

Article

URMIBALI Research Project: Exploring How Digital Documentation Technologies Can Enhance Knowledge and Support the Reuse of Materials in Traditional and Historic Buildings Within an Urban Mining Approach [†]

Sophie Trachte ^{1,*} , Ophélie Noël ¹, Simon Boutet ² , Philippe Sosnowska ² and Pierre Hallot ² 

¹ Research Lab ACTE, Research Unit Art, Archéologie et Patrimoine (AAP), Université de Liège (ULiège), 4000 Liège, Belgium; ophelie.noel@uliege.be

² Research Lab DIVA, Research Unit Art, Archéologie et Patrimoine (AAP), Université de Liège (ULiège), 4000 Liège, Belgium; simon.boutet@uliege.be (S.B.); philippe.sosnowska@uliege.be (P.S.); p.hallot@uliege.be (P.H.)

* Correspondence: sophie.trachte@uliege.be

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Abstract

Meeting European carbon neutrality and energy performance targets requires large-scale rehabilitation of historic and traditional buildings, one of the construction sector’s key challenges by 2050. This will significantly increase demand for new materials and the production of waste, which already accounts for 39% of waste in Wallonia. From a circular economy and urban mining perspective, however, this waste can be viewed as a valuable resource for reuse and recovery. Despite this potential, Wallonia lacks detailed information on the material composition of its historic building stock, including material types, quantities, and reuse potential. Such knowledge is crucial for designing effective renovation strategies and promoting circular construction practices. The URMIBALI project addresses this gap by investigating traditional residential buildings built before 1919 in Liège (Belgium). Based on six case studies, the project develops two complementary research parts. The first part focuses on inventorying existing material stocks, estimating waste flows resulting from energy renovations, and evaluating the reuse potential of the main waste fractions. The second part proposes an initial digital methodology for the rapid and efficient acquisition of façade material data. The project’s novelty lies in its multi-material, bottom-up, and transdisciplinary approach, as well as in the creation of previously unavailable data on building-stock composition and the development of simple and flexible digital methods to acquire those data. These outputs improve knowledge of traditional buildings, support projections of renovation waste up to 2050, and facilitate urban-scale management of material flows, including transport, supply chains, and environmental impacts. This contribution presents the research methodology, key findings, and the transferability of the digital method to other building typologies and European contexts.

Keywords: historic residential buildings; traditional residential buildings; digital tools; heritage documentation; building materials reuse; urban mining



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1. Introduction

This study first presents the methodological development of the URMIBALI research project, focusing on the acquisition of data on the material deposits that constitute traditional historic residential buildings in Liège, as well as the waste flows that may be generated by their energy renovation. It then presents and compares data obtained through theoretical analysis (estimates of material stocks and waste flows) with those derived from the developed digital method (estimates of façade materials stocks). Finally, it discusses the potential transferability of this digital method to other building types and outlines directions for future research.

The URMIBALI research project is based on six case studies that are sufficiently representative of the traditional historic residential building stock built before 1919 in Liège. It adopts a bottom-up, interdisciplinary approach, which contributes to its originality. The aim is to rapidly develop, through theoretical analysis based on case studies and digital technologies, a better understanding of the composition of traditional historic residential buildings in terms of material types, characteristics, quantities, and potential reuse. This knowledge, currently nonexistent in Wallonia buildings databases, is intended to support the implementation of energy rehabilitation strategies adapted to these buildings, in response to the carbon neutrality objective, while promoting circular and material reuse practices and ultimately enhancing sustainability in the construction sector.

The project provides strong and valuable support to both urban mining and digital technologies for building documentation. In the field of urban mining, it implements a comprehensive multi-material approach covering all building components, generates previously unavailable data on the material composition of traditional historic residential buildings in Wallonia, and considers multiple rehabilitation scenarios, which together enable the estimation of the resulting waste flows. In terms of digital technologies, it introduces an innovative, accessible workflow that uses readily available, simple tools to train an AI model capable of identifying façade materials from images of varying quality. This flexible approach enables large-scale material data acquisition while reducing the time, cost, reliance on specialized equipment, and level of expertise required. Together, these contributions represent a significant step forward, adding tangible value to geographic information systems, heritage documentation, and circular construction and reuse practices.

The construction sector occupies a central position in the transition toward a sustainable, circular, and carbon-neutral economy, given that building stocks account for approximately 40% of total final energy consumption, 35% of natural resource depletion, and constitute a major source of CO₂ emissions and waste in Europe [1–5]. Accelerating the energy retrofitting of existing buildings would thus substantially advance the European Union's objectives of reducing energy consumption and managing resources and waste more sustainably, particularly as rising renovation rates will simultaneously intensify material demand and waste generation [5]. In this context, European regulatory frameworks have progressively tightened requirements: since 2018, Member States have been required to develop long-term strategies targeting a highly efficient building stock by 2050, with annual renovation rates rising from approximately 1% to 3% [6–8]. The 2024 recast of the Energy Performance of Buildings Directive further consolidates these ambitions by mandating reductions in embodied and operational carbon emissions, encouraging the use of biobased and reused materials, and extending energy performance obligations to previously exempted heritage buildings [9].

