levels, so it ships LoD0, LoD1.2, LoD1.3, and LoD2.2. CityGML 2.0 itself defines only the integer levels LoD0 to LoD4, so the 3DBAG LoD1.2 block and LoD2.2 surfaces are ingested as the CityGML LoD1 and LoD2 representations; this section names the source geometry with the refined 3DBAG label and the CityGML slot it lands in with the integer one, which is why both LoD2.2 and LoD2 appear in what follows.

6.3.3. Energy performance (EP-Online)

Energy performance came from the EP-Online register, the national store of registered Dutch energy labels, joined to the building units. A unit was matched to a certificate first by its BAG identifier and, where that failed, by a normalised address key; on a match the pipeline read about 20 of the register's 42 columns. The energy label became the `label` of a `nrg3:EnergyPerformanceCertificate` on the unit and also drove the building's fill colour through an `app:Appearance` theme, so the A-to-G class is both an attribute and a visible rendering. The registration, inspection, and expiry dates filled the certificate's date slots, and the calculation method its `certificationMethod`. Table 35 shows a certificate as the viewer presents it. The certificate can also point back to its register entry through the CityGML external-reference mechanism. The last rows of Table 35 show the form this takes, with the register's public search page as the information system and the BAG identifier as the key, which that search resolves directly.

Name	Value	Description
`nrg3:EnergyPerformanceCertificate`		
├ `nrg3:label`	A	
├ `nrg3:value`	129.7 kWh/m2/a	
├ `nrg3:type`	totalEnergyDemand	
├ `nrg3:status`	actual	
├ `nrg3:certificationMethod`	Basisopname / NTA 8800:2024	
├ `nrg3:validFrom`	2026-02-02	
└ `nrg3:validTo`	2036-01-13	
`core:externalReference`		
├ `core:informationSystem`	https://www.ep-online.nl/Energylabel/Search	
└ `core:externalObject → core:name`	0114010000357334	BAG `verblijfsobject` identifier

Table 35: An EP-Online certificate mapped onto `nrg3:EnergyPerformanceCertificate`, as read in the KITModelViewer inspector. The `core:externalReference` rows illustrate how a certificate links back to its EP-Online register entry: the register's public search resolves a BAG identifier directly. The pipeline does not yet emit this reference. Own work.

The energy figures are where the units-of-measure discipline of Section 5.1.2 proves its value, because EP-Online carries three calculation regimes side by side. Certificates computed under the current NTA 8800 method report demand per square metre per year, while older certificates under the legacy methods report an absolute total in megajoules per year. The same register column therefore holds quantities that differ by three orders of magnitude. Without an explicit unit on each value the two would be indistinguishable, and any downstream aggregation would silently average across incompatible quantities. Because every `nrg3:Energy` resource carries its `uom`, the pipeline could classify each certificate by its method and keep a per-area NTA 8800 figure separable from a legacy total. This is the semantic-interoperability property that motivated an open geospatial data model in the first place (Section 2.3), now seen on real national data. The Dutch building type was recorded on the building as a native `nrg3:bdgType`, kept as the verbatim Dutch term under its own code space rather than forced onto the coarser Energy ADE building-type codelist. Forcing it onto that codelist would have merged distinctions the renovation context depends on. Year of construction is recorded from both BAG and EP-Online, each with its own `nrg3:Metadata` source block, which is what makes the year-disagreement finding of Section 6.4 observable. In the small-area scene 302 certificates were attached across the units.

Source field	Mapped to	How
`BAGVerblijfsobjectID`	matched to the BAG unit (primary join key)	Filter-only
`Postcode`	address-key join; already on `core:Address` from BAG	Filter-only
`Huisnummer`	address-key join	Filter-only
`Huisletter`	address-key join	Filter-only
`Huisnummertoevoeging`	address-key join	Filter-only
`Registratiedatum`	`nrg3:EnergyPerformanceCertificate/validFrom`	Native
`GeldigTot`	`nrg3:EnergyPerformanceCertificate/validTo`	Native
`Opnamedatum`	`core:creationDate` on the certificate	Native
`Energieklasse`	`nrg3:EnergyPerformanceCertificate/label` + `energyLabel` appearance	Native
`Berekeningstype`	`nrg3:EnergyPerformanceCertificate/certificationMethod`	Native
`SoortOpname`	joined into `certificationMethod`	Native
`Status`	read but not written; no native lifecycle slot	Latent
`OpBasisVanReferentiegebouw`	read but not written; quality flag	Latent
`Certificaathouder`	(none); certifier name, privacy	Dropped
`Gebouwklasse`	(none); coarse, redundant with `Gebouwtype`	Latent
`Gebouwtype`	`nrg3:bdgType` on the building (RVO term verbatim)	Native
`Gebouwsubtype`	`gen:stringAttribute bdgSubtypeEPOnline` on the unit	GenericAttribute
`SBICode`	(none); utility buildings only	Latent
`BAGLigplaatsID`	(none); houseboat mooring, out of scope	Dropped
`BAGStandplaatsID`	(none); caravan plot, out of scope	Dropped
`BAGPandIDs`	(none); redundant with the BAG join	Dropped
`Projectnaam`	(none); operator free text	Dropped
`Projectobject`	(none); operator free text	Dropped
`Detailaanduiding`	(none); BAG address is authoritative	Dropped
`Bouwjaar`	`gen:intAttribute yearOfConstructionEPOnline` on the building + `nrg3:Metadata` (BAG holds `bldg:yearOfConstruction`)	GenericAttribute
`GebruiksoppervlakteThermischeZone`	second `nrg3:QualifiedArea` on the unit (NTA 8800 rows only)	Native
`Compactheid`	(none); no shape-descriptor slot	Latent
`EnergieIndex`	(none); pre-NTA 8800, incompatible	Dropped
`EnergieIndexEMGForfaitair`	(none); legacy EMG variant	Dropped
`Energiebehoefte` (BENG-1)	`nrg3:Energy` (`type="net"`)	Native
`Warmtebehoefte`	`nrg3:Energy` (`type="net"`, `endUse="spaceHeating"`)	Native
`PrimaireFossieleEnergie` (BENG-2)	`nrg3:Energy` (`type="primary"`), also carries `co2Equivalent`	Native
`PrimaireFossieleEnergieEMGForfaitair`	(none); EMG-forfait variant	Dropped
`AandeelHernieuwbareEnergie` (BENG-3)	`gen:measureAttribute` on the certificate; conceptual home `nrg3:Indicator`	GenericAttribute
`AandeelHernieuwbareEnergieEMGForfaitair`	(none); EMG-forfait variant	Dropped
`BerekendeCO2Emissie`	`nrg3:Energy/co2Equivalent` (regime-aware)	Native
`BerekendeEnergieverbruik`	`nrg3:Energy` (`final` or `primary` by regime) + `EnergyPerformanceCertificate/value`	Native
`Temperatuuroverschrijding` (BENG-4)	(none); no thermal-comfort slot	Latent
`EisEnergiebehoefte`	(none); regulatory threshold	Latent
`EisPrimaireFossieleEnergie`	(none); regulatory threshold	Latent
`EisAandeelHernieuwbareEnergie`	(none); regulatory threshold	Latent
`EisTemperatuuroverschrijding`	(none); regulatory threshold	Latent

Table 36: EP-Online (`Mutatiebestand`) to Energy ADE mapping, all 42 columns. About 20 are read, 3 of them through a `gen:*Attribute` fallback (building subtype, EP-Online construction year, renewable-energy share). For the first two the schema has no native slot. The renewable share does have a conceptual home, the `nrg3:Indicator` mechanism that the mapping of Section 4.2 names for it, so its generic attribute is a pipeline shortcut rather than a schema gap. The certificate `status` (`actual`) and `type` (`totalEnergyDemand`) are emitted as constants, not from a column. The energy metrics are emitted regime-aware: NTA 8800 rows carry per-area values, legacy rows an absolute total, as described above. Own work.

6.3.4. Rooftop solar panels (panel-polygon dataset)

The rooftop solar layer came from an open dataset of panel polygons annotated from aerial imagery over the area [79]. The pipeline read the panel geometry, clipped it to the area, and matched each polygon to the LoD2 roof surface beneath it. Each matched polygon became one `nrg3:GenericSolarCollector` parented to its building, carrying the projected roof geometry, a module area, an inclination and azimuth derived from the roof plane, and an `installedOn` relation to the roof surface. The generic class is used here rather than the dedicated `nrg3:PhotovoltaicCollector` of the per-building file (Section 5.3.2), because the aerial source marks only a panel footprint. Asserting a photovoltaic cell type it does not record would overstate what is known. The small-area scene carries 390 such collectors (Figure 6.5). The same repeated `installedOn` relation pattern as at audit depth recurs here in large numbers, against the 2,995 roof surfaces of the scene.

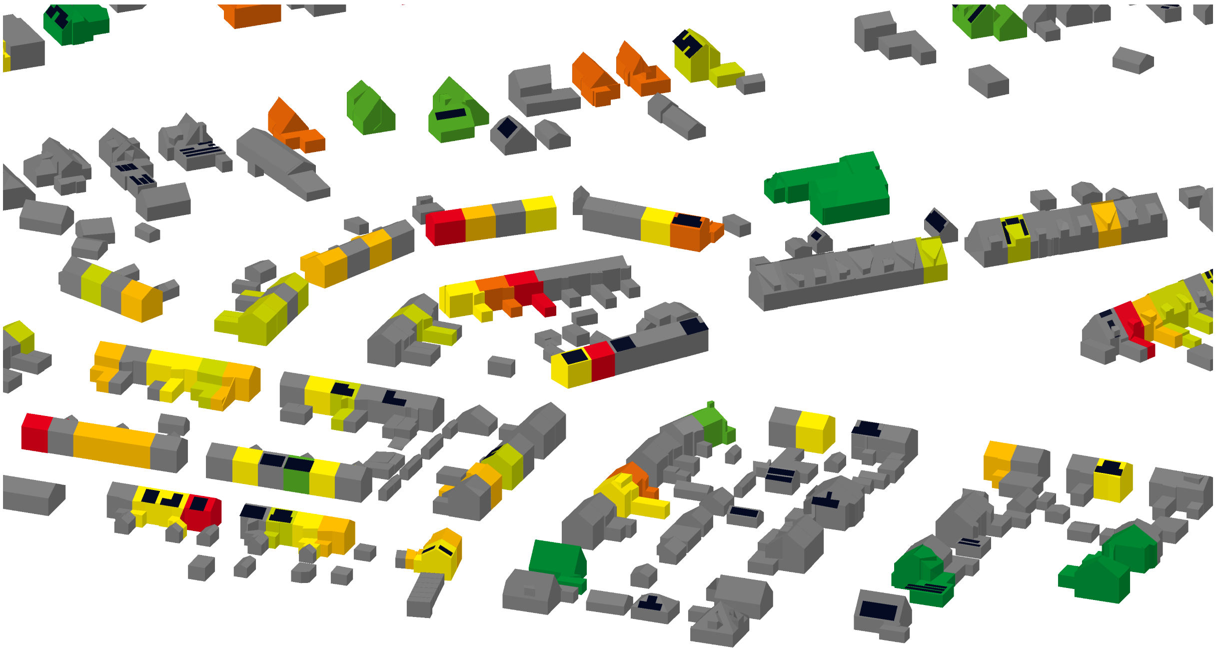


Figure 6.5: Rooftop `nrg3:GenericSolarCollector` instances mapped from the panel-polygon dataset, visible as the dark panels on the building roofs (buildings shaded by energy label). Screenshot of KITModelViewer (KIT); model by the author.

Source field	Mapped to	How
`fid`	`gml:id` (`solar_<pand>_<fid>`, for traceability)	Native
`geom` (polygon)	`lod2MultiSurface` (projected onto the matched roof plane)	Native
(polygon area)	`nrg3:moduleArea`	Computed
(roof plane)	`nrg3:inclination`	Computed
(roof plane)	`nrg3:azimuth`	Computed
(panel centroid + roof plane)	`nrg3:referencePoint`	Computed
(matched roof surface)	`nrg3:CityObjectRelation installedOn`	Computed
(no source)	`nrg3:cellType` left unset	Dropped
(no source)	`nrg3:installedPower` left unset	Dropped
(no source)	`nrg3:nominalEfficiency` left unset	Dropped

Table 37: Solar-panel GeoPackage to `nrg3:GenericSolarCollector` mapping (2 columns plus geometry shipped, both read). The aerial source marks only a panel footprint, so the technology-agnostic `nrg3:GenericSolarCollector` is used rather than `nrg3:PhotovoltaicCollector`: asserting a photovoltaic `cellType` would overstate what the source records. Module geometry and orientation are computed from the polygon and its roof plane; the remaining collector fields (`model`, `yearOfManufacture`, `apertureArea`, and the rest) are left unset because the source provides no values for them. Own work.

6.3.5. Vegetation (CFTree, BGT, and protected-tree records)

Trees entered the scene from three sources combined. The geometry and morphometrics came from CFTree reconstructions [80] built from airborne lidar. The pipeline read these as LoD3 tree meshes and mapped them onto `veg:SolitaryVegetationObject` instances with a `veg:lod3Geometry`, carrying height, trunk diameter, and crown diameter on the native vegetation slots. Each tree was then matched against the BGT topographic register; a match attached a `core:externalReference` back to the authoritative BGT feature, which doubles as a signal that the tree is a municipally maintained public-space tree rather than a private-garden one. Where the area falls inside the municipality of Emmen, a third match against the municipal protected-tree records filled the `veg:species` slot with the Latin species name and added the protection status and planting details. Vegetation is outside Energy ADE's energy focus, so the fields with no native schema slot (the secondary crown metrics, the protection status, and the planting details) are carried as generic attributes, in a structured and queryable form rather than dropped; a dedicated vegetation ADE would hold them more formally. The small-area scene carries 702 vegetation objects, of which roughly a third matched a BGT record (Figure 6.6). No single source carried all three of geometry, public-space status, and species; the integrated object is an assembly that none of the three publishes on its own.

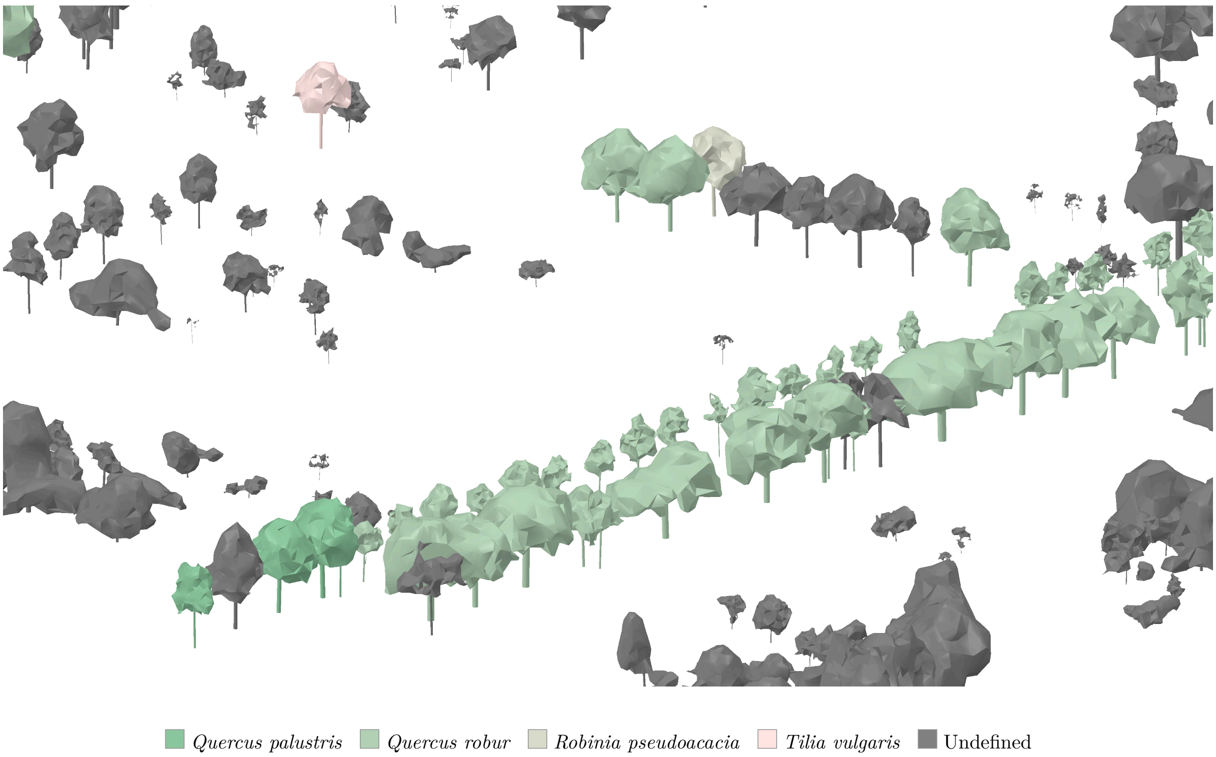


Figure 6.6: LoD3 vegetation objects coloured by `veg:species`. Only 83 of the 702 trees carry a Latin species name (from the Emmen protected-tree register); the remaining 619 (grey) are unmatched. Assembled from CFTree, BGT, and protected-tree records. Screenshot of KITModelViewer (KIT); model by the author.