The existing building stock represents a large share of dwellings, 82% in Wallonia [10] and 64% across Europe [3], with a predominance of single-family houses [3,11]. A significant portion of this stock consists of historic and traditional buildings built before 1919 and defined by Webb, from a constructive point of view, as structures characterized by

irregular geometry, poorly insulated envelopes, vernacular construction methods, natural and non-standardized materials, and passive, non-mechanical indoor climate management strategies. According to Troi [12], 14.3% of buildings in the European Union were constructed before 1919, compared to 11.5% in Belgium [3]. In Wallonia, and particularly in the city of Liège, this proportion is even higher, with 25% and 33% of dwellings, respectively, built before 1918 [10].

In this context, improving knowledge of traditional and historic residential building stock and the materials that compose it is essential for supporting both energy rehabilitation efforts and the transition to circular practices through enhanced maintenance and reuse. The 19th-century building stock, which is highly prevalent in the urban fabric of Liège and in Wallonia, as well as across Europe, and well documented [13–16], constitutes a relevant field of study for analyzing material stocks and anticipating the waste flows generated by energy rehabilitation.

However, Wallonia lacks high-granularity data on its residential building stock, including material deposits and demolition waste flows. The only existing databases on the Walloon building stock are the cadastral matrix—initiated under French rule, the “primitive cadastre” was not definitively ratified until 1834 for the whole of Belgium, except for the provinces of Luxembourg and Limburg, whose fieldwork could not be completed until 1844—and statistical data from Statbel [10]. Neither municipal nor regional administrations maintain comprehensive building inventories or materials databases at the territorial scale. The cadastral matrix is primarily designed for administrative and fiscal purposes. As a result, it provides only limited information on building use, construction date, dimensions, floor area, and number of floors. It contains no data on building materials and is updated infrequently, as revisions depend on building permits. Similarly, urban planning permits do not include systematic information on the nature, type, or quantity of materials used.

Estimating waste flows is equally challenging. Most renovation works are carried out without planning permission, except when structural demolition or a change of use is involved. Even where inventories and waste management plans are required, the information is neither systematically collected nor stored in accessible databases. Furthermore, construction waste statistics are reported only in broad categories (e.g., mineral or wood waste), making it impossible to identify specific material flows such as bricks, tiles, timber, or natural stone.

These limitations explain the current lack of detailed data on material stocks and waste flows in the Walloon residential building sector. At present, such data can only be obtained through a bottom-up approach based on in-depth analyses of representative case studies and statistical assessments of renovation activities. However, these methods are time-consuming, resource-intensive, and costly, and require access to all surveyed buildings, potentially raising concerns about occupants’ privacy. Consequently, integrating artificial intelligence with existing digital tools for built heritage documentation and pathology detection could significantly streamline and accelerate data collection.

1.1. State of the Art

The transition toward circular construction, the promotion of material reuse practices as well as the integration of digital technologies in both new construction and energy rehabilitation of traditional historic buildings, regardless of their conservation status, have emerged as key challenges for Wallonia and many other European regions [1,2,9]. Over the past decade, researchers have shown growing interest in approaches that promote the spatial adaptability and technical reversibility of buildings, urban mining strategies, and the reuse of existing materials. At the same time, increasing attention has been devoted to the energy rehabilitation of traditional historic buildings, aiming to reconcile thermal comfort,

heritage value, and energy efficiency. These developments have been accompanied by significant advances in the digital documentation of the built heritage and the application of artificial intelligence to support data acquisition and analysis. Although these areas have generated numerous research projects, scientific publications, and conferences, they have generally been addressed in isolation, with limited cross-connection.

The first series of research work is situated within the development of circular practices in the construction sector. A circular economy is defined as a system in which materials do not become waste but are kept in circulation through processes such as reuse, repair, refurbishment, or recycling. Applied to the built environment, this approach involves viewing the existing building stock as a source of materials that can be recovered and valued. Within this perspective, reuse plays a central role. Defined by Directive 2008/98/EC as the reuse of a product for the same purpose for which it was originally conceived, it differs from recycling and other forms of recovery by its low level of transformation and energy demand. Several studies have highlighted its potential in reducing environmental impacts, particularly embodied carbon [17–19]. Historically, reuse was a common practice in the construction sector before declining during the 20th century due to industrialization and resource abundance; it has recently regained interest in the context of ecological transition. This renewed interest has led to the development of research projects such as EU-H2020-BAMB, FEDER-BBSM, and Interreg FCRBE. Those projects have contributed to structuring this research area by developing tools and methodologies aimed at facilitating the circulation of construction materials. These works have notably highlighted the relevance of material passports and design approaches integrating disassembly, such as Design for Disassembly, Design with Reuse (DwR) or Design for Deconstruction and Reuse (DfDR).

In parallel, professional initiatives such as reuse platforms and experts, in Brussels and Wallonia [20–22] as well as in France [23,24] have contributed to connecting stakeholders involved in material reuse, and to structuring and professionalizing the sector. Moreover, the ABER project, notably led by Centre Scientifique et Technique du Bâtiment (CSTB) and Bellastock in France, follows a complementary approach by aiming to improve knowledge of materials present in the existing building stock and to facilitate their characterization for reuse. The project focuses on the resource diagnosis phase, seeking to make archival information more accessible and usable while strengthening the link between material characteristics and their potential for valorization.

Notwithstanding these advances, the literature highlights significant barriers to the implementation of reuse and circular economy principles within rehabilitation practices [25,26], particularly regarding the lack of data on materials in existing buildings, as well as technical and regulatory constraints [27,28]. In fact, despite the existence of the ISO 20887 standard [29] and the various action plans implemented at the European level [30], no comprehensive regulatory framework for material reuse has yet been established in Wallonia as in Belgium. As a result, reuse practices currently rely largely on the voluntary commitment of stakeholders and are primarily driven by the practical experience of a limited number of specialized actors. Moreover, unlike new materials currently on the market, reclaimed materials are often not, or are no longer, accompanied by technical documentation demonstrating their suitability for reuse under current standards and regulations [31]. This lack of technical data directly undermines stakeholder confidence, as certification serves as a key guarantee of quality and a means of mitigating associated risks [32].

In this context, the concept of Urban Mining (UM) [33,34] has emerged as a structuring analytical framework to assess resources embedded in cities. Originating from the field of urban metabolism [33,35], it aims to quantify material stocks and flows within urban territories by considering buildings as sources of secondary materials [36,37]. Applied to

the building sector, it enables the anticipation of waste flows generated by rehabilitation operations and the identification of reuse and recycling potentials [38]. In the construction sector, UM studies primarily center on residential buildings, using primarily top-down methodologies based on statistical data analysis [39] and focusing on a single material such as metals, aggregates, sand, or concrete [40]. However, despite their prevalence in old traditional and historic buildings, wood, stone, bricks, and tiles have not received thorough examination, although some research has investigated spatiotemporal frameworks for mapping structural bricks [41] and the potential for reusing old bricks [42]. Moreover, few studies have analyzed the entire deposit present in the old traditional building stock and/or the influence of energy rehabilitation on waste flows, especially due to a lack of data and methods [38]. Conversely, bottom-up approaches, based on detailed case study analysis, allow for a more precise characterization of material stocks but remain underdeveloped, notably due to the lack of adapted methodologies and the high cost of data collection [40]. Overall, the literature highlights a lack of studies simultaneously addressing both the characterization of the building stock and the analysis of waste flows generated by energy rehabilitation [38,43]. In addition, several recent studies emphasize the relevance of combining urban mining approaches with digital tools for mapping materials within the urban fabric to improve knowledge of material stocks, facilitate renovation planning, and support the development of reuse strategies at multiple scales [41,44,45].

The second series of research has developed around the use of digital tools for documenting the existing building stock, particularly in heritage [46–49]. Three-dimensional digitization technologies, such as laser scanning and photogrammetry, now enable the acquisition of detailed geometric and visual data of buildings with a high level of accuracy [48,49]. These tools are increasingly used in survey operations, complementing traditional methods, due to their ability to produce digital models suitable for analysis and conservation [50]. Among these approaches, multi-view photogrammetry (MVP) stands out as a particularly accessible solution. It enables the reconstruction of three-dimensional geometry while simultaneously generating rich visual datasets that can support material identification and, to some extent, heritage value assessment. Its relatively low investment cost and limited disturbance to occupants make it well suited for use in occupied buildings. In addition, MVP can be deployed across multiple scales, from material detail to neighborhood level, and allows access to otherwise inaccessible areas using drones [51].

Beyond geometric acquisition, these techniques can be complemented by non-destructive investigation methods, such as ground-penetrating radar (GPR) and infrared thermography (IRT). These methods provide access to information on the internal structure of building elements and on physical phenomena related to moisture and heat transfer. Infrared thermography enables the identification of thermal anomalies associated with variations in material properties, thicknesses, thermal bridges, air leakages, moisture presence, or degradation processes. However, more in-depth investigations, such as endoscopic examinations or core sampling, are often required to achieve a comprehensive understanding of the building envelope, including its stratigraphy, material composition, and dimensional characteristics [52,53].

In parallel, other advanced analytical approaches have been developed to extend building knowledge at different scales. Dynamic thermal and hygrometric simulation tools, initially developed for new constructions, are increasingly adapted to the study of historical buildings. These tools support the analysis of energy performance, conservation conditions, and retrofit strategies, although their application remains constrained by the lack of reliable thermophysical data for historical materials [52]. At a broader scale, methods derived from remote sensing [54–56], such as multi-spectral and hyperspectral imaging [55,57,58],

enable large-scale inventories by identifying certain types of coverings, the presence of solar panels or asbestos, or vegetated areas.