Source field	Mapped to	How
`gtid`	`gml:id` + `gml:name`	Native
crown + trunk solids	`veg:lod3Geometry` (merged `gml:MultiSurface`)	Native
`trunk_H_m`	`veg:height`	Native
`trunk_DBH_m`	`veg:trunkDiameter`	Native
`crown_width_m`	`veg:crownDiameter`	Native
`crown_median_z`	`gen:doubleAttribute crown_median_z`	GenericAttribute
`crown_r50_m`	`gen:doubleAttribute crown_r50_m`	GenericAttribute
`crown_porosity`	`gen:doubleAttribute crown_porosity`	GenericAttribute
`trunk_base_height_m`	`gen:doubleAttribute trunk_base_height_m`	GenericAttribute
`trunk_radius_m`	(none); redundant with `trunk_DBH_m`	Dropped

Table 38: CFTree reconstruction to `veg:SolitaryVegetationObject` mapping (10 attributes plus LoD3 geometry shipped, 9 plus geometry read; the `tile_id` debug field is not used). CFTree provides the only native geometry and morphometrics for a tree. Own work.

Source field	Mapped to	How
lokaal_id	core:externalReference (marks a public-space tree)	Cross-ref
creation_date	gen:dateAttribute bgtCreationDate	GenericAttribute
plus_type	filter: non-tree features dropped	Filter-only
status	filter: former trees dropped	Filter-only
geometry (point)	4 m nearest-neighbour match against the CFTree crown	Filter-only
bronhouder	read but not written; latent multi-municipality key	Latent

Table 39: BGT vegetatieobject_punt to cross-reference mapping (23 properties plus geometry shipped, 5 read). BGT carries no biological attributes; it contributes only a cross-reference that flags a tree as municipally maintained. The remaining around 18 IMGeo bookkeeping fields (version, tijdstip_registratie, type, the code-space *_leeg fields, and similar) are out of scope and not mapped. Own work.

Source field	Mapped to	How
boom_id	core:externalReference	Cross-ref
soortnaam	veg:species (Latin name)	Native
soortnaam_ned	gen:stringAttribute speciesCommonName	GenericAttribute
jaarvanaanleg	gen:intAttribute plantingYear	GenericAttribute
boomhoogteklasseactueel	gen:stringAttribute heightClass	GenericAttribute
stamdiameterklasse	gen:stringAttribute trunkDiameterClass	GenericAttribute
beschermingsstatus	gen:stringAttribute protectionStatus	GenericAttribute
beschermingsstatus_detail	gen:stringAttribute protectionStatusDetail	GenericAttribute
type	gen:stringAttribute growthForm	GenericAttribute
standplaats	gen:stringAttribute standLocation	GenericAttribute
standplaats_detail	gen:stringAttribute standLocationDetail	GenericAttribute

Table 40: Emmen municipality *Beheer Openbare Ruimte* (BOR, public-space-management register) to species and generic attributes (11 fields, all read). The register is the only source that fills veg:species; the protection regime and growth-form descriptors fall to generic attributes, because the CityGML 2.0 vegetation module has no typed slot for them. Used only in Emmen runs. Own work.

6.3.6. Neighbourhood energy aggregates (CBS Postcode-6)

The last source is neighbourhood context. CBS publishes dwelling and energy statistics per six-digit postcode, and the pipeline read the postcode polygons together with their average gas and electricity use and their dwelling counts. Because these are area averages rather than per-building facts, attaching them to an individual building would overstate what they record. Each postcode therefore became one nrg3:UrbanFunctionArea, the Energy ADE aggregation feature, carrying its polygon, its area, two nrg3:Energy resources for the average gas and electricity use, and the dwelling counts as generic attributes. Each aggregate links to the buildings that fall inside it through grp:groupMember references, so a reader can move between the neighbourhood figure and the individual buildings it summarises. Where CBS suppresses a value for privacy, below a six-dwelling threshold, the suppression code is preserved verbatim rather than silently zeroed, so the absence is visible as a deliberate suppression. The small-area scene carries 68 such aggregates; Table 41 shows one as read in the inspector, and Figure 6.7 shows the aggregate boundaries drawn over the buildings they group.

Name	Value	Description
nrg3:UrbanFunctionArea		
├ nrg3:code	7881AB	
├ nrg3:area	16228 m^2	
├ dwellingCount	20	
├ nrg3:Energy (naturalGas)	1860 m^3/a	type actual, per dwelling
└ nrg3:Energy (electricity)	2790 kWh/a	type actual, per dwelling

Table 41: A CBS postcode aggregate mapped onto nrg3:UrbanFunctionArea, as read in the KITModelViewer inspector. Own work.

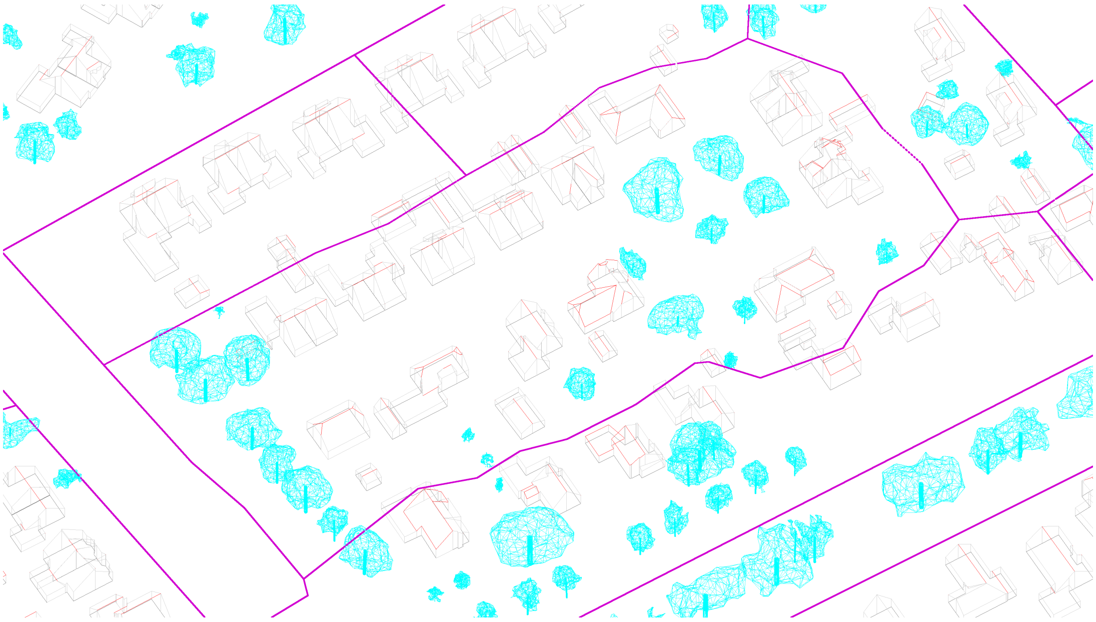


Figure 6.7: The CBS six-digit-postcode boundaries (magenta) of the small-area scene, each mapped to one `nrg3:UrbanFunctionArea`, drawn over the faint building wireframes they group through `grp:groupMember`; the cyan meshes are the scene's LoD3 trees. Screenshot of KITModelViewer (KIT); model by the author.

Source field	Mapped to	How
`postcode6`	`gml:id` + `gml:name` + `nrg3:code` + `core:externalReference`	Native
`geom` (polygon)	`grp:geometry` (`gml:MultiSurface`) + `nrg3:UrbanFunctionArea/area`	Native
`gemiddeldGasverbruikWoning`	`nrg3:Energy` (`naturalGas`, `type="actual"`, per dwelling)	Native
`gemiddeldElektriciteitsverbruikWoning`	`nrg3:Energy` (`electricity`, `type="actual"`, per dwelling)	Native
`aantalWoningen`	`gen:intAttribute dwellingCount`	GenericAttribute
`aantalNietBewoondeWoningen`	`gen:intAttribute vacantDwellingCount`, when present; omitted under CBS privacy suppression, so none appears in this scene	GenericAttribute
(building centroids)	`grp:groupMember` xlinks to the contained buildings	Computed

Table 42: CBS Postcode-6 to `nrg3:UrbanFunctionArea` mapping (around 132 properties plus geometry shipped, 5 read). Each postcode becomes one `nrg3:UrbanFunctionArea`, because the figures are area averages rather than per-building facts; a privacy-suppressed energy value keeps its CBS suppression code in the `amount` slot rather than being zeroed, so the suppression stays visible to a reader. The remaining around 125 demographic, amenity, and education columns are out of scope and are not mapped. Own work.

Taken together, these six sources appear in one scene as a building's geometry, its energy label and energy figures, its rooftop solar, the trees around it, and the neighbourhood aggregate that contains it. That combination is itself a result, and it is taken up in Section 6.4.

6.4. Cross-cutting analysis

The city-scale pipeline of Section 6.3 produces an integrated output that brings building geometry, energy performance, address registration, rooftop solar, and neighbourhood context together in a single scene. Running it across four areas (the full settlement of Emmer-Compascuum and the full municipalities of Delft, Groningen, and Zwolle) produces a body of integrated data that can be read for cross-source patterns. The four areas are shown individually in Figure 6.8, Figure 6.9, Figure 6.10, and Figure 6.11. This section presents six findings drawn from it. Four show how the integration makes a data-quality problem visible, and these are measured across the stock of all four runs. Two show what the integrated, semantically defined model makes possible that the source datasets, in isolation, do not, and these are demonstrated on the integrated scene rather than quantified. The findings are reported constructively, as reconciliation targets rather than as criticism of any one register; the more critical reading is taken up in Section 7.1.

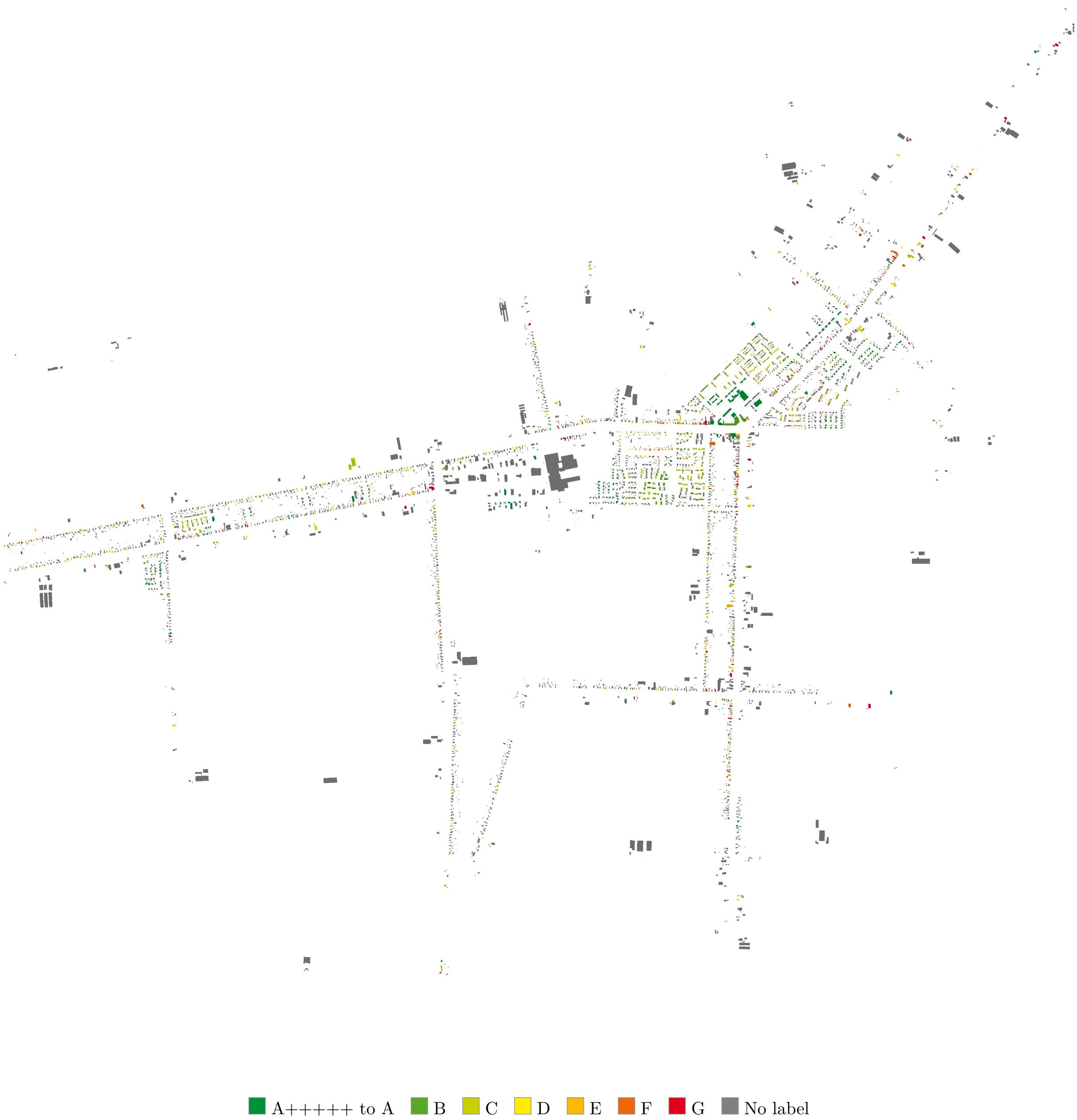


Figure 6.8: Emmer-Compascuum, shown as building footprints coloured by the average EP-Online energy label of the addressable units (*verblijfsobjecten*) they contain. North-oriented top view. Screenshot of KITModelViewer (KIT); model by the author.

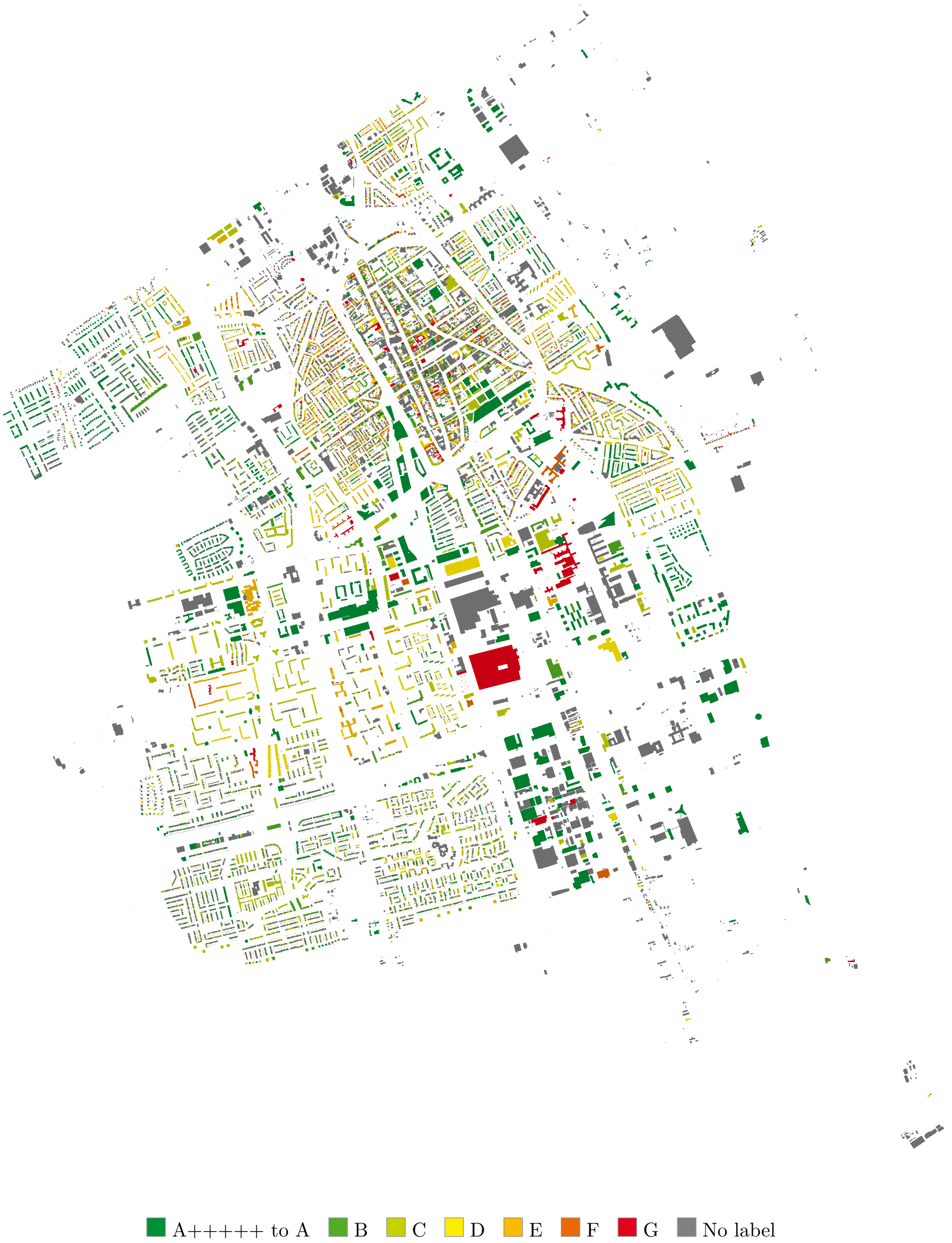


Figure 6.9: Delft, shown as building footprints coloured by the average EP-Online energy label of the addressable units (*verblijfsobjecten*) they contain. North-oriented top view. Screenshot of KITModelViewer (KIT); model by the author.