Taken together, these approaches contribute to a multi-layered understanding of existing buildings by combining geometric documentation, surface observation, internal diagnosis, and environmental or energetic analysis. However, these technologies also present constraints in terms of cost, implementation complexity, and data processing, particularly for remote sensing approaches. Moreover, their scope often remains fragmented: while some methods provide detailed geometric or diagnostic information, others operate at larger scales with limited resolution. As a result, these approaches remain largely focused on geometric documentation and pathology diagnosis and are still rarely used for the systematic inventory of materials for reuse, particularly at the scale of individual building components.

Finally, a last series of research has developed around the automation of material identification and quantification using digital tools and artificial intelligence. These works build on recent advances in deep learning and computer vision to process data from various sources, such as images, point clouds, or urban databases. In this context, digital tools applied to material mapping constitute a rapidly growing research field, aiming to identify, locate, and quantify materials present in the urban environment [41,44,45,59–62]. These studies address multiple challenges and contribute to improving construction project management, particularly in terms of modeling, monitoring, and quality control [63], as well as to estimating material stocks available in the existing building stock, whose volumes evolve according to renovation dynamics [44,45,60]. Some research goes beyond mass estimation and proposes identification in terms of products or building elements, thus facilitating the assessment of reuse potential [41,45].

The objective of these works is to develop models capable of automatically recognizing materials within the urban fabric [41,44,45,59–62,64]. The methodologies generally rely on the creation of annotated datasets used to train deep learning models capable of recognizing different types of materials or building elements. Depending on the objectives, these models can be applied to classification, object detection, or instance or semantic segmentation tasks, the latter enabling fine identification at the pixel scale and offering the potential for accurate estimation of material surfaces. These approaches rely on the acquisition of representative datasets from various sources, such as cameras with operators, Street View imagery [44,59,61,64], drone surveys [45,59], laser scanning [60], satellite imagery, or cadastral records [41].

Overall, these studies share a common methodological foundation, which is adapted according to objectives, available data, and scales of analysis. The main differences lie in data acquisition methods, the choice of deep learning models, and image processing techniques, whether for object detection or segmentation. Some initiatives, such as those developed by the Belgian research center Buildwise [51,65] or within the De Sloopwijzer project [66] developed by research center Vito, have demonstrated the potential of these approaches for mapping materials at the urban scale and estimating available stocks in the existing building stock.

Nevertheless, these works are still under development and present several limitations, notably related to the quality and representativeness of training data, as well as to the complexity of materials and construction systems found in historic buildings [63]. Moreover, few studies propose a comprehensive integration of these approaches within a global framework for analyzing material stocks and associated flows.

1.2. Aims of the URMIBALI Research Project

Funded by the Human Sciences Research Council of the University of Liège (ULiège), and initiated in March 2024, the URMIBALI research project [67] integrates a broad reflection led by the two ULiège laboratories ACTE and DIVA on the reuse of construction materials, and the study of old traditional buildings, both from a historical perspective and a contemporary architectural approach, in line with a series of current societal and environmental challenges.

In line with the research projects FEDER-BBSM, Interreg FCRBE, and ABER, the project URMIBALI aims to address the lack of data on existing materials by developing a comprehensive multi-material Urban Mining approach encompassing all materials constituting traditional historic residential buildings in Liège. The study focuses on residential buildings built before 1919, whether they were protected or not. These buildings represent 30% of the Walloon building stock and 53% of the stock in Liège [10]. Their extensive documentation and relatively limited palette of construction materials, despite a diversity of construction types, make them particularly suitable for large-scale material stock assessment and reuse studies. Being well-documented, they feature a diverse range of construction types, primarily using a limited selection of materials [14].

The main objective of the project is to provide previously unavailable data on both the material composition of these buildings and the waste flows likely to be generated by their future rehabilitation. This objective is developed through two complementary parts. The first, theoretical, establishes, based on six case studies and existing historical and archaeological knowledge of traditional historic buildings, inventories of material stocks, defines renovation scenarios, estimates the waste streams generated by their implementation, and assesses the reuse potential of the main waste fractions. The second part, more practical, develops a preliminary digital method for rapidly and easily acquiring detailed data to inventory and quantify existing façade material stocks. It combines heritage documentation technologies with AI model training to enable reliable material identification and surface area estimation through an accessible image-based method based solely on camera-acquired data, offering an alternative to highly specialized documentation techniques.

The project's innovation lies in three key contributions. First, it generates previously unavailable data on material stocks in Walloon traditional historic residential buildings and on the waste flows resulting from their rehabilitation, adopting a multi-material urban mining perspective. Second, it develops a novel digital method for the rapid acquisition of this information based on simple digital tools and AI model training. Third, it combines expertise in construction archaeology, architectural history, heritage digitization, circular construction, and material reuse within a bottom-up interdisciplinary framework.

This contribution is structured as follows. Section 2, "Methodology," presents the overall methodological approach, the selected case studies, and the various methodological steps. Section 3, "Results and Discussion," first outlines the data on building material deposits and flows collected both theoretically and digitally, then compares these two types of data and discusses their contribution to improving data acquisition on buildings and reuse practices. Section 4, "Conclusions and Perspectives," summarizes the main findings and introduces possible directions for future work.

2. Methodological Approach and Research Steps

2.1. Methodological Approach

The URMIBALI research project aligns European and Walloon objectives regarding the massification of energy rehabilitation [9], especially on traditional historic residential build-

ings, and the sustainable and circular management of waste and resources [1], adopting a bottom-up and interdisciplinary approach.

2.1.1. Bottom-Up Approach

The research is based on six case studies presented in Section 2.2 and considered, by the authors, as sufficiently representative of traditional historic residential buildings constructed before 1919 in Liège. These cases supported the development of theoretical material deposits inventories, the design of energy retrofitting scenarios, and the estimation of resulting waste flows for each scenario. Data collected from these buildings and their constituent materials also enabled the creation of technical sheets enhancing reuse practices, as well as the development of a preliminary draft of a new flexible digital acquisition method. This bottom-up approach made it possible to account for the specific characteristics of different old traditional building types and to better tailor rehabilitation scenarios and waste flow estimations on a case-by-case basis.

2.1.2. Interdisciplinary Approach

The research integrates knowledge, expertise, and methodologies from both Applied Building Sciences and Human Sciences. It draws on disciplines such as circular construction, urban mining, geographic information systems, digital documentation of heritage, construction history, and building archaeology. The project is embedded within a broader research ecosystem co-developed by the two research laboratories, which focuses on ancient materials, their characterization and documentation, as well as their reuse and recycling potential. This interdisciplinary approach plays a key role in advancing the circular economy and strengthening practices related to the management and reuse of construction materials, as well as the development of adapted rehabilitation solutions.

2.2. Selected Case Studies in Liège

The theoretical material deposits inventories were developed through an in-depth analysis of six case studies (Table 1). These cases were chosen for their representativeness in both the Liège residential buildings stock and the construction techniques and materials used from the 14th century until the First World War.

According to the Belgian Statistical Office (Statbel), residential house-type buildings account for 79% of the total building stock in Liège, representing approximately 52,280 buildings. As shown in Figure 1, 30% of this stock was built before 1900, and a further 23% between 1900 and 1918, prior to the adoption of “sliding wall” or “double wall” construction techniques. These buildings therefore represent a significant share of the residential stock. Most are poorly insulated and will require energy retrofit by 2050 to meet European carbon neutrality targets.

Regarding the constitution of the corpus, the selected case studies encompass the main building materials employed from the late medieval period through to the early 20th century. Among lithic materials: local carboniferous sandstone, Mosan limestone, Maastricht tuffeau, and Petit granit, the latter used predominantly during the 19th century; among timber materials: oak; and among architectural ceramics: traditional solid brick. Depending on the period, either lime mortar or cement mortar was used as a binding agent. The buildings under study further represent a range of private civil building typologies and constructive techniques characteristic of the urban landscape of Liège throughout the period under consideration.

According to the literature on construction techniques [68,69], traditional historic residential buildings are largely built with timber-framed elements integrated into the vertical walls, floors, and roof structures. Until the late 19th century, structural timber was predominantly made from hardwood species, with timber-to-timber joints. The structural

system relies primarily on load-bearing walls supporting the floor and roof assemblies. These walls consist either of a timber frame infilled with wattle-and-daub or brick, from the 17th and 18th centuries onward, or of brick or stone masonry bonded with lime mortar. The foundations as well as the wall bases are typically built of stone—most notably Mosan limestone and Belgian blue limestone. Cellar floors are generally formed as single vaults, built in stone or brick, or as fully vaulted brick floor systems with wood or steel beams. The main interior coatings are stone and wood for floors, as well as lime plasters for walls and ceilings. Some decorative stones, such as local marbles, are used for chimneys and window shelves. Cement tiles will appear later, at the end of the 19th century. Moreover, buildings built during the second half of the 19th century also feature steel beams and larger glazed surfaces.

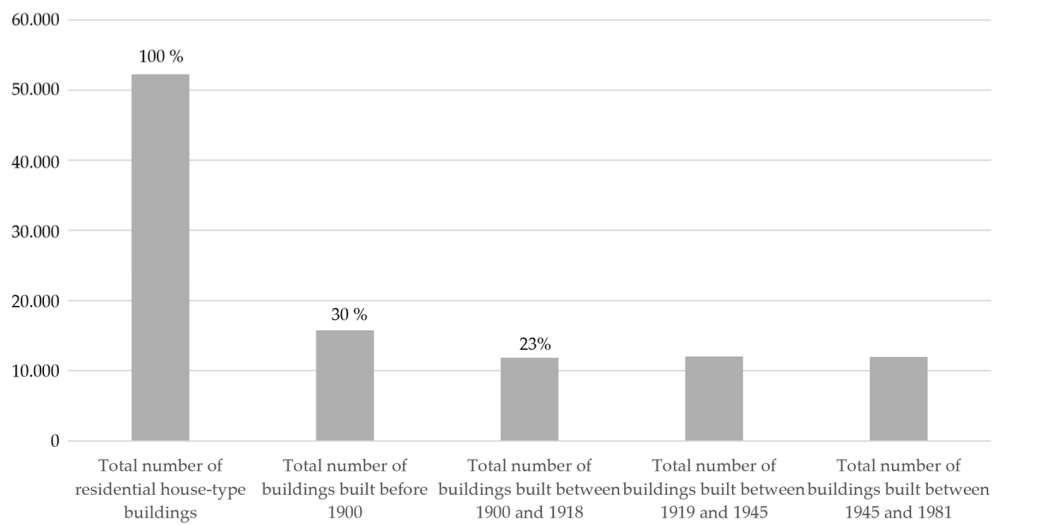


Figure 1. Liège residential house-type building stock distribution by construction period based on Statbel statistical housing data. © S. Trachte.