Figure 6.10: Groningen, shown as building footprints coloured by the average EP-Online energy label of the addressable units (*verblijfsobjecten*) they contain. North-oriented top view. Screenshot of KITModelViewer (KIT); model by the author.

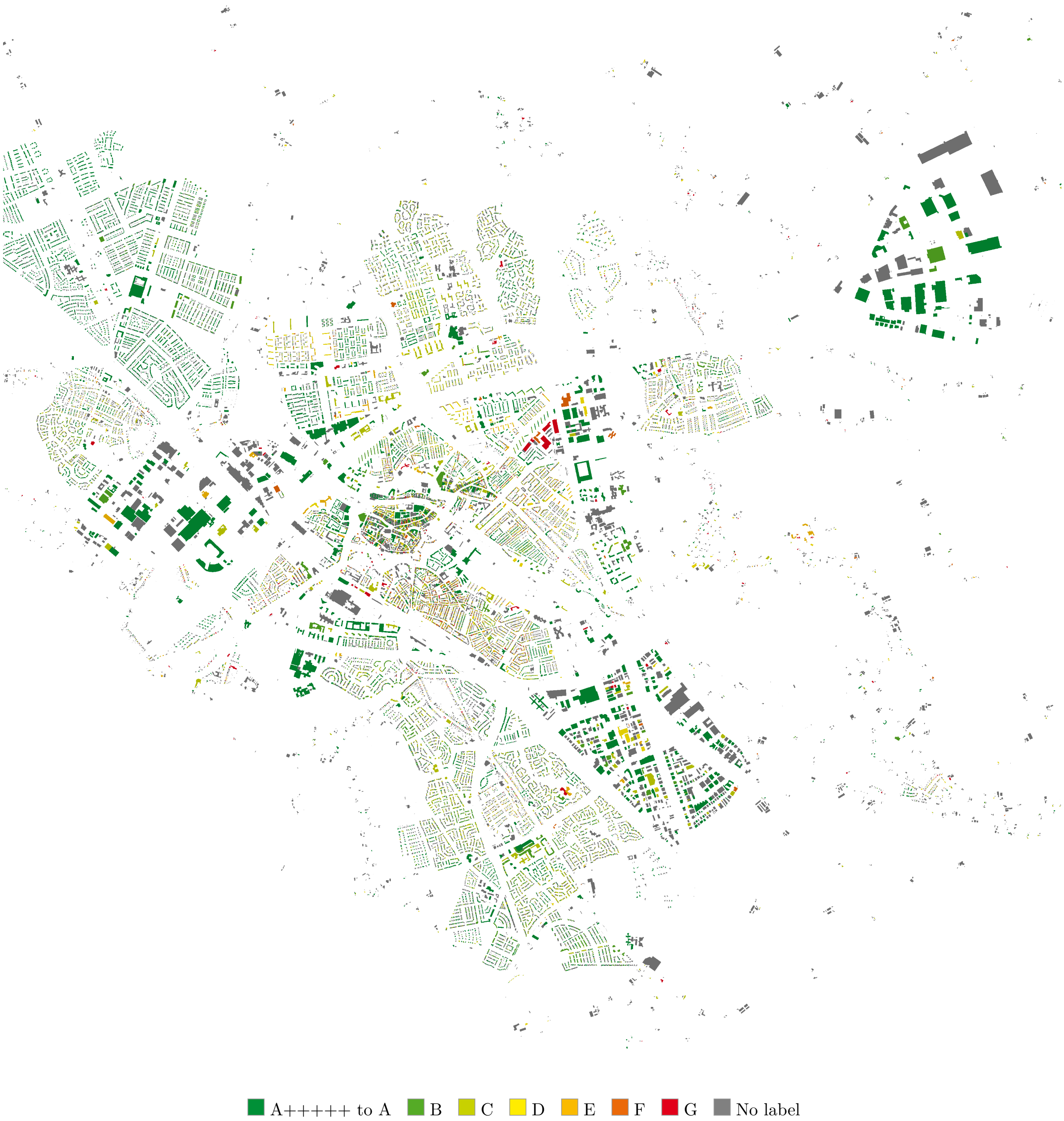


Figure 6.11: Zwolle, shown as building footprints coloured by the average EP-Online energy label of the addressable units (*verblijfsobjecten*) they contain. North-oriented top view. Screenshot of KITModelViewer (KIT); model by the author.

6.4.1. Data-quality findings

These data-quality findings emerged from the modelling approach rather than from any plan to audit the registers. The integrated model places facts from different registers on the same building, each tagged with the register it came from, so a cross-register comparison becomes a direct query on one model rather than a purpose-built join. The four findings below share one thread. Once those facts lie side by side they often disagree, sometimes on something as basic as the year a building was built, and the integration does not resolve the disagreement but makes it systematically visible, and therefore addressable.

BAG and EP-Online disagree on the year of construction

Across all four areas, BAG and EP-Online agree exactly on the year of construction only about three-fifths of the time, and disagree on it for roughly two in five buildings. Both registers record the year, and because the pipeline carries both values on the same building, each tagged with its source, the two can be compared directly across the whole stock. Agreement to within a few years is higher, around 86%, but the central finding is that two authoritative national registers differ on a basic, supposedly objective fact for a large share of the stock. Figure 6.12 shows the per-city distribution of the gap between the two sources.

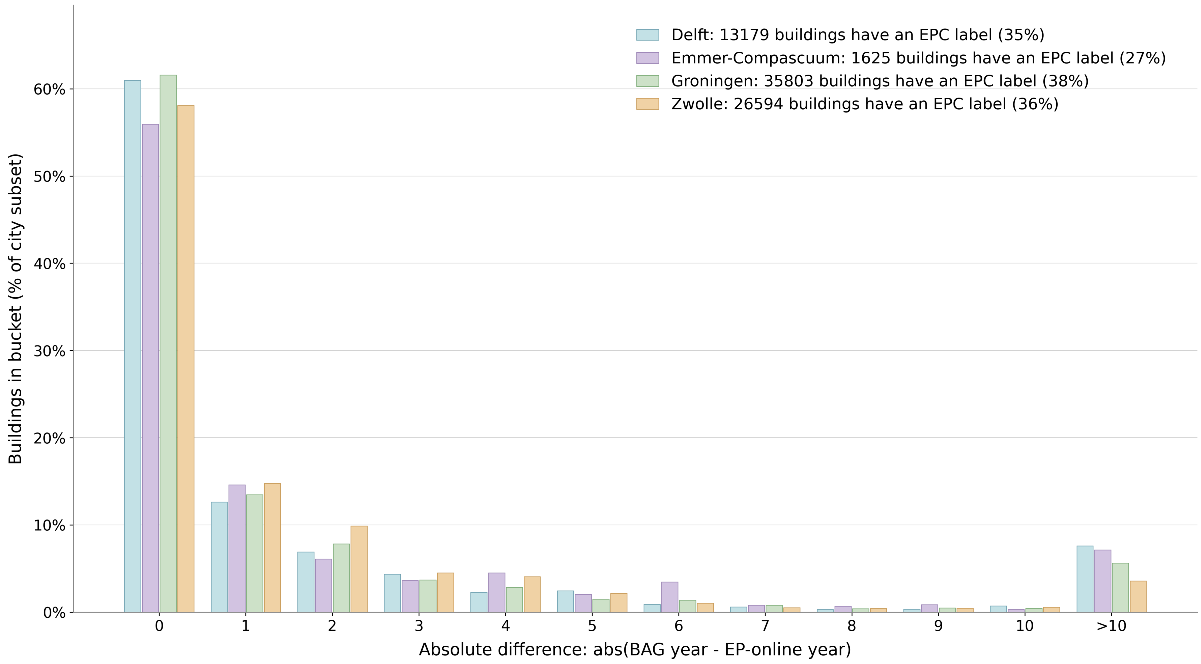


Figure 6.12: Agreement between the BAG and EP-Online year of construction across the four areas; the bars give the share of buildings whose two recorded years agree exactly, within one year, within three years, and beyond. Own work.

The two registers should be reconciled, and the integrated output is what makes a systematic reconciliation possible. Every building where the two sources differ can be queried directly from the model, so the disagreement can be quantified, attributed, and worked through, rather than remaining invisible in two registers that are never read against each other. The next two findings look at where the EP-Online side of that disagreement comes from.

A single year acts as a placeholder in EP-Online

Part of the disagreement is structural. One year, 1930, is carried by a disproportionate share of EP-Online certificates, between roughly 7% and 12% of labelled buildings per area and highest in Delft at about an eighth of the stock. The BAG years of those same buildings span several centuries. A single year held by that many buildings of such varied real age is not a coincidence; 1930 behaves as a placeholder value rather than a real construction year. The pattern is only visible once the EP-Online year is set against an authoritative comparator, which is exactly what the integration provides. Figure 6.13 shows the year clusters per city.

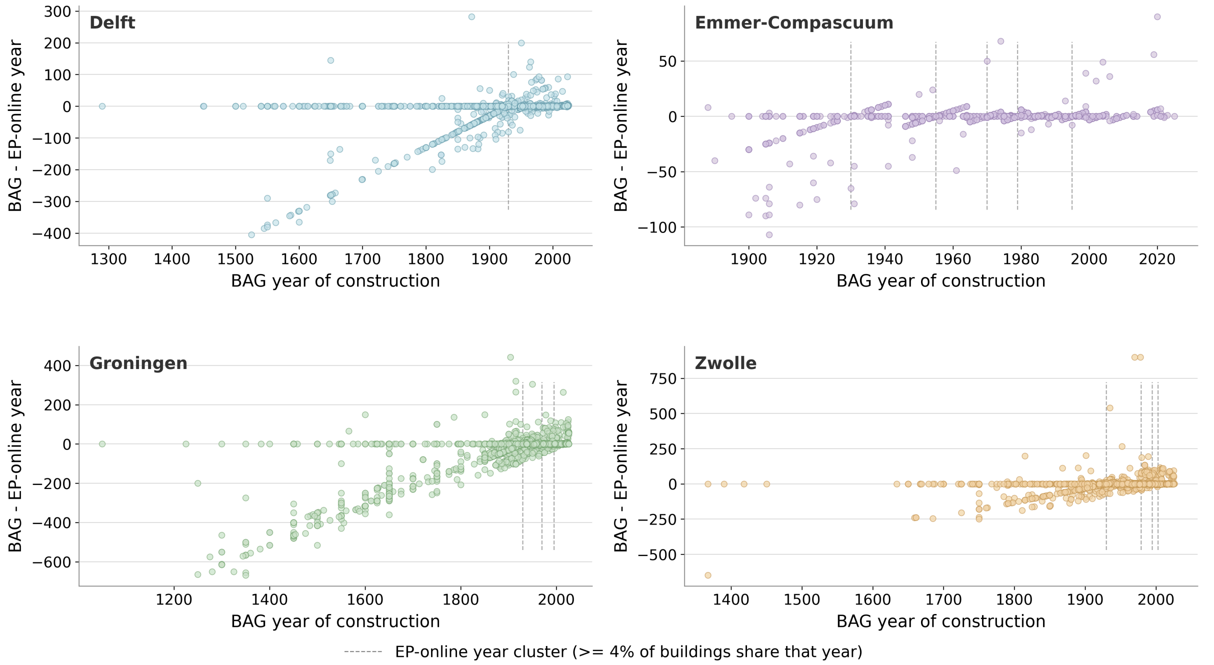


Figure 6.13: Over-represented EP-Online year clusters across the four areas, with the 1930 placeholder most prominent; each point is a building, plotted by its EP-Online year against the signed gap to its BAG year. Own work.

Naming the placeholder year is the first step to handling it. A consumer that knows 1930 is a likely placeholder can flag those records or prefer the BAG year for them, and the integrated model is what lets that rule be written and applied across the whole stock at once.

The same data carries a second, milder version of the same problem: rounding. Even setting the placeholder aside, EP-Online construction years cluster on round numbers, with years ending in zero (and, to a lesser extent, five) appearing at roughly twice their expected share. About a quarter of EP-Online years end in zero, against the 10% a uniform distribution would give, while the BAG and 3DBAG-derived years sit notably closer to uniform. So even where EP-Online does record a year, it is often a rounded estimate rather than a precise record. Because the integrated model carries the more uniform BAG-derived year alongside it, the rounded values can be identified and, where a precise year matters, replaced.

BAG and EP-Online disagree on floor area, and the gap is structured by building type

The same disagreement appears on a second basic quantity, floor area, and here the integrated model shows that the gap is not random noise but a structured effect. BAG records a usable floor area per addressable unit, while EP-Online records the heated floor area its energy label is computed on. Because the pipeline carries both on the same building unit, the two can be differenced directly across the stock. Figure 6.14 shows the distribution of that signed gap, one row per building typology, with the four areas overlaid.

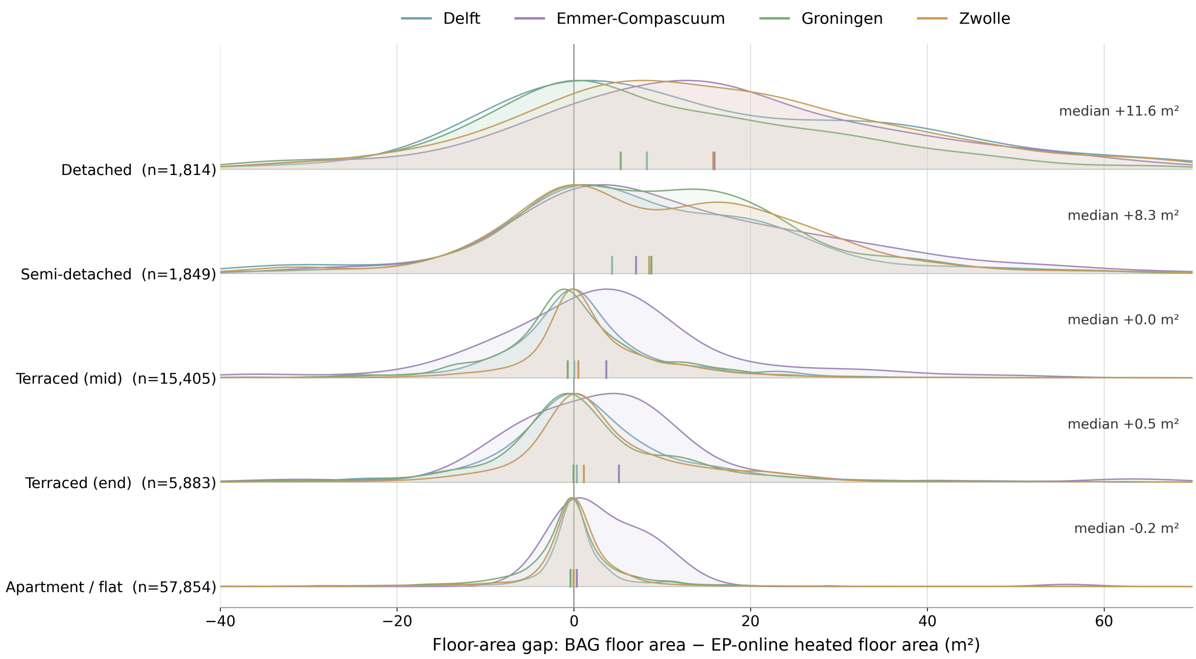


Figure 6.14: Signed floor-area gap (BAG floor area minus EP-Online heated floor area, in m²) per building typology, with the four areas overlaid as normalised kernel-density curves and a short tick at each area's median. The typology is derived by grouping the EP-Online `nrg3:bdgType` values; the right-hand value is the pooled median gap. A curve to the right of zero means BAG records more area than the label's heated area. Own work.

The gap is near zero for apartments and terraced houses but grows steadily through semi-detached to detached dwellings, where the pooled median reaches roughly 12 m². This rightward shift holds in every city. The most likely reading is not that either register is wrong but that the two measure different things. BAG counts unheated indoor space such as integral garages and attics that the energy label's heated floor area excludes, and detached and semi-detached homes have much more of it than terraced houses and apartments. The two areas therefore converge for compact dwellings and diverge for less compact ones. The left tail, where EP-Online records the larger area, is dominated by collective registrations in which one certificate's heated area spans several BAG units. As with the year of construction, the discrepancy is systematic and explainable, and the integrated model is what turns it from an invisible mismatch between two registers into a quantity that can be measured per typology and reconciled deliberately.