Table 1. Description of the architectural, structural, and material features of the selected case studies, along with the heritage elements specified in the classification orders for Cases 01, 02, and 03.

Case Study	Architectural, Occupancy, Structural, and Constructive Characteristics and Listed Elements
Case 01  Two listed houses from 13th, 14th, and 16th c. Facade dimensions: 26 × 8 m Floor area: 278 m²	Architectural characteristics Infirmary erected in 14th c., with two storeys and a rectangular two-cell plan, and built primarily from Mosan limestone blocks. Rear elevation facing the courtyard retaining medieval remains; mid-19th-c. alterations, including partial one-storey raising, extension by one bay, and reconstruction of the street façade into two independent elevations. Accordingly, 19th c. works mainly in brick with structural stone elements (base course, doorway, and window openings). Occupancy Previously dedicated to care functions, including infirmaries and dormitories, they are currently unoccupied. Structural system Combination between stone/brick load-bearing and timber framing walls and wood-framed floor and roof. Main materials Brick masonry, Mosan limestone, Maastricht tuffeau, and wood (mainly hardwood such as oak). Listed elements The entire building is listed.

Table 1. Cont.

Case Study	Architectural, Occupancy, Structural, and Constructive Characteristics and Listed Elements
Case 02  Fortified house from 16th c. Facade dimensions: 16 × 8 m Floor area: around 190 m²	Architectural characteristics Detached fortified house dated 1512, located at the end of a paved courtyard; based on a rectangular plan with two storeys. Main south-facing façade with two large bays; crossed windows preserved only on the upper floor. Turret present on the southwest corner. Gable roof covered with tiles. Occupancy Residential occupancy for the main part of the building; currently unoccupied. Structural system Brick load-bearing wall (facade and interiors) and wood-framed floor and roof. Main materials Brick masonry, Mosan limestone, and wood (mainly hardwood such as oak). Listed elements All facades are listed, including the turret.
Case 03  Mansion/residence dating from 16th c. Facade dimensions: 11 × 10 m Floor area: 159 m²	Architectural characteristics Building dating from 16th to 20th c.; originally 16th c. timber-framed structure and heavily modified in late 17th c. (partial reconstruction and petrification of the timber frame). Front façade (likely late 18th c.) with three storeys and five bays, combining Meuse limestone structural elements with brick masonry; rear façade (17th c.) using the same materials but with a different bay rhythm. Gable end characterized by a timber frame with brick infill. Occupancy Residential occupancy for the main part of the building. Structural system Brick load-bearing walls, timber framing walls, and wood-framed floor and roof. Main materials Brick masonry, Mosan limestone, and wood (mainly hardwood such as oak). Listed elements Front and rear facades, half-timbered gable wall, roof, and entrance porch are listed.
Case 04  Building from 13th c. Facade dimensions: 39 × 15 m Floor area: 152 m²	Architectural characteristics Priory in 13th c.; military hospital in 18th c.; military barracks in 19th c.; educational facility occupied since early 21st c. Buildings belonging to the former conventional structures, likely dating from 14th c.; four levels organized into seven bays; major alterations in 17th or 18th c. Ground-floor façade in limestone masonry; upper storeys in fired-clay brick Occupancy First religious, then military, and finally, educational. Structural system Combination between stone/brick load-bearing wall and wood-framed floor and roof. Main materials Brick masonry, Mosan limestone (corner quoins, window surrounds, sills, stringcourses, and pediment), Maastricht tuffeau (vaults in the chapter house), and wood (mainly hardwood such as oak).

Table 1. Cont.

Case Study	Architectural, Occupancy, Structural, and Constructive Characteristics and Listed Elements
Case 05  Bourgeois-type house from 19th c. Facade dimensions: 8 × 13 m Floor area: 59 m²	Architectural characteristics Built in 1895; minor alterations in 1922 (ground-floor openings on main façade) and spatial reorganization in the 1960s–1970s. Façades in brick masonry coated with brick-colored cement render, with Meuse limestone elements and decorative features. Front façade organized into three equal bays with a door and large openings. Projecting cornice supported by painted wooden brackets. Occupancy Residential Structural system Brick load-bearing wall and wood-framed floor and roof. Main materials Brick masonry, Mosan limestone, and wood (mainly softwood such as spruce).
Case 06  Military building from late 19th c. Facade dimensions: 25 × 11 m Floor area: 198 m²	Architectural characteristics Built in 1898; intended for military use; very few alterations; retains materials and construction systems characteristic of late 19th c. practices. Brick masonry with stone architectural elements and cast-iron columns and beams on the ground floor, structuring the openings. Modifications limited to changes in façade openings, replacement of window frames and doors, and interior refurbishments. Occupancy Previously used for military purposes; currently unoccupied, with a housing rehabilitation project underway. Structural system Combination between brick load-bearing wall and cast-iron structures. Main materials Brick masonry, Mosan limestone (plinth, sills, corner quoins), Belgian blue stone, and cast-iron structure.