Rooftop solar area shows no relationship to the energy label

The last data-quality finding is a negative one. Putting the rooftop solar area and the energy label on the same building, across the stock, shows no clear relationship between them. Buildings carry comparable amounts of solar across all label bands, and the installed area is highly skewed, with most installations modest and a few very large. Figure 6.15 plots solar area against label band.

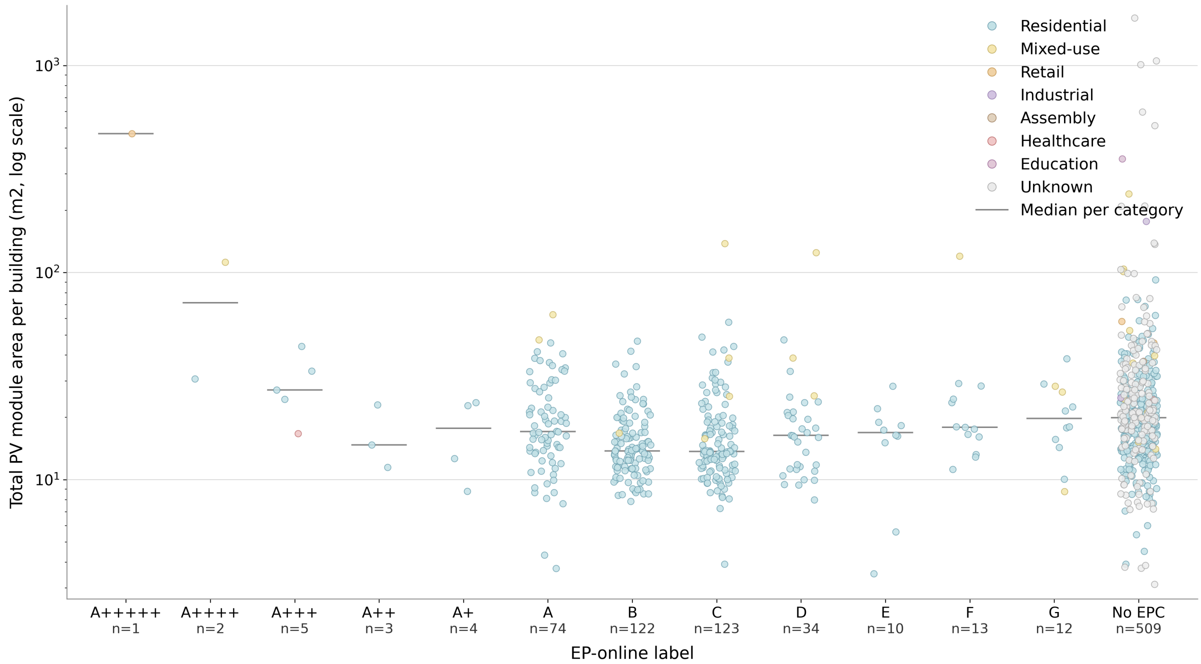


Figure 6.15: Rooftop solar module area against the EP-Online label band; each point is a building, with module area on a log scale and a separate bucket for buildings that carry no certificate. Own work.

The absence of a relationship is itself diagnostic, and a large share of the solar-bearing buildings carry no certificate at all. One caveat on reading the figure: the highest label bands, from A+++ ++ down to A+, hold very few buildings each, so no trend should be read into their points; the bulk of the stock sits in the A-to-G bands where the comparison is meaningful. The integration is what makes the decoupling visible, since the label register knows nothing of the panels and the panel dataset nothing of the label. Why the two are decoupled is taken up in Section 7.1.

6.4.2. What the integration enables

The same integration that exposes those disagreements also makes two things possible that no source provides on its own.

The cross-source link is a traversable relation

Linking a dwelling to its energy certificate is normally a spreadsheet join repeated per analysis. In the integrated output it is a relation in the model. Each certificate is attached to its building unit, and each unit and building carries the identifiers and external references that record where its data came from. The chain from a building to its certificate and back to the source register is therefore traversable in a single pass over the GML. A substantial majority of units link to a certificate, on the order of two-thirds across the four areas and lower where the stock is older and more rural.[7] The unmatched remainder is itself a result: it marks where the address normalisation or the register coverage needs work. The point is that the link is an explicit, queryable part of the model, not that the rate is high.

Five data themes come together in one model

The small-area scene of Section 6.3 carries five independent data themes on a single CityGML model. It holds building geometry from 3DBAG, thermal performance from EP-Online, rooftop solar from the panel dataset, vegetation from the combined tree records, and neighbourhood

[7]Reported from the pipeline build logs as the share of addressable units that matched an EP-Online certificate; the figure is a close proxy rather than an exact per-unit rate, and the unmatched share includes units that simply have no registered label.

energy aggregates from CBS. Three of these (the energy label, solar, and vegetation) are exposed as their own appearance themes in the viewer (Figure 6.4). No single source publishes this combination, and assembling it is what the semantically defined data model makes possible. Each theme attaches to the same buildings through shared identifiers and spatial relations rather than living in a separate file with its own keys. This is the positive counterpart to the data-quality findings above: the same integration that makes the registers' disagreements visible lets the themes be analysed together, and it is the central thing the implementation test demonstrates about the model.

6.5. The populated model in a spatial database

The results above are reported from GML documents read in the KITModelViewer, but the file is not the only way the populated model can be held. The same content was also ingested into a 3DCityDB instance with an FME Workbench from the Energy ADE 3.0 GitHub repository[8] (Appendix A). Figure 6.16 shows three populated tables of that database, read relationally rather than from the GML. The point is that CityGML 2.0 + Energy ADE 3.0 (beta 8) is the conceptual model being tested, while the GML file and the spatial database are two lossless encodings of it. Working with files is practical for a single building and for testing; at the scale of a building stock, geospatial data is best managed in a spatial database. The schema used here builds on 3DCityDB, the most widely used open-source SQL implementation of CityGML, which widens the range of tools and programming languages that can work with the data.

	id [PK] bigint	type character varying	type_codespace character varying	label character	value numeric	value_uom character varying	cert_method character varying	space_id bigint	building_id bigint
1	19722	totalEnergyDema...	http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0/EPCTypeValue....	C	142090.15	MJ/a	Rekenmethodiek Definitief Energielabel, versie 1.2, 16 september 2014	19119	[null]
2	19723	totalEnergyDema...	http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0/EPCTypeValue....	D	96445.3	MJ/a	Rekenmethodiek Definitief Energielabel, versie 1.2, 16 september 2014	19120	[null]
3	19724	totalEnergyDema...	http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0/EPCTypeValue....	C	91555.91	MJ/a	Rekenmethodiek Definitief Energielabel, versie 1.2, 16 september 2014	19122	[null]
4	19725	totalEnergyDema...	http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0/EPCTypeValue....	B	128766.22	MJ/a	Rekenmethodiek Definitief Energielabel, versie 1.2, 16 september 2014	19127	[null]
5	19726	totalEnergyDema...	http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0/EPCTypeValue....	B	98644.51	MJ/a	Rekenmethodiek Definitief Energielabel, versie 1.2, 16 september 2014	19130	[null]
6	19727	totalEnergyDema...	http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0/EPCTypeValue....	B	170.48	kWh/m2/a	Basisopname / NTA 8800:2022 (basisopname woningbouw)	19134	[null]
7	19728	totalEnergyDema...	http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0/EPCTypeValue....	B	98644.51	MJ/a	Rekenmethodiek Definitief Energielabel, versie 1.2, 16 september 2014	19136	[null]
8	19729	totalEnergyDema...	http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0/EPCTypeValue....	F	209249.16	MJ/a	Rekenmethodiek Definitief Energielabel, versie 1.2, 16 september 2014	19140	[null]
9	19730	totalEnergyDema...	http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0/EPCTypeValue....	D	86316.48	MJ/a	Nader Voorschrift, versie 1.0, 1 februari 2014 met erratalijst, addendum 1 juli 2...	19147	[null]
10	19731	totalEnergyDema...	http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0/EPCTypeValue....	D	86316.48	MJ/a	Nader Voorschrift, versie 1.0, 1 februari 2014 met erratalijst, addendum 1 juli 2...	19148	[null]
11	19732	totalEnergyDema...	http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0/EPCTypeValue....	D	86316.48	MJ/a	Nader Voorschrift, versie 1.0, 1 februari 2014 met erratalijst, addendum 1 juli 2...	19149	[null]
12	19733	totalEnergyDema...	http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0/EPCTypeValue....	B	164.92	kWh/m2/a	Basisopname / NTA 8800:2024 (basisopname woningbouw)	19150	[null]
13	19734	totalEnergyDema...	http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0/EPCTypeValue....	B	188.98	kWh/m2/a	Basisopname / NTA 8800:2024 (basisopname woningbouw)	19151	[null]
14	19735	totalEnergyDema...	http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0/EPCTypeValue....	C	103958.08	MJ/a	Rekenmethodiek Definitief Energielabel, versie 1.2, 16 september 2014	19152	[null]
15	19736	totalEnergyDema...	http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0/EPCTypeValue....	G	250072.67	MJ/a	Rekenmethodiek Definitief Energielabel, versie 1.2, 16 september 2014	19155	[null]
16	19737	totalEnergyDema...	http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0/EPCTypeValue....	G	255138.1	MJ/a	Rekenmethodiek Definitief Energielabel, versie 1.2, 16 september 2014	19157	[null]
17	19738	totalEnergyDema...	http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0/EPCTypeValue....	G	459.36	kWh/m2/a	Basisopname / NTA 8800:2022 (basisopname woningbouw)	19164	[null]
18	19739	totalEnergyDema...	http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0/EPCTypeValue....	D	315.32	kWh/m2/a	Basisopname / NTA 8800:2020 (basisopname woningbouw)	19165	[null]
19	19740	totalEnergyDema...	http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0/EPCTypeValue....	E	101151.5	MJ/a	Nader Voorschrift, versie 1.0, 1 februari 2014 met erratalijst, addendum 1 juli 2...	19169	[null]
20	19741	totalEnergyDema...	http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0/EPCTypeValue....	C	125121.47	MJ/a	Rekenmethodiek Definitief Energielabel, versie 1.2, 16 september 2014	19170	[null]
21	19742	totalEnergyDema...	http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0/EPCTypeValue....	A	83897.09	MJ/a	Rekenmethodiek Definitief Energielabel, versie 1.2, 16 september 2014	19171	[null]
22	19743	totalEnergyDema...	http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0/EPCTypeValue....	C	251.47	kWh/m2/a	Basisopname / NTA 8800:2022 (basisopname woningbouw)	19173	[null]
23	19744	totalEnergyDema...	http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0/EPCTypeValue....	D	360.34	kWh/m2/a	Basisopname / NTA 8800:2023 (basisopname utiliteitsbouw)	19174	[null]
24	19745	totalEnergyDema...	http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0/EPCTypeValue....	F	364.43	kWh/m2/a	Basisopname / NTA 8800:2024 (basisopname woningbouw)	19178	[null]
25	19746	totalEnergyDema...	http://3dcities.bk.tudelft.nl/citygml/2.0/energy/3.0/EPCTypeValue....	G	250072.67	MJ/a	Rekenmethodiek Definitief Energielabel, versie 1.2, 16 september 2014	19179	[null]

	id [PK] bigint	type character varying	type_codespace character varying	owner_name character varying	ownership_type character varying	ownership_type_c character varying	num_of_building_units integer	is_protected numeric	constr_weight character varying	constr_weight_codespace character varying	attic_thm_status character varying
1	1	[null]	[null]	[null]	[null]	[null]	[null]	0	[null]	[null]	[null]
2	11	[null]	[null]	[null]	[null]	[null]	[null]	0	[null]	[null]	[null]
3	21	Twee-onder-één-kap	https://raw.githubuserco...	[null]	[null]	[null]	[null]	0	[null]	[null]	[null]
4	38	[null]	[null]	[null]	[null]	[null]	[null]	0	[null]	[null]	[null]
5	54	[null]	[null]	[null]	[null]	[null]	[null]	0	[null]	[null]	[null]
6	64	Twee-onder-een-kap / ri...	https://raw.githubuserco...	[null]	[null]	[null]	[null]	0	[null]	[null]	[null]
7	82	[null]	[null]	[null]	[null]	[null]	[null]	0	[null]	[null]	[null]
8	102	[null]	[null]	[null]	[null]	[null]	[null]	0	[null]	[null]	[null]
9	109	Vrijstaande woning	https://raw.githubuserco...	[null]	[null]	[null]	[null]	0	[null]	[null]	[null]
10	136	Twee-onder-een-kap / ri...	https://raw.githubuserco...	[null]	[null]	[null]	[null]	0	[null]	[null]	[null]
11	173	Vrijstaande woning	https://raw.githubuserco...	[null]	[null]	[null]	[null]	0	[null]	[null]	[null]
12	211	Vrijstaande woning	https://raw.githubuserco...	[null]	[null]	[null]	[null]	0	[null]	[null]	[null]
13	249	Vrijstaande woning	https://raw.githubuserco...	[null]	[null]	[null]	[null]	0	[null]	[null]	[null]
14	279	Twee-onder-één-kap	https://raw.githubuserco...	[null]	[null]	[null]	[null]	0	[null]	[null]	[null]
15	299	[null]	[null]	[null]	[null]	[null]	[null]	0	[null]	[null]	[null]
16	337	Twee-onder-één-kap	https://raw.githubuserco...	[null]	[null]	[null]	[null]	0	[null]	[null]	[null]
17	381	[null]	[null]	[null]	[null]	[null]	[null]	0	[null]	[null]	[null]
18	409	[null]	[null]	[null]	[null]	[null]	[null]	0	[null]	[null]	[null]
19	441	[null]	[null]	[null]	[null]	[null]	[null]	0	[null]	[null]	[null]
20	455	[null]	[null]	[null]	[null]	[null]	[null]	0	[null]	[null]	[null]
21	465	[null]	[null]	[null]	[null]	[null]	[null]	0	[null]	[null]	[null]
22	475	Rijwoning tussen	https://raw.githubuserco...	[null]	[null]	[null]	[null]	0	[null]	[null]	[null]
23	507	[null]	[null]	[null]	[null]	[null]	[null]	0	[null]	[null]	[null]
24	514	[null]	[null]	[null]	[null]	[null]	[null]	0	[null]	[null]	[null]

	id [PK] bigint	objectclass_id integer	type characte	type_cod character	cell_type characte	cell_typ characte	module_area numeric	module_area_uom character varying	azimuth numeric	azimuth_uom character varying	inclination numeric	inclination_uom character varying	aperture_area numeric	aperture_area_uom character varying	opt_efficiency numeric
1	22979	11761	[null]	[null]	[null]	[null]	13.787	m2	225.92	deg	48.07	deg	[null]	[null]	[null]
2	22980	11761	[null]	[null]	[null]	[null]	33.215	m2	225.55	deg	40.03	deg	[null]	[null]	[null]
3	22981	11761	[null]	[null]	[null]	[null]	8.774	m2	225.85	deg	49.99	deg	[null]	[null]	[null]
4	22982	11761	[null]	[null]	[null]	[null]	17.642	m2	180.87	deg	27.67	deg	[null]	[null]	[null]
5	22983	11761	[null]	[null]	[null]	[null]	10.735	m2	138.92	deg	26.74	deg	[null]	[null]	[null]
6	22984	11761	[null]	[null]	[null]	[null]	3.319	m2	223.34	deg	44.95	deg	[null]	[null]	[null]
7	22985	11761	[null]	[null]	[null]	[null]	3.071	m2	220.98	deg	32.03	deg	[null]	[null]	[null]
8	22986	11761	[null]	[null]	[null]	[null]	5.447	m2	220.98	deg	32.03	deg	[null]	[null]	[null]
9	22987	11761	[null]	[null]	[null]	[null]	4.13	m2	220.98	deg	32.03	deg	[null]	[null]	[null]
10	22988	11761	[null]	[null]	[null]	[null]	3.962	m2	72.06	deg	1.35	deg	[null]	[null]	[null]
11	22989	11761	[null]	[null]	[null]	[null]	4.155	m2	72.06	deg	1.35	deg	[null]	[null]	[null]
12	22990	11761	[null]	[null]	[null]	[null]	8.841	m2	223.98	deg	27.32	deg	[null]	[null]	[null]
13	22991	11761	[null]	[null]	[null]	[null]	9.537	m2	252.92	deg	1.34	deg	[null]	[null]	[null]
14	22992	11761	[null]	[null]	[null]	[null]	10.312	m2	252.92	deg	1.34	deg	[null]	[null]	[null]
15	22993	11761	[null]	[null]	[null]	[null]	10.567	m2	226.95	deg	50.37	deg	[null]	[null]	[null]
16	22994	11761	[null]	[null]	[null]	[null]	3.673	m2	31.41	deg	0.48	deg	[null]	[null]	[null]
17	22995	11761	[null]	[null]	[null]	[null]	4.69	m2	31.41	deg	0.48	deg	[null]	[null]	[null]
18	22996	11761	[null]	[null]	[null]	[null]	4.678	m2	31.41	deg	0.48	deg	[null]	[null]	[null]
19	22997	11761	[null]	[null]	[null]	[null]	5.658	m2	31.41	deg	0.46	deg	[null]	[null]	[null]
20	22998	11761	[null]	[null]	[null]	[null]	4.412	m2	31.41	deg	0.48	deg	[null]	[null]	[null]
21	22999	11761	[null]	[null]	[null]	[null]	5.689	m2	31.41	deg	0.48	deg	[null]	[null]	[null]
22	23000	11761	[null]	[null]	[null]	[null]	17.442	m2	180.67	deg	28.82	deg	[null]	[null]	[null]
23	23001	11761	[null]	[null]	[null]	[null]	18.224	m2	224.34	deg	32.06	deg	[null]	[null]	[null]
24	23002	11761	[null]	[null]	[null]	[null]	28.656	m2	226.66	deg	37.94	deg	[null]	[null]	[null]
25	23003	11761	[null]	[null]	[null]	[null]	24.958	m2	224.66	deg	34.89	deg	[null]	[null]	[null]

Figure 6.16: The author's data read from a populated 3DCityDB instance as relational tables, rather than from the GML file. Top: the energy certificates, with their label, calculation method, and unit of measure. Bottom left: the native Dutch building types (`Vrijstaande woning`, `Twee-onder-een-kap`). Bottom right: the rooftop solar collectors, with module area, azimuth, and inclination. Database ingestion via the FME Workbench freely available on the Energy ADE 3.0 (beta 8) GitHub repository; model by the author.

[8] github.com/tudelft3d/Energy_ADE

7. Discussion and Conclusion

7.1. Discussion

This discussion organises the findings around the main research question: to what extent does CityGML 2.0 + Energy ADE 3.0 (beta 8) constitute a meaningful starting point for a Building Renovation Passport data model, and what targeted extensions are required to close the gaps? The answer is read across two lines of evidence. The systematic comparison of Chapter 4 establishes how much of the MSRD the existing schema can carry. The two-pipeline implementation of Chapter 6 tests that the schema holds under real Dutch building-stock data at two scales.

The conceptual analysis of Chapter 4 answers the structural half of the question. Across the relevance-filtered MSRD, CityGML 2.0 + Energy ADE 3.0 (beta 8) provides a mapping target for 262 of the 276 fields, roughly 95% (Section 4.3). Coverage is complete for 8 of the 13 modules, including the whole assessment layer of energy performance, indoor environmental quality, and smart readiness. The schema-fit answer to the main research question is therefore yes, with targeted extensions. The large majority of the data a BRP needs already has a place in an open, formally specified data model, and the 14 remaining gaps are few and localised rather than spread across the model. Most of them concentrate in the renovation-advice module, the staged roadmap that is the instrument's defining feature, where a relatively high share of the module's fields have no mapping target rather than a single attribute being absent. The one gap that falls outside that cluster is the subsidies and funding programmes of Module 8, which the Energy ADE's still-minimal cost model cannot yet hold faithfully, an open modelling question rather than a missing attribute.

The implementation of Chapter 6 answers the empirical half. The schema covered the data at both scales. The per-building file validates against the bundled Energy ADE 3.0 (beta 8) schema set, and the four full city-scale runs carry the same mapping across the national open-data stock up to roughly 94,000 buildings without structural failure. Confirming that the schema holds is the direct answer to the third sub-question. The integrated output does more than confirm fit, though. Bringing the Dutch sources together in one model made the data quality of that stock visible, revealing four data-quality patterns and enabled two analyses (Section 6.4) that the source datasets, viewed apart, do not show. The audit-depth test of Section 6.2 shows where the result reaches its limits. Of the two situations it raised, one resolves into a modelling rule within the existing schema, and one stands as a finding where the data is present but the modelling decision is under-specified. The proposed responses are consolidated in Section 7.3.

The two lines converge on one answer, with one nuance drawn from the practitioner view. The convergence is that CityGML 2.0 + Energy ADE 3.0 (beta 8) is a strong, near-complete starting point; the schema side answers yes with targeted extensions, and the empirical side confirms that answer under real data. The remaining gaps are localised and not structural. The practitioner findings of the parallel MBE thesis enter as one of the three inputs to the discretionary relevance filter (Section 3.2.3), alongside frequency of inclusion across the surveyed initiatives and regulatory mandate in the EPBD recast. Their role is confirmation rather than validation. The interviews confirmed two choices the MSRD had already made, giving renovation history its own module and keeping most fields optional and multi-resolution. The validation burden stays with the depth and breadth tests of this thesis. What the practitioner view adds to the discussion is the nuance that practitioners weight some field families differently from the systematic comparison. Three-dimensional geometry at dwelling-advice scale, behavioural and occupancy data, and the granularity appropriate to each use case are all valued differently depending on whether the BRP is read as a building record or as an advisory tool. The data model accommodates this without having to choose between the readings, because its fields are optional by design and can be populated at the level a given use case needs. The city-scale pipeline leaves interior building physics empty while the per-building pipeline fills it, and the same schema carries both. That emptiness is a data limit rather than a schema limit, and one likely to recede. Tools that convert archived floor-plan PDFs into geodata are emerging[9], and enriching an LoD2 building stock with the window and door openings LoD3 carries is a substantial increase in the detail an energy assessment can draw on. The per-building test shows the data model is ready to receive both without a redesign. The divergence between the systematic and the practitioner view is therefore evidence that the optional design of the model is serving its purpose, not a tension the model has to resolve. The research gap of Section 1.2 is that existing BRP data models are closed or specified only as semi-structured Excel files and cannot be assessed for coverage. Against it, the contribution is to show that an open, formally specified data model already covers most of what a BRP needs, and to name precisely where it does not.

7.2. Conclusion

This section answers the research questions of Section 1.4 directly. The interpretive work has already happened in Section 7.1, so the answers here are stated plainly, the sub-questions first and then the main question, before the contributions of the thesis are listed.

7.2.1. Sub-questions

The first sub-question asks which data fields constitute the MSRD for Building Renovation Passports. The MSRD is the 276 fields, organised into 13 modules and 3 layers, that remain once the discretionary relevance filter is applied across the 14 surveyed European initiatives. It is built in Section 4.2 and consolidated in the cross-module summary of Section 4.3.

The second sub-question asks to what extent CityGML 2.0 + Energy ADE 3.0 (beta 8) covers the MSRD. It covers it to roughly 95%, 262 of 276 fields, with coverage complete for 8 of the 13 modules, including the entire assessment layer (Section 4.3). The renovation-advice module is the principal exception, at 73% coverage.

The third sub-question asks what testing the schema at per-building and city scales on real Dutch building-stock data reveals about its adequacy and gaps. The tests show the schema to be adequate to carry the data and to make the data's quality problems tractable, with the remaining gaps localised rather than structural. The schema held at both scales, producing XSD-valid output from a single audited dwelling up to roughly 94,000 buildings. Beyond covering the data, the integrated output revealed four data-quality patterns and enabled two analyses that the source datasets, in isolation, do not show (Section 6.4). The audit-depth test raised two further situations; one resolved into a modelling rule within the existing schema, and one finding showed where the model still handles a real situation only partially (Section 6.2).

7.2.2. Main research question

The main research question asks: to what extent does CityGML 2.0 + Energy ADE 3.0 (beta 8) constitute a meaningful starting point for a Building Renovation Passport data model, and what targeted extensions are required to close the gaps? The answer is that it is a meaningful

[9] For example pdf2gis by Coders Co.: https://codersco.com/pdf2gis/.

starting point, and a strong and near-complete one. The existing schema already provides a mapping target for 262 of the 276 relevance-filtered MSRD fields, roughly 95% (Section 4.3). The implementation tests confirm that the mapping holds on real Dutch building-stock data at both per-building and city scales (Chapter 5, Chapter 6). The 14 fields the existing schema does not cover are localised rather than spread across the model, most of them concentrated in the renovation-advice module that is the BRP's defining feature. The targeted extensions the question asks for are the proposed responses to those gaps, together with the proposal responding to the audit-depth metadata finding of Section 6.2, consolidated in Section 7.3. They are proposals to improve the data model, addressing gaps that the current one does not yet sufficiently cover.

7.2.3. Contributions

The thesis makes five contributions:

- the MSRD, a 276-field reference set organised into 13 modules and 3 layers, synthesised from 14 European initiatives whose own data models are mostly closed, specified only as semi-structured Excel files, or not documented at all;
- a systematic coverage mapping of that MSRD onto CityGML 2.0 + Energy ADE 3.0 (beta 8), with a per-field gap register that locates the 14 uncovered fields precisely;
- a two-scale implementation test method, pairing a per-building audit-depth test with a city-scale breadth test, released as an open-source pipeline (Appendix A) that produces XSD-valid GML from real Dutch open data and makes the quality of that data visible through integration;
- a consolidated set of targeted extension proposals (Section 7.3), offered as input to the Energy ADE development effort; and
- refinements to the Energy ADE 3.0 schema itself, informed by the mapping and audit work and taken up during its ongoing development as beta 7 evolved toward the frozen beta 8, distinct from the still-proposed extensions above.

Complementary contributions on the practitioner side, including its taxonomy of renovation stakeholders and its findings on which Dutch data sources are used and trusted in the field, come from the parallel MBE thesis (Section 1.7). They are drawn on here only as one input to the relevance filter.

7.3. Proposed extensions to CityGML 2.0 + Energy ADE 3.0 (beta 8)

This section consolidates the targeted extensions to CityGML 2.0 + Energy ADE 3.0 (beta 8) that the three research lines of this thesis show to be needed, both to cover the MSRD and to resolve the schema-level ambiguities the implementation tests uncovered. The consolidation draws on the module-level coverage gaps reported in Section 4.3 and on the findings the implementation tests of Chapter 6 brought to light, where the schema covered the data but left a modelling decision under-specified. The proposals here are recommendations on how to close those gaps; the gaps themselves are the research findings, established in Chapter 4 and Chapter 6.

The extensions are proposals, presented as input to the Energy ADE development effort, not finished artefacts. Each is described in prose rather than as a worked schema. The aim is to name the kind of class, attribute, or modelling rule that would close the gap, and to record the alternatives and the open questions, not to commit to a single resolved design. Where the right direction is not yet clear, the case is carried forward as an open question for future work in Section 7.5. The proposals are grouped by the shape of the change rather than by MSRD module, because the audit-depth proposals do not map onto the module order. The first four respond to coverage gaps, the next to the audit-depth metadata finding of Section 6.2, and the last to a codelist gap the city-scale output audit exposed.

7.3.1. A renovation-roadmap structure for the functional layer

The largest coverage gap is the renovation-advice module, where seven of the relevance-filtered fields have no mapping target (Section 4.3). These fields describe the staged renovation roadmap that is the BRP's defining feature, an ordered sequence of renovation steps, each with an indicative timing, a narrative description, and an expected effect on energy performance and cost.

The schema is not silent on renovation, and the starting point is what it already carries. Energy ADE 3.0 (beta 8) has an `nrg3:Intervention` feature that records a single renovation measure, with an action drawn from a codelist (for example `insulatedRoof`, `installedHeatPump`, or `changedWindows`), an intervention type, and start and end dates. The generic `status` hook lets that measure be marked `planned` or `suggested` rather than completed. An intervention attaches to a building or one of its parts, and a building can carry several. As Section 4.3 records, a single measure therefore maps cleanly onto the existing class. What the schema does not provide is the roadmap as a roadmap. The ordering of the measures into a sequence, the per-step descriptors of renovation depth, priority, and motivation, the scheduling attributes of estimated duration and best opportunity, and the expected per-step change in energy demand and cost all have no structured place. The gap is the sequenced, descriptive layer over the interventions, not the measures themselves.

Two directions can close it. The first is incremental and stays inside Energy ADE. It treats the roadmap as an ordered set of `nrg3:Intervention` features and adds the missing per-step attributes to, or alongside, that class, with a lightweight container feature that groups the ordered steps into one named passport. This keeps the roadmap queryable as structured data, reuses a construct that already exists, and is the smaller change. The second is to adopt the draft Scenario ADE, an extension developed alongside Energy ADE, with a contribution from a separate MSc thesis by Frederick Auer on testing and enhancing the Scenario ADE for building energy performance simulations in Rotterdam [83]. It backports the CityGML 3.0 versioning module and adds scenario and simulation modules. There a roadmap is a base `Version` for the current state, a `Scenario` that references it, and a `VersionTransition` per step that carries the inserts and edits the measure makes, such as swapping a construction or adding a heat pump. The outcome of each step is then available for simulation and comparison. This is the more powerful route for forward-looking, what-if renovation planning, but it pairs a second, still-draft ADE with an Energy ADE that is itself still in beta, stacking the tooling limitations of two pre-release schemas.

The recommendation is to build on the existing `nrg3:Intervention` construct for a first, queryable roadmap, and to reference the Scenario ADE work rather than define a competing renovation-scenario class. The richer scenario-and-simulation capability can then be taken up from that effort if and when it leaves beta. Which of the two routes to commit to is a genuine open design question, carried forward to Section 7.5. The open questions either route must settle include the granularity of a step (per-component or per-building), how a step links to the as-built feature it modifies, and whether the expected post-step state is modelled as a full scenario or as a set of deltas against the current state.

7.3.2. Envelope condition and airtightness attributes

Four fields in the envelope module have no direct mapping target (Section 4.3), the two damage-observation fields, an opening-level airtightness class, and a count of identical openings. Energy ADE 3.0 (beta 8) models the thermal performance of constructions and openings in detail, but it does not record the observed physical condition of a construction. It also does not carry an airtightness class at the level of an individual opening.

One possible direction is to add a small set of condition attributes to the construction and thematic-surface classes, with damage recorded through a codelist-typed attribute rather than free text, and to add an airtightness-class attribute on the opening. Recording condition only as free text was set aside because it cannot be queried across a stock. The count of identical openings is treated differently. It is better read as a proxy than modelled as a new attribute, because the total surface area and opaque area the schema already carries convey the same information for an energy assessment. A bare count says little without the size and U-value of the opening. No multiplicity attribute is therefore proposed for it. The open questions that remain are the choice of codelist for damage types, and how an opening-level airtightness class relates to the whole-zone infiltration the schema already models.

7.3.3. A controls and automation attribute on technical systems

One field in the technical-systems module has no mapping target (Section 4.3), the control and automation class of a system. Energy ADE 3.0 (beta 8) models the systems themselves, including heat generation, distribution, and storage, but not the level of control or automation under which they can run. One possible direction is a codelist-typed attribute on the relevant system classes capturing that control class. Storing it as a generic attribute was considered and set aside because it would lose the semantics that make the field useful. The open question is how this attribute aligns with the smart-readiness indicators already covered in the smart-readiness module, which describe a related but building-level property.

7.3.4. A free-text auditor-recommendation attribute

One field in the operation module has no mapping target (Section 4.3), the auditor's narrative recommendation. Energy ADE 3.0 (beta 8) covers operation and use, but it has no dedicated place for the free-text advice an auditor attaches to a building or unit. One possible direction is a free-text recommendation attribute on the building unit; the alternative is to attach the advice through the existing document-reference mechanism, which is workable but removes the advice from inline access. A third option follows from Section 7.3.1. If the roadmap is modelled through the `nrg3:Intervention` construct or the Scenario ADE, the auditor's narrative belongs naturally on the renovation step it concerns, carried in that step's own description rather than as a separate building-level attribute. The open question is the overlap with those per-step narratives, which a single design should reconcile rather than duplicate.

7.3.5. Native multi-value storage and per-value provenance

The audit-depth metadata finding (Section 6.2) is better read as a refinement than as a problem, because the schema already handles the common case. Where two sources disagree on the same quantity, as the owner-occupier usable floor area does between the BAG figure of 122.0 m^2 and the measured 3D-model figure of 104.2 m^2, the repeating `nrg3:QualifiedArea` pattern carries both values side by side, each tagged with its own `nrg3:source`. The multi-source case is therefore covered natively, and both values resolve to the same building unit.