The case studies are situated in the old districts of the center of the city of Liège and belong either to private owners (Cases 02, 03, and 05) or to public institutions, including the University of Liège (Case 04), the Walloon Heritage Administration (Case 01), and the social housing company Le Logis Social de Liège (Case 06). They provide an overview of the construction history of the city of Liège as well as the evolution of buildings materials and technologies, spanning from buildings of the 13th and 14th centuries to bourgeois houses built at the end of the 19th century.

Cases 01, 02, and 03 are listed as heritage monuments. Case 01 consists of two houses, featuring numerous remains from the 13th, 14th, and 16th centuries. Case 02 is a fortified house from the 16th century. It is a detached building that has not been restored and therefore remains largely unaltered. Case 03 is a listed building owned by a private individual. Built in timber frames in 1509, it underwent several extensions using different construction techniques between the 17th and 19th centuries [70]. Cases 04, 05, and 06 are not listed; however, they are representative of the residential architecture of Liège and of 18th- and 19th-century construction techniques. Case 04 is a brick-and-limestone building constructed in the 18th century and altered in the 19th century. Although originally intended for military use, it displays a distinct Meuse-region character and employs materials and construction systems typical of contemporary residential architecture. Case 05 is a terraced bourgeois house built in 1895 and slightly modified in 1922, representative of late 19th- and early 20th-century urban housing. Case 06, built in 1898, was also designed

for military use but has undergone a few alterations. It exemplifies late 19th-century construction practices, combining traditional materials with industrial ones, such as cast iron. Table 1 summarizes the principal architectural, structural, and material characteristics of the selected case studies.

2.3. Research Steps

The research project was structured around five distinct and complementary steps as illustrated in Figure 2.

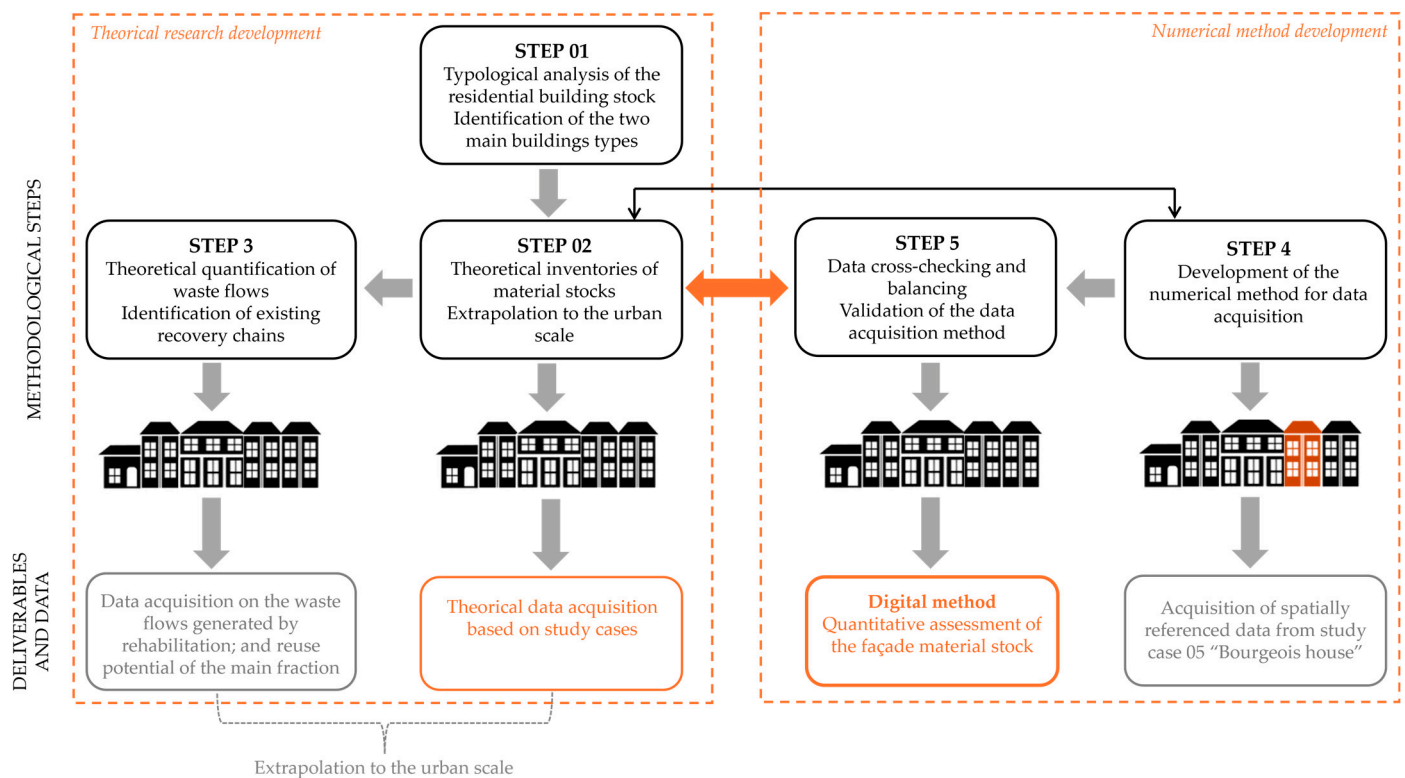


Figure 2. The five main research steps of the project URMIBALI. © S. Trachte.