Two smaller limitations remain around this pattern. First, the provenance a `nrg3:QualifiedArea` carries is a free-text `source` string. Richer structured provenance lives in `nrg3:Metadata`, which extends `gml:MetaDataPropertyType` and carries no `gml:id`, so it cannot be the target of an `xlink` from an individual value. Adding a `gml:id` to `nrg3:Metadata` would let a per-value provenance record be referenced from the value it describes, a small change with a wide effect. Second, the multiplicity the schema offers is meant for different types of one quantity, a gross floor area next to a net floor area next to an energy reference area, not for keeping several copies of the same type indefinitely. Same-type disagreement, such as the BAG-against-model usable area above, is an integration-phase state: carrying both values makes the disagreement visible and auditable, but a passport ultimately keeps one canonical value per type and resolves the rest. Read this way, the year-of-construction case from the city-scale pipeline, where a second sourced value had to fall back on a generic attribute, asks for a place to hold a competing value during reconciliation rather than for permanently raised multiplicities. Both limitations connect to the multi-value-with-metadata design question of Section 7.5, which asks whether a field with several competing sources should carry all values with provenance or one canonical value that points to the others.

7.3.6. Codelist extensions

Because `gml:CodeType` is an open vocabulary, an off-codelist value is not XSD-invalid, but it is a clean signal that the catalogue is missing a value the implementation needs. The output audit found one such case while encoding Dutch building-stock data. `HeightTypeValue.xml` enumerates only absolute-elevation reference points, such as `topOfConstruction` and `highestRoofEdge`, and has no member for a height measured above ground level, so the Dutch convention of a roof height relative to the terrain, which the city-scale pipeline records, has no fitting entry. A `maxHeightAboveGround` member would provide one. A second candidate, an `EnergyEndUseValue.xml` entry for electricity fed back to the grid, was considered and dropped. The flow direction is already carried by the resource model itself. Every `nrg3:Energy` resource declares through its mandatory `operationType` whether the energy is produced or consumed, so a feed-in end-use entry would duplicate that distinction. What the resource model does not yet distinguish is the finer split between production that is sold and production that is self-consumed, which is carried forward as an open question rather than as a codelist fix.

The recommendation is to extend the official Energy ADE codelists themselves. If the schema cannot represent a height-above-ground measurement with an official catalogue value, every national pipeline targeting the schema will invent its own term, and the normalising role of the codelist erodes. The height case is the one this thesis happened to hit, not a complete list, and the wider recommendation is a systematic review of the codelists against the values a Dutch implementation actually uses, extending them where a common national value has no member. This matters most if the data model is to be adopted as the official basis for Dutch building renovation passports and logbooks, and used by the software vendors that build on it, such as Vitec Vabi. Every such consumer that meets a missing value will otherwise invent its own. A non-blocking fallback that does not wait for review is to publish a TU Delft extension codelist at the existing catalogue URLs, listing both the official entries and the additions, so that a consumer who dereferences the `@codeSpace` reads a self-documenting union.

7.4. Broader implications and recommendations

Beyond the per-extension proposals of Section 7.3, the findings carry implications for two audiences, EU and Dutch policy and the Energy ADE development effort, and they deliver concrete inputs to the RenoDAT consortium that this work is part of.

For policy, the proposed extensions mark where the regulatory definition of a BRP goes beyond what the existing open data model covers. The renovation-roadmap gap of Section 7.3.1 is exactly the part the EPBD recast emphasises in its Article 12 and Annex VIII description of a renovation passport [4]. The proposals therefore serve as recommendations for closing that gap, addressed to the policy side as much as to the standardisation side. On the Dutch side, the launch instrument is the *gebouwrenovatiepaspoort*, the existing *maatwerkadvies* carrying the renovation-passport designation, which becomes available on May 29, 2026. The MSRD provides one candidate field set against which that instrument can be benchmarked once it exists, though the benchmark cannot be run within this thesis (Section 7.6.2). At the data layer, the city-scale pipeline of Section 5.3 already exercises the Dutch open data the *Landelijke Voorziening Gebouwgegevens* (LVG, the national building-data facility under development) is shaping, drawing on BAG, 3DBAG, EP-Online, BGT, and CBS Postcode-6 aggregates. The data-quality patterns reported in Section 6.4, the BAG and EP-Online disagreement on construction year, the placeholder and round-number artefacts in EP-Online, are concrete inputs to LVG scoping. They name where a national facility joining these sources will have to reconcile them.

For the Energy ADE development effort, a recommendation that accompanies the per-extension proposals concerns the port of the Energy ADE conceptual model to CityGML 3.0. The groundwork exists. In Bachert et al. [65], the Energy ADE 1.0 conceptual model was mapped to CityGML 3.0 in a model-driven exercise and validated through a working XSD. The lessons of that work fed the design of Energy ADE 3.0, which itself still extends CityGML 2.0. None of the proposals above requires the port, because the audit-depth cases resolve within the current pairing and the CityGML-3.0-style `identifier` is already backported as `nrg3:identifier`. The port therefore remains beneficial rather than required, and future BRP work could then use CityGML 3.0 features directly rather than through backports. As throughout Section 7.3, these are proposals rather than finished artefacts, and review by the development effort is invited.

This work was carried out within the RenoDAT consortium, a TU Delft-led, NWO-funded research effort on the data infrastructure for Dutch renovation, running from 2025 to 2029 and introduced in Chapter 1. It delivers three things the consortium can build on. The two open-source pipelines (Appendix A) are a starting point for wider data-integration work. The data-quality findings of Section 6.4 name specific reconciliation targets the consortium's infrastructure work can address. And the MSRD itself (Section 4.3) is a candidate field set the consortium can test, contest, and extend.

7.5. Future work

The gaps and open questions raised across the thesis point to concrete next steps. They fall into two groups. The first is extensions of the implementation tests, which continue the depth- and breadth-testing directly. The second is open design questions for the standardisation effort, which the extension proposals of Section 7.3 leave deliberately unresolved.

7.5.1. Extending the implementation tests

The city-scale pipeline of Section 5.3 runs on three full municipalities and the Emmer-Compascuum settlement, and generalises to whole-Netherlands coverage. Scaling it to the full national stock is the most direct continuation, and the data-quality patterns of Section 6.4 would gain statistical weight at that scale. Such a run could build on, and extend, the Energy BAG of León-Sánchez [85][10], which pursues an energy-enriched BAG at national scale. A second direction is to test the data model against the open data of other EU member states. The implementation

[10] https://3d.bk.tudelft.nl/projects/EnergyBAG/.

tests here exercise Dutch building-stock data only, and the Dutch test is one credible case rather than a complete one. Member states such as Flanders, Germany, France, and Italy have different open-data layers and different national BRP and DBL framings. Testing against them would either strengthen the EU-broad claim or expose member-state-specific gaps the Dutch test did not show. More tests, and better ones, would strengthen the claim about the adequacy of the data model. These continuations also have a home beyond RenoDAT, since the FlexPED project[11], which builds on DigiTwins4PEDs, is a second effort positioned to take them up.

Within the Dutch case, the largest unbuilt piece is full per-*verblijfsobject* renovation-history modelling. The renovation history has its own module in the MSRD but is not populated by either pipeline, and the parallel MBE thesis reports it as the single most consistently named missing element of a future Dutch BRP. This makes it the highest-value next target. The per-building test modelled the building only as it stands today, because that was the data available. The historical dimension was meant to be tested against a richer dataset from The Green Village, the TU Delft living lab. That dataset carries the history a renovation passport needs, including changes in occupancy, renovation works, system replacements, and temperature measurements over time. That data could not be transferred within the thesis period because of legal and administrative delays, but it is still expected to reach the RenoDAT project. Running the per-building pipeline against it, to populate and test the renovation-history modelling end to end, is the most valuable single continuation of the depth test.

A further direction follows the toolchain. A production CityGML 3.0 path opens once the Energy ADE port to CityGML 3.0 lands. The present GML output already ingests into a version-4 3DCityDB with essentially no custom tooling, using the openly available toolkit. What remains future work is therefore the version-5, CityGML 3.0, Energy ADE 3.0 combination, not the act of database ingestion itself.

7.5.2. Open design questions and standardisation

Several extension proposals are left as open design questions rather than resolved designs, and settling them is future work in its own right. The multi-value-with-metadata question is the broader form of the provenance proposal of Section 7.3.5. For a field such as year of construction that has several competing sources, BAG and EP-Online among them, the schema could carry every value with its own provenance, or one canonical value whose provenance points to the others. The two designs serve different consumers. Resolving these, and the other open questions attached to the renovation-roadmap and codelist proposals, would benefit from a feedback loop with the ongoing development of the Energy ADE, which could land the agreed extensions as official Energy ADE 3.x items.

Finally, the MSRD itself awaits validation against the Dutch launch instrument. The *gebouwrenovatiepaspoort* went live on May 29, 2026, just before submission of this thesis, too late to be included (Section 7.6.2). Benchmarking the MSRD against the field set the Dutch instrument actually mandates is the validation this thesis could not perform.

7.6. Limitations

This section lists what the thesis does and does not establish. The limitations are organised into three subsections by where they originate. The first lies in the method, the second in the validation of the MSRD, and the third in the schema, tooling, and data scope of the implementation.

[11] https://flexped.eu/.

7.6.1. Methodological limitations

The 14 reviewed initiatives are not exhaustive of European developments in this area. The selection was driven by what is openly available. Initiatives whose documentation could be found online and that published a concrete data model or field-level proposal were included, while instruments with closed or non-public documentation, including some operational national tools and private-sector products, are not represented. The MSRD is therefore the field set that this comparison yields, not the field set that an exhaustive census would.

Many of the reviewed initiatives publish no formal data-model specification, so their field structures had to be reconstructed from Excel templates, user interfaces, and prose deliverables, and in one case from less conventional material still. ALDREN presented its full data model only in a YouTube video rather than in a written specification. This reconstruction can misread semantic intent, and it can miss fields that are implicit in an instrument but not visible in its published artefacts. The coverage figure of Section 4.3 is exact against the reconstructed MSRD, but the reconstruction itself carries this uncertainty.

The targeted extensions of Section 7.3 are proposals to improve the data model, not yet adopted parts of it. Whether any of them is taken up depends on review by the Energy ADE development effort, which lies outside the scope of this thesis. They are tested only as proposals, against the gaps that motivate them, not as implemented schema against real data.

7.6.2. MSRD validation limitations

The MSRD is proposed and tested at two scales in Chapter 6, but it is not benchmarked against the Dutch BRP launch instrument. The *gebouwrenovatiepaspoort* went live on May 29, 2026, just before submission, too late to be included. Its scope should be kept in proportion, though. As launched, it is the existing *maatwerkadvies* carrying the renovation-passport designation, a short advisory document of a building's current state and a recommended set of steps rather than a full data model. The *maatwerkadvies* as delivered through tools such as the Vitec Vabi EPA software is already among the initiatives compared in Chapter 4. The un-benchmarked part is therefore the specific field set the launched instrument mandates, not a wholly unseen model. Reflection on the Dutch BRP still has to be EU-level, against the EPBD recast and against Belgian, French, and German precedents, rather than against a live Dutch instrument. The benchmarking this prevents is named as future work in Section 7.5.

The parallel MBE thesis offers a different kind of evidence, but it is a practitioner-side confirmation rather than a validation. It used the MSRD-based data model as an interview prompt with 17 respondents across 9 stakeholder categories, and it is explicit that it does not endorse or test the MSRD itself. A Dutch launch instrument would provide a regulatory-side benchmark. Neither the practitioner confirmation nor a future regulatory benchmark is conclusive on its own, and the thesis carries its own validation through the depth- and breadth-tests, not through the interviews.

7.6.3. Schema, tooling, and data-scope limitations

Energy ADE 3.0 is at its beta-8 release. The mapping decisions are held against that version, which is stable for the thesis but is not the long-term version, and they may need revision if a later beta or the 3.0 final release changes the schema. A CityGML 3.0 pairing of Energy ADE does not yet exist as production-ready tooling, since beta 8 extends CityGML 2.0, and it is carried as a future-work path in Section 7.5.

In the city-scale pipeline (Section 5.3), the vegetation integration (combining CFTree records with a BGT cross-reference and Emmen municipal species data) and the CBS Postcode-6 dwelling-energy aggregates are demonstrator integrations rather than full integrations against the authoritative national data layers. They show that the schema has a place for these themes, not that the integration is production-grade.

The implementation tests were run on Dutch building-stock data only, at per-building scale (one owner-occupier dwelling in Delft) and at city scale (Emmer-Compascuum, with Delft, Groningen, and Zwolle as comparators). The data-model evaluation is EU-broad, but other EU contexts have not been tested empirically, which is why the EU-broad claim is stated as one credible case rather than a settled result.

7.7. Reflection

I ran this thesis in parallel with an MBE thesis (Section 1.7) that approached the same problem, the building data a Dutch BRP needs, from the practitioner side rather than the data-modelling side. When I started, I expected the two to feed each other in a loop, with practitioner findings reshaping the data model and the data model sharpening the next round of interviews. In practice the relationship turned out to be sequential, and the cleaner direction ran from this thesis into the MBE thesis rather than back. The MSRD-based data model became the concrete artefact that the interviews reacted to, which gave those interviews something specific to respond to. The reverse direction worked as confirmation rather than redesign. The practitioner finding that renovation history is the most consistently named missing element confirmed a choice the MSRD had already made, to give renovation history its own module. The practitioner emphasis on different data at different levels of detail confirmed a strength the data model already has, that most fields are optional and available at more than one resolution.

What the practitioner lens did change was my sense of which fields are relevant in practice, and that is exactly where it belonged, as one input to the relevance filter (Section 3.2.3). The clearest case is EP-Online. The MBE interviews show it as a source used often in the field but trusted almost nowhere, leaned on because no better metric exists rather than because it is believed. The interviews also showed me where practitioners weight the data differently from the systematic comparison. Three-dimensional geometry that looks essential from a modelling standpoint was seen as more than dwelling-level advice needs and valuable mainly at block level, behavioural and occupancy data divided opinion sharply, and the absence of any sense of what is actually buildable on site, the data-determinism critique one government respondent raised, is a gap no field list closes on its own. None of these undermine the data model, because its optional fields let a use case populate only what it needs.

On the research approach itself, the part that worked was running the question at two layers. The schema-fit question is answered structurally in Chapter 4 and empirically in Chapter 6. Having both meant a gap found in the comparison could be checked against a real building, and a problem found on a real building could be traced back to a structural cause. The single most useful result came from integration rather than from either layer alone. Bringing the Dutch sources together in one model made the data quality of the building stock visible, the construction-year disagreements and the placeholder and round-number artefacts of Section 6.4, in a way that reading each source on its own does not. I did not set out to study data quality, and it became one of the more interesting findings. Preliminary work on the Energy BAG, an energy-enriched national version of the BAG, reports similar quality issues, among them erroneous floor areas [85].

What I would do differently is push harder, and earlier, to secure historical building data. The per-building test could only model the dwelling as it stands today, because that was the data

I had. The dimension I most wanted and could not reach was change over time, the renovation history and the shifts in occupancy, systems, and measured conditions that a richer dataset from The Green Village would have carried. That data did not arrive within the thesis period because of legal and administrative delays. It was a real loss for the depth test, because populating and testing the renovation-history modelling on a building that actually has a history would have been one of the most valuable things I could have done. I was also struck, more than I expected, by how far the Dutch sources disagree on basic figures. The divergence between BAG and EP-Online on something as plain as construction year, and the placeholder and round-number artefacts in EP-Online, surprised me rather than frustrated me. I cannot fully explain why authoritative registers differ so much. I have kept the reporting of these constructive, because the point is that an integrated model makes them tractable rather than that the sources are bad.

Stepping back, the thesis spans the full arc of a Geomatics project. It synthesises a conceptual field set from heterogeneous and mostly undocumented sources, maps it onto an open international data model, builds pipelines that ingest the national open-data layer at two scales, and analyses the resulting integrated model for the data quality it carries. That span, from conceptual synthesis through implementation to spatial-data analysis, is what I take the programme to be about, and it is the part of the work I am most satisfied with. The stakes outside the discipline are not abstract. The building stock drives a large share of EU energy use and emissions, and the renovation rate has to rise sharply to meet the 2050 goals [6]. Yet a renovation passport is useful only if the data it depends on accumulates, stays current, accurate, and reliable, and is reachable through one route. Decisions taken now about that data infrastructure, the Dutch *gebouwrenovatiepaspoort* launched in May 2026 and the *Landelijke Voorziening Gebouwgegevens* taking shape behind it, will shape what is possible for years. Showing that an open, formally specified data model already covers most of what a BRP needs, and naming precisely where it does not, is a small but concrete contribution to getting those decisions right.

A Reproducibility self-assessment

This appendix assesses the reproducibility of the work against the criteria of Nüst et al. [86], which score input data, methods, and results each on a four-level scale from 0 (unavailable) to 3 (available, open, and permanent).

A.1 Reproducibility scorecard

Axis	Level (0-3)	Basis
Input data	2	All input data is shared open with a DOI except, for the city-pipeline, the EP-Online part, since this comes from a register with a license that prevents redistribution of individual-level records in large quantities.
Methods: preprocessing	3	The input fetchers and parsers are public under MIT, and the initiative-comparison workbook is shared under CC-BY-4.0.
Methods: analysis and processing	3	The toolkit is public under MIT, with pinned dependencies (`uv.lock`, Python 3.12), end-to-end tests, local lint and type checks, and a citable archived release.
Methods: computational environment	3	The environment is pinned (`uv.lock`, Python 3.12) and packaged as a digest-pinned container image that continuous integration runs offline to regenerate and validate the per-building document before publishing; the `Dockerfile` is archived with the code release, so the full environment is reconstructable on any host.
Results	3	The produced GML documents and the figures are shared open with a DOI.

Table 43: Reproducibility self-assessment against the criteria of Nüst et al. [86]. Own work.

A.2 Data availability

The used inputs and the produced outputs are deposited together in one 4TU.ResearchData dataset under CC-BY-4.0 (`doi.org/10.4121/89f8909b-4473-4958-8f93-46b55546764d`), giving each a permanent DOI. The dataset bundles the worked-area city-scale document and its curated inputs, the per-building document with its input JSON and STEP geometry, the master initiative-comparison workbook covering all 14 initiatives across 13 modules, and the data-derived figures. The three comparator municipalities (Delft, Groningen, Zwolle) are not bundled as data; their build configurations are public in the code repository, and a replicator regenerates them with an own EP-Online key.

EP-Online is the one input that cannot be redistributed. The register carries no open licence, and its terms forbid supplying individual-level records in large quantities as part of the original data file; the per-dwelling energy figures are also personal data, since each attaches to an address. The public deposit therefore omits EP-Online.

The per-building model is the author's own work, built for one real owner-occupier dwelling whose owner gave permission to use and publish the data in anonymised form, with the direct identifiers and the exact address replaced by placeholders. The anonymised input JSON, the STEP geometry, and the produced GML are deposited, so the audit-depth case can be reproduced. The repository additionally carries a geometry-free `NL-single-family-house_sample.json` as a structural reference. Table 44 lists all sources:

Source	Endpoint	Version / accessed	Licence
BAG	`service.pdok.nl/lv/bag/wfs/v2_0` `bag:pand` / `bag:verblijfsobject`	accessed 2026-06-02	Public domain (CC0)
3DBAG [75]	`data.3dbag.nl/latest/`	v2025.09.03 via the moving `/latest/` alias, accessed 2026-06-02	CC-BY-4.0
EP-Online	`public.ep-online.nl/api/v5/Mutatiebestand/DownloadInfo`	API v5, accessed 2026-06-02	No open licence (RVO, restricted)
BGT	`api.pdok.nl/lv/bgt/ogc/v1`	accessed 2026-06-02	Public domain (CC0)
CBS Postcode-6	`service.pdok.nl/cbs/postcode6/2023/wfs/v1_0`	year 2023, accessed 2026-06-02	CC-BY-4.0 (attribution)
Municipality boundary	`service.pdok.nl/kadaster/bestuurlijkegebieden/wfs/v1_0`	accessed 2026-06-02	CC-BY-4.0 (attribution)
Solar-panel polygons [79]	`doi.org/10.5281/zenodo.14860030`	published 2025	CC-BY-4.0
Trees: CFTree [80] reconstruction of AHN6 LiDAR, enriched with Emmen BOR	`basisdata.nl/hwh-ahn/AHN6/01_LAZ/` (AHN6) `github.com/NoahAlting/CFTree` `github.com/DaanSchlosser/CFTree` `services3.arcgis.com/YaBq8GMTp0Kh437n` (Emmen BOR)	accessed 2026-06-02	AHN6 LiDAR: CC-BY-4.0 (attribution); CFTree: GPL-3.0 (algorithm); Emmen BOR: free use + attribution
Per-building case	JSON + Rhino STEP geometry	authored from one real audited dwelling	CC-BY-4.0

Table 44: City-scale and per-building data sources: endpoint, version, and licence. Own work.

A.3 Code availability

The implementation is released as one public repository under the MIT licence [87], with an archived release on Zenodo for a citable, permanent DOI. This toolkit `citygml2.0-energyade3.0-beta8-creator` (repository `CityGML2.0-EnergyADE3.0_creator`) holds both the per-building and city-scale pipelines and emits CityGML 2.0 + Energy ADE 3.0 (beta 8) GML files. A pinned container image, with its base image pinned by digest and the Python environment resolved from `uv.lock`, is published to the GitHub Container Registry, and its `Dockerfile` is archived with the Zenodo code release, so the exact computational environment can be reconstructed without a local toolchain. The published image is verified on every release: continuous integration runs it with networking disabled to regenerate and validate the per-building document before the image is pushed, so a release cannot ship an environment that fails to reproduce.

A.4 Results availability

The produced GML documents and the data-derived figures are deposited in the same 4TU.ResearchData dataset, so each carries a permanent DOI alongside the inputs that generated it. The deposited city-scale document has its EP-Online energy values omitted, as described under data availability; every other attribute is retained.

A.5 Documentation

The repository contains a `README` with a quick-start, the configuration reference, an output description, and design notes. It additionally contains a `CONTEXT.md`, the in-repo glossary that fixes the domain vocabulary used across the code, the mapping docs, and this thesis. It also contains a `docs/` set covering the per-building and city-scale source-to-schema mappings (`docs/mapping_building.md`, `docs/mapping_city.md`) and the architecture decision records (ADRs).

B Per-module initiative-inclusion tables

Module 2: General building characteristics

Feature	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	Total	%
Year of building construction	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	14	100%
Date of demolition							✓								1	7%
Number of floors	✓	✓	✓	✓		✓	✓	✓	✓	✓		✓	✓	✓	12	86%
Year of last (major) renovation, and description	✓	✓	✓	✓			✓		✓	✓			✓		8	57%
Building use/function	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓			✓	11	79%
Building type (MFH, SFH, office, etc.)	✓	✓	✓	✓	✓		✓		✓	✓	✓	✓	✓	✓	12	86%
Building name (or project name)	✓	✓	✓	✓	✓		✓		✓	✓		✓	✓		10	71%
Number of dwelling units			✓	✓			✓		✓	✓	✓		✓		7	50%
Number of total units (or as linked to)			✓	✓	✓		✓								4	29%
Type of roof (flat, gabled, hipped)	✓						✓	✓		✓		✓		✓	6	43%
Number of (specific type/ total) rooms		✓		✓			✓			✓					4	29%
Main orientation the building faces				✓		✓			✓	✓					4	29%
Details on barrier-free design (e.g. ramps)	✓		✓			✓									3	21%
Existence of elevators	✓		✓				✓								3	21%
Building state (new, in-design, existing, etc.)	✓				✓		✓			✓	✓				5	36%
The floor of the unit			✓	✓						✓					3	21%
Overall building conservation status (bad, good, etc.)				✓			✓						✓		3	21%
Number of (disabled) car parking spaces	✓			✓											2	14%
Whether the building has any sort of historical status	✓							✓		✓	✓	✓		✓	6	43%
Is the topmost floor heated?	✓									✓			✓	✓	4	29%
Whether the basement floor(s) is/are heated	✓									✓			✓		3	21%
Expected building lifetime						✓		✓							2	14%
If there are thermally (un)conditioned sport facilities		✓								✓					2	14%
Number of swimming pools, elevators, balconies							✓								1	7%

Table 45: Overview of the features of module 2: General building characteristics. Initiative IDs (I1-I14) are defined in Table 3. Own work.

Module 3 (part 1): Envelope, construction & materials

Feature	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	Total	%
High-level envelope & construction																
The high-level type of construction	✓	✓					✓			✓					4	29%
The high-level facade type (glass, steel, etc.)	✓						✓	✓		✓		✓			5	36%
The main structure of the building		✓				✓	✓	✓		✓					5	36%
Identified damages (cracks, degradation, etc.)								✓					✓		2	14%
Identified post-catastrophic damages								✓							1	7%
Details on thermal bridges	✓		✓			✓			✓	✓			✓		6	43%
Internal heat capacity per m²	✓				✓				✓	✓					4	29%
Infiltration rate (1/h)	✓					✓			✓	✓			✓		5	36%
Openings (Windows, Skylights, Doors)																
Only description of the necessity of describing openings				✓											1	7%
Indication what kind of opening it is	✓	✓	✓					✓	✓	✓		✓	✓		8	57%
Total area of the opening (m²)	✓	✓	✓			✓			✓	✓			✓		7	50%
g-value of the opening	✓	✓				✓			✓	✓			✓		6	43%
Type of the window glazing (single, double, triple, etc.)	✓		✓			✓		✓	✓	✓		✓	✓	✓	9	64%
The type of sun shading (e.g. no shading, external, etc.)	✓	✓	✓			✓				✓					5	36%
Frame to glass proportion/ percentage indication	✓		✓			✓			✓	✓					5	36%
The materials of the opening, like frame, glazing, etc.	✓		✓						✓	✓		✓			5	36%
Frame U-value (W/m²K)	✓		✓			✓			✓	✓					5	36%
Glazing U-value (W/m²K)			✓			✓			✓	✓					4	29%
Total U-value of the opening (W/m²K)	✓	✓	✓		✓	✓	✓	✓	✓	✓			✓		10	71%
Orientation of the opening			✓			✓			✓	✓					4	29%
Light Transmission (LT) factor	✓								✓						2	14%
Producer/ Brand	✓									✓					2	14%
Model number	✓									✓					2	14%
Airtightness class		✓											✓		2	14%
Total height & total width			✓						✓	✓					3	21%
Digital Product Passport			✓												1	7%
Specific mention of images/photographs of the opening									✓						1	7%
Quantity of identical openings									✓						1	7%
Source used (e.g. by inspection or by specifications)										✓					1	7%
Description of the state of the opening (e.g. leaky)												✓	✓		2	14%

Table 46: Overview of the features of module 3 (part 1): Envelope, construction & materials. Initiative IDs (I1-I14) are defined in Table 3. Own work.

Module 3 (part 2): Envelope, construction & materials

Feature	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	Total	%
Walls, Floor, Roof																
Wall orientation	✓		✓			✓			✓	✓			✓		6	43%
Wall U-value (W/m²K)	✓	✓	✓		✓	✓	✓	✓	✓	✓			✓		10	71%
Floor U-value (W/m²K)	✓	✓	✓		✓	✓	✓	✓	✓	✓			✓		10	71%
Roof U-value (W/m²K)	✓	✓	✓		✓	✓	✓	✓	✓	✓			✓		10	71%
Surface area(s) per type (m²)	✓		✓			✓			✓	✓			✓		6	43%
Ordered layers (materials, thickness, etc.)	✓		✓			✓			✓	✓					5	36%
Installation/renovation date	✓	✓	✓	✓					✓	✓			✓		7	50%
Layer details																
Material of the layer	✓		✓			✓		✓	✓						5	36%
Layer thickness	✓	✓	✓			✓			✓	✓				✓	7	50%
Layer thermal capacity	✓								✓						2	14%
Material weight (mass of each building element)	✓		✓			✓		✓							4	29%
Layer volume per material	✓		✓			✓		✓							4	29%
Global Warming Potential (GWP) - embodied carbon	✓					✓		✓							3	21%
Total Renewable Primary Energy (PERT)	✓														1	7%
Total non-Renewable Primary Energy (PENRT)	✓														1	7%
Embodied energy coefficient	✓														1	8%
Material library																
No details on materials		✓		✓	✓					✓	✓		✓		6	43%
Material type (& subtype)	✓		✓			✓	✓	✓	✓			✓			7	50%
Life span expectancy of building material	✓		✓			✓		✓							4	29%
Certificates, like a Environmental Product Declaration	✓		✓			✓		✓							4	29%
Material thermal conductivity	✓					✓			✓						3	21%
Fire resistance class	✓					✓		✓							3	21%
Waste category	✓					✓		✓							3	21%
Chemical declaration	✓					✓		✓							3	21%
Global Trade Item Number (GTIN)	✓					✓		✓							3	21%
Material density	✓														1	7%
Material vapour permeability	✓														1	7%
Reuse capacity description			✓												1	7%
Recycling capacity description			✓												1	7%
Heat capacity															0	0%

Table 47: Overview of the features of module 3 (part 2): Envelope, construction & materials. Initiative IDs (I1-I14) are defined in Table 3. Own work.

Module 4: Technical systems

Feature	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	Total	%
System inventory (Heating / DHW / Cooling / Ventilation / Lighting / Shading / BMS)																
Presence indicatable per system?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	14	100%
System category	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	14	100%
How grouped the system is (e.g. (de)centralised)	✓					✓			✓	✓	✓	✓			6	43%
Served area / served units		✓	✓			✓			✓	✓			✓		6	43%
System description field (e.g. its type)		✓	✓			✓		✓	✓	✓	✓	✓	✓	✓	10	71%
System description																
Energy carrier / source	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	14	100%
Technology / system type	✓	✓				✓	✓	✓	✓	✓	✓	✓	✓	✓	11	79%
Distribution type / medium		✓				✓				✓	✓	✓		✓	6	43%
Performance parameters																
Efficiency metric (e.g. heat recovery COP)	✓	✓	✓			✓			✓	✓			✓		7	50%
Rated capacity (e.g. in kW)	✓	✓				✓			✓	✓			✓	✓	7	58%
Recorded efficiency value	✓	✓	✓			✓				✓			✓		6	50%
Control / automation class (manual, fully integrated, etc.)	✓	✓				✓				✓					4	33%
Renewable contribution indicator	✓	✓		✓	✓	✓		✓	✓	✓		✓	✓	✓	11	92%
Emissions factor / CO_2 intensity available		✓			✓	✓			✓	✓			✓		6	50%
Asset identity & lifecycle																
Manufacturer / producer	✓	✓				✓				✓					4	33%
Model name/number	✓					✓				✓					3	25%
Installation year	✓	✓	✓	✓		✓			✓	✓			✓	✓	9	75%
Unique asset ID / serial number						✓									1	8%
Expected lifespan / end-of-life year	✓		✓			✓									3	25%
Condition / state rating	✓								✓			✓			3	25%
Maintenance record present	✓		✓			✓		✓				✓			5	42%
Last maintenance / inspection date			✓			✓						✓			3	25%
Metering, monitoring & evidence																
System-level sub-metering available	✓					✓		✓							3	25%
Annual energy use per system recorded	✓	✓	✓			✓			✓				✓		6	50%
Operational data available	✓					✓		✓		✓		✓	✓		6	50%
BMS/IoT integration link	✓					✓		✓							3	25%
Documents attached for the system	✓					✓			✓			✓			4	33%
Evidence/source type					✓	✓			✓	✓			✓		5	42%
Data collection date						✓			✓		✓				3	25%
Recommended upgrade measure per system									✓	✓		✓	✓	✓	5	42%

Table 48: Overview of the features of module 4: Technical systems. Initiative IDs (I1-I14) are defined in Table 3. Own work.

Module 5: Attachable documents (file repository)

Feature	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	Total	%
Proprietary and/or open BIM/GEO formats	✓	✓	✓	✓		✓	✓	✓	✓						8	57%
Regular documents (like PDFs)	✓	✓	✓	✓	✓	✓		✓	✓			✓		✓	10	71%
Metadata fields (e.g. issue date, issuer, document type)	✓	✓		✓	✓	✓	✓	✓						✓	8	57%
Image files	✓	✓		✓					✓			✓		✓	6	43%

Table 49: Overview of the features of module 5: Attachable documents (file repository). Initiative IDs (I1-I14) are defined in Table 3. Own work.

Module 6: Dimensions

Feature	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	Total	%
Floor areas																
Net floor area (NFA)	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	13	93%
Heated/conditioned floor area	✓	✓	✓	✓		✓		✓	✓	✓		✓	✓		10	71%
Gross floor area (GFA)	✓		✓		✓	✓	✓	✓	✓	✓					8	57%
Cooled floor area	✓		✓	✓		✓			✓	✓					6	43%
Footprint (of ground floor) area	✓					✓	✓		✓	✓	✓		✓		7	50%
Non-floor surface areas																
Total envelope surface area (derived sum)	✓	✓	✓		✓	✓			✓	✓	✓		✓		9	64%
External wall area (total)	✓		✓			✓			✓	✓	✓		✓		7	50%
Roof area (total)	✓		✓			✓			✓	✓	✓		✓		7	50%
Window/glazing area (total)	✓		✓			✓			✓	✓			✓		6	43%
Door area						✓				✓			✓		3	21%
Heights																
Height above/below terrain height	✓			✓			✓			✓	✓				5	36%
Room/ Ceiling height	✓			✓									✓		3	21%
Base height of building (sometimes altitude)	✓			✓			✓				✓				4	29%
Volumes																
Heated/conditioned volume	✓	✓	✓	✓	✓	✓			✓				✓		8	57%
Gross volume	✓	✓					✓				✓				4	29%
Net volume				✓			✓		✓				✓		4	29%
Cooled volume			✓			✓									2	14%
Shape factor and compactness																
Shape factor (envelope area / gross volume)	✓	✓							✓				✓		4	29%
Compactness (envelope area / gross floor area)									✓	✓					2	14%

Table 50: Overview of the features of module 6: Dimensions. Initiative IDs (I1-I14) are defined in Table 3. Own work.

Module 7: Operation and use

Feature	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	Total	%
Behavioural patterns/ user profile	✓	✓	✓	✓		✓		✓	✓	✓			✓	✓	10	71%
Number of occupants	✓		✓	✓		✓		✓	✓	✓				✓	8	57%
Set points for heating and cooling	✓	✓		✓		✓		✓		✓			✓	✓	8	57%
Hot water usage intensity (low, medium, high)	✓			✓						✓			✓	✓	5	36%
Annual usage days	✓			✓											2	14%
Daily HVAC system operating hours	✓								✓					✓	3	21%
Ventilation habits				✓						✓			✓	✓	4	29%
Room for auditor advice regarding usage habits				✓						✓			✓	✓	4	29%
Heating usage intensity (low, medium, high)	✓									✓				✓	3	21%
Cooling usage intensity (low, medium, high)	✓									✓					2	14%
Electricity usage intensity (low, medium, high)	✓									✓				✓	3	21%
Owner satisfaction regarding room temperature				✓											1	7%
The type of cooking (electric vs. gas)										✓	✓			✓	3	21%

Table 51: Overview of the features of module 7: Operation and use. Initiative IDs (I1-I14) are defined in Table 3. Own work.

Module 8: Legal and finance

Feature	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	Total	%
Property valuations																
Property tax valuation / Official value	✓		✓	✓		✓	✓	✓			✓				7	50%
Market value / Property value	✓		✓	✓		✓	✓	✓	✓						7	50%
Annual maintenance cost	✓		✓			✓		✓	✓				✓		6	43%
Renewal / Renovation cost	✓				✓	✓		✓	✓				✓		6	43%
Rental value / Annual rent	✓					✓	✓	✓							4	29%
Property yield (%)	✓		✓			✓		✓							4	29%
Lifecycle and maintenance costs																
Sales transaction value / Property price paid	✓														1	7%
Life Cycle Cost (LCC)	✓								✓						2	14%
Valuation metadata																
Valuation date	✓		✓			✓	✓	✓							5	36%
Valuation method / approach	✓		✓			✓		✓							4	29%
Valuation conducted by (name/contact)	✓		✓			✓		✓							4	29%
Valuation document (linked file)			✓			✓		✓							3	21%
Financial data collecting date / last update			✓				✓								2	14%
Valuation purpose	✓														1	7%
Valuation cost (€)	✓														1	7%
Property selling date	✓														1	7%
Economic observation period (years)													✓	✓	2	14%
Operational energy costs																
Annual energy costs (total)	✓		✓	✓					✓		✓		✓	✓	7	50%
Annual energy cost by carrier (electricity/ gas/ etc.)	✓		✓	✓		✓		✓	✓				✓	✓	8	57%
Annual water cost	✓		✓			✓		✓							4	29%
Subsidies / Grants / Financial programs				✓	✓						✓		✓	✓	5	36%
Annual energy cost by use (heating/ cooling/ etc.)									✓						1	7%
Building insurance cost	✓														1	7%
Certification costs (EPC/ BREEAM/ LEED/ etc.)	✓														1	7%
Legal and property documents																
Tenancy agreement	✓		✓			✓		✓	✓						5	36%
Insurance policy / document			✓			✓		✓							3	21%
Clean soil statement					✓		✓								2	14%
Permits and licenses																
Building / Construction / Use permits	✓		✓	✓	✓	✓		✓				✓			7	50%
Maintenance service contract / log	✓		✓			✓		✓				✓			5	36%
Utility contracts	✓		✓			✓		✓							4	29%
Ownership information																
Owner information	✓			✓		✓	✓	✓				✓			6	43%
Legal / Fiscal property registration	✓			✓			✓					✓			4	29%
Tenant information							✓		✓						2	14%

Table 52: Overview of the features of module 8: Legal and finance. Initiative IDs (I1-I14) are defined in Table 3. Own work.

Module 9: Ancillary data & (environmental) context

Feature	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	Total	%
Climate zone	✓	✓	✓	✓		✓		✓	✓	✓		✓			9	64%
District heat network connection availability	✓		✓			✓		✓	✓		✓	✓			7	50%
Green-blue level / climate resilience	✓		✓		✓	✓		✓							5	36%
Associated cadastral parcel details	✓				✓		✓					✓			4	29%
The type of soil/terrain	✓		✓			✓		✓							4	29%
Textual description of the building's surroundings	✓							✓							2	14%
External noise pollution					✓	✓									2	14%
Soil/ground cleanliness/ contamination details					✓							✓			2	14%
Drinkwater connection availability					✓		✓	✓				✓			4	29%
Flood susceptibility					✓			✓				✓			3	21%
Sewerage available & details on the current connection					✓		✓	✓				✓			4	29%
Whether a building is (dis)connected to/from gas							✓				✓	✓		✓	4	29%
Energy community access availability			✓												1	7%
Groundwater well availability					✓										1	7%
Heat stress					✓					✓					2	14%
Outdoor air quality					✓										1	7%
Mobility details, like public transport options					✓										1	7%
Space & greenery details					✓										1	7%
Radiation (by wireless internet and telecom antennas)															0	0%
Perceived light (pollution) at night					✓										1	7%
Spatial planning of own and surrounding plots					✓										1	7%
Immovable heritage of own and surrounding buildings					✓							✓			2	14%
Whether a building is, or can be connected to electricity							✓				✓	✓			3	21%
The communication types available/connected (e.g. 5G)							✓								1	7%
Regulations in force at the time of construction									✓						1	7%

Table 53: Overview of the features of module 9: Ancillary data & (environmental) context. Initiative IDs (I1-I14) are defined in Table 3. Own work.

Module 10: Energy performance

Feature	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	Total	%
Official ratings and certification																
EPC class / label	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	14	100%
Numeric indicator	✓	✓	✓	✓	✓	✓		✓	✓	✓		✓	✓		11	79%
EPC rating basis (actual / potential)	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓		12	86%
Renovation target / status	✓	✓	✓		✓	✓			✓	✓		✓	✓		9	64%
EPC document as PDF	✓		✓	✓	✓	✓						✓			6	43%
Energy consumption																
Total source energy (including grid losses)	✓	✓	✓	✓	✓	✓			✓	✓			✓		9	64%
Final / delivered energy	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	14	100%
Heating demand	✓	✓	✓	✓		✓		✓	✓	✓			✓	✓	10	71%
Cooling demand	✓	✓	✓	✓		✓			✓	✓					7	50%
DHW (hot water) demand	✓	✓	✓	✓		✓			✓	✓			✓		8	57%
Lighting and aux	✓	✓	✓	✓		✓			✓	✓			✓		8	57%
Calculation type	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓		11	79%
Energy production																
Renewable energy production	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	12	86%
Self-consumption ratio	✓	✓							✓						3	21%
Renewable energy share (%)	✓				✓				✓	✓			✓		5	36%
Calculation zones																
Area (or volume) per zone										✓					1	7%
Surface area of envelope area per zone										✓					1	7%

Table 54: Overview of the features of module 10: Energy performance. Initiative IDs (I1-I14) are defined in Table 3. Own work.

Module 11 (part 1): Indoor environmental quality

Feature	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	Total	%
Temperature assessment																
Air temperature (average)	✓	✓	✓					✓							4	29%
Hours outside comfort range	✓	✓													2	14%
Set point temperature										✓			✓	✓	3	21%
Temperature variation		✓													1	7%
Humidity assessment																
Average indoor relative humidity	✓	✓	✓					✓				✓			5	36%
Time with RH outside 30–60% comfort range		✓													1	7%
PMV/PPD assessment																
Predicted mean vote (PMV)		✓													1	7%
Predicted percentage dissatisfied (PPD)		✓													1	7%
Hours with PPD above thresholds		✓													1	7%
Summer comfort / overheating																
Summer thermal discomfort	✓	✓													2	14%
Climate resilience (2050)	✓							✓							2	14%
Owner satisfaction		✓		✓											2	14%

Table 55: Overview of the features of module 11 (part 1): Indoor environmental quality. Initiative IDs (I1-I14) are defined in Table 3. Own work.

Module 11 (part 2): Indoor environmental quality

Feature	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	Total	%
CO_2 concentration																
CO_2 concentration (average)	✓	✓	✓												3	21%
Hours with CO_2 above thresholds		✓													1	7%
Ventilation assessment																
Ventilation rate	✓									✓					2	14%
Ventilation system type	✓		✓			✓	✓	✓	✓	✓		✓	✓	✓	10	71%
Heat recovery efficiency						✓			✓	✓			✓		4	29%
Air tightness (n50/q50)						✓			✓	✓			✓		4	29%
Air quality indicator		✓		✓											2	14%
Pollutant concentrations																
Total volatile organic compounds (VOCs)	✓														1	7%
CMR VOCs	✓														1	7%
Formaldehyde	✓														1	7%
PM2.5 / PM10			✓					✓							2	14%
Radon						✓						✓			2	14%
R-value (pollutant index)	✓														1	7%
Outdoor air quality context																
Outdoor air quality					✓										1	7%
Nitrogen dioxide (NO_2)					✓										1	7%

Table 56: Overview of the features of module 11 (part 2): Indoor environmental quality. Initiative IDs (I1-I14) are defined in Table 3. Own work.

Module 11 (part 3): Indoor environmental quality

Feature	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	Total	%
Daylight assessment																
Daylight provision	✓	✓													2	14%
Light (lux) level		✓	✓												2	14%
Light pollution					✓										1	7%
Artificial lighting																
Lighting system type	✓		✓			✓		✓	✓	✓			✓		7	50%
Installed lighting power density										✓					1	7%
Lighting control systems								✓							1	7%

Table 57: Overview of the features of module 11 (part 3): Indoor environmental quality. Initiative IDs (I1-I14) are defined in Table 3. Own work.

Module 11 (part 4): Indoor environmental quality

Feature	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	Total	%
Material health																
Asbestos presence						✓									1	7%
Material chemical declaration						✓		✓							2	14%
General health context																
Health comfort indicator				✓											1	7%
Flood sensitivity					✓			✓							2	14%
Heat stress risk					✓			✓							2	14%

Table 58: Overview of the features of module 11 (part 4): Indoor environmental quality. Initiative IDs (I1-I14) are defined in Table 3. Own work.

Module 11 (part 5): Indoor environmental quality

Feature	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	Total	%
Noise assessment																
Noise control (general)		✓		✓											2	14%
Traffic noise exposure					✓										1	7%

Table 59: Overview of the features of module 11 (part 5): Indoor environmental quality. Initiative IDs (I1-I14) are defined in Table 3. Own work.

Module 11 (part 6): Indoor environmental quality

Feature	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	Total	%
Data collection approach																
Requires physical measurements	✓	✓						✓		✓					4	29%
Requires dynamic simulation		✓													1	7%
Static data entry only	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	13	93%
Monitoring data integration			✓					✓				✓			3	21%
Standard references																
EN 15251 / EN 16798		✓						✓							2	14%
Sustainability certification link	✓									✓		✓			3	21%

Table 60: Overview of the features of module 11 (part 6): Indoor environmental quality. Initiative IDs (I1-I14) are defined in Table 3. Own work.

Module 12 (part 1): Smart Readiness Indicator

Feature	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	Total	%
SRI core indicators																
SRI result / score	✓		✓	✓		✓	✓	✓	✓						7	50%
SRI class (A–F rating)									✓						1	7%
SRI weighting factors (KF1–KF3)									✓						1	7%
SRI report / document			✓												1	7%
E-mobility and EV charging																
EV charging infrastructure (yes / no)	✓		✓	✓				✓							4	29%
Number of EV charging points	✓		✓				✓								3	21%
Total parking spaces	✓														1	7%
Pre-cabled recharging stations	✓														1	7%
EV charging station types (private / public)	✓														1	7%
EV charging types (grid / non-grid / market)	✓														1	7%
EV charging capacity (kW)	✓														1	7%
EV grid balancing	✓					✓									2	14%
EV charging information and connectivity	✓					✓									2	14%
Energy storage and load shifting																
Storage of locally generated energy		✓	✓			✓			✓	✓					5	36%
Electrical storage system			✓						✓						2	14%
Heating system thermal storage / shifting		✓	✓			✓									3	21%
Cooling system thermal storage / shifting						✓									1	7%
Control of DHW storage charging						✓									1	7%
Optimising self-consumption		✓													1	7%
Grid integration and demand response																
Smart grid integration						✓									1	7%
Demand response potential	✓		✓			✓		✓							4	29%
Occupant participation in DR events								✓							1	7%

Table 61: Overview of the features of module 12 (part 1): Smart Readiness Indicator. Initiative IDs (I1-I14) are defined in Table 3. Own work.

Module 12 (part 2): Smart Readiness Indicator

Feature	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	Total	%
Building automation and control (BACS)																
BACS description			✓							✓					2	14%
Control system for heating (class)		✓													1	7%
Control system for cooling (class)		✓								✓					2	14%
Emission control for TABS		✓	✓												2	14%
Control of distribution heat temperature		✓	✓												2	14%
Control of distribution pumps		✓													1	7%
Intermittent control		✓													1	7%
CHP control		✓													1	7%
Technical building management systems			✓												1	7%
IoT sensors and monitoring																
Sensors for energy consumption (HVAC / lighting)								✓							1	7%
Sensors for air temperature / humidity / presence								✓							1	7%
IoT continuous vibration sensors								✓							1	7%
IoT weather station data								✓							1	7%
Self-attentive sensing configuration								✓							1	7%
Fault detection and structural health																
Fault detection of sensors								✓							1	7%
Alerts / warnings for anomalies								✓							1	7%
SHM thresholds								✓							1	7%
District and external integration																
Smart district potential / indicators	✓		✓	✓		✓		✓							5	36%
Building energy model (BEM)								✓							1	7%
Climate and resilience																
Solar potential (roofs / facades)			✓		✓		✓	✓							4	29%
Climate resilience potential			✓					✓							2	14%
Metering and data collection																
Digital energy meters					✓	✓		✓				✓			4	29%
Data collection timestamp			✓					✓				✓			3	21%

Table 62: Overview of the features of module 12 (part 2): Smart Readiness Indicator. Initiative IDs (I1-I14) are defined in Table 3. Own work.

Module 13: Renovation advice

Feature	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	Total	%
Only general recommendation to include renovation data						✓		✓				✓			3	21%
Administrative (step) information																
Renovation measure proposals on specific elements	✓	✓			✓			✓	✓	✓	✓	✓	✓	✓	10	71%
Textual renovation (stage) description	✓		✓	✓	✓				✓	✓	✓		✓	✓	9	64%
Year of this renovation/ stage	✓	✓	✓	✓					✓				✓		6	43%
Attachable documents which relate to the renovation	✓		✓	✓	✓				✓			✓	✓	✓	8	57%
Achieved/ desired renovation depth (descriptive)		✓	✓							✓			✓	✓	5	36%
Energy & resource consumption improvements																
Resource consumption (kWh) vs. pre-renovation	✓	✓	✓	✓	✓				✓	✓	✓	✓	✓	✓	11	79%
Energy label before/after (letter or colour)	✓	✓		✓	✓				✓	✓	✓	✓	✓		9	64%
Resource demand (kW) vs. pre-renovation	✓		✓	✓					✓	✓			✓		6	43%
Energy efficiency before / after renovation	✓	✓								✓	✓	✓	✓		6	43%
Finances																
Investment costs per measure/ step		✓	✓	✓	✓			✓	✓	✓	✓		✓	✓	10	71%
Current total energy costs per year			✓	✓				✓	✓	✓	✓		✓	✓	8	57%
Business as usual costs (or if it can be derived)			✓	✓				✓	✓	✓	✓		✓		7	50%
Public funding program details			✓	✓	✓				✓		✓		✓	✓	7	50%
Public funding investment amount (available)			✓	✓					✓		✓		✓	✓	6	43%
Overall total investment costs (staged or all at once)										✓			✓	✓	3	21%
Tax incentive (name)			✓	✓											2	14%
Reasoning & timelining																
Renovation measure priority level		✓		✓	✓			✓		✓			✓	✓	7	50%
Motivation on why this specific measure is necessary**										✓	✓		✓	✓	4	29%
Estimation of the renovation works time**								✓	✓						2	14%
The first/best opportunity to do this renovation**		✓								✓					2	14%
Ideal season for executing the renovation step**									✓	✓					2	14%
Non monetary benefits																
Indication of new thermal comfort**	✓	✓		✓					✓				✓	✓	6	43%
Descriptive explanation of other non-monetary benefits**		✓		✓					✓				✓	✓	5	36%
Negatives																
Constraints that limit/block certain renovations		✓									✓	✓	✓	✓	5	36%
Estimation of users' disruption**		✓						✓							2	14%
Renovation risks (e.g. mold growth if not done properly)		✓											✓	✓	3	21%

Table 63: Overview of the features of module 13: Renovation advice. Initiative IDs (I1-I14) are defined in Table 3. Own work.

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