2.3.1. Typological Analysis and Identification of Main Building Archetypes

The first research step was a typological analysis of the traditional residential building stock in Liège. This study relied on a historical analysis of the geographical, economic, and political contexts that have shaped the development of Liège. It was conducted through the analysis of specialized studies and archival sources, with the aim of defining building archetypes in terms of use, dimensions, spatial organization, and construction techniques. Although it also considers the period from the Middle Ages to the 17th century, from which a portion of the building fabric remains, the study focuses mainly on two key periods: the first spanning the late 17th to the 19th century, and the second covering the late 19th to the early 20th century. The first spans from the 1691 bombardment of the city by the armies of Louis XIV to the major public works of the first half of the 19th century, which profoundly reshaped the urban landscape [71]. The second covers the second half of the 19th century, a period of major urban transformation driven by Liège's economic prosperity [72] and the first buildings regulations [73,74], with a focus on sanitation, urban improvement, and advances in mobility [68].

Despite the overlapping and progressive modifications of the construction techniques, two main archetypes were identified: (1) the urban house, which emerged from the medieval city intramuros parceling, characterized by a dense and narrow plot and influenced

by the Mosan style; (2) the bourgeois terraced house, built on more spacious plots along wider streets, reflecting French architectural influences (Figure 3). These two archetypes served as a basis for selecting the case studies.



Figure 3. Evolution of house types in Liège, from the 17th to the early 20th century. © A. Romboux and O. Noël.

2.3.2. Theoretical Quantitative Inventories of Material Deposits in the Six Case Studies

The second step focused on a theoretical, quantitative inventory of material deposits, developed from the six case studies. The objective was to better identify the type, nature, dimensions, and quantities of materials used in traditional residential buildings, as well as how these materials were implemented and assembled. In addition to providing new knowledge, currently absent from Walloon databases, on the materials used in these specific residential buildings stock, these inventories have served as a basis for developing and validating the data acquired through the digital method.

Data collection for the case studies was made possible through graphic and iconographic materials provided by the building owners. These were complemented by photographic surveys and, in some cases, by digital techniques such as photogrammetry and 3D scanning. These tools were primarily used to identify the nature of the materials and to collect data on their surfaces (Figure 4).



Figure 4. Case study 01: first-floor scan captured by the NavVis system, showing a half-timbered wall with brick infill. © Research lab Diva.

The analysis primarily focused on envelope components (façade, roof and slab), internal partition walls and floors, while excluding building services (lighting, heat and hot water production and emission. . .), external and internal joinery, interior decoration elements such as fireplace, stucco, or wood paneling. Except for external joinery, these elements are generally preserved during rehabilitation works, including in unlisted buildings. Furthermore, the materials they comprise, mainly brick, natural stone, lime plaster, and wood, represent only a small proportion of the building's total material stock.

The first step consisted of measuring the surfaces of the building's external walls (façades and roof) and internal elements (partition walls, floors, and slabs). Each wall was measured using the available graphic and iconographic documentation, distinguishing solid surfaces from voids such as door and window openings, as well as specific architectural elements such as stone or wooden lintel, stone threshold, and windowsills or wooden cornice. Table 2 presents, as an example, the measures taken on the facade wall of the ground floor of Case 05.

Table 2. Measurement of the façade wall on the ground floor for Case 05. The openings (windows and doors) and architectural elements are carved out of the façade surface. Given the shape of the bay frames, these were calculated directly via the Software Autodesk AutoCAD 2025.

Designation	Piece	Width [m]	Height [m]	Surface [m ²]	Total Surface [m ²]
Façade wall	1	7.92	3.06	24.24	7.25
Windows	−2	1.11	2.52	−5.59	
Door	−1	1.60	3.24	−5.18	
Stone framing—windows	−2	/	/	−3.98	
Stone framing—door	−1	/	/	−2.23	

As presented in Table 3, the second step consisted of the decomposition of each wall into three main layers (internal finishing, structural, external finishing) and sublayers. This decomposition relied on the decomposition method proposed by the FEDER BBSM research project [38,75]. Material used in the sublayers was assigned a percentage, enabling the estimation of its quantity within the same layer thickness. For example, in a 36 cm thick brick masonry wall, mortar accounts for approximately 10% of the volume and bricks for 90%. Similarly, in a roof structure composed of 7 cm thick wooden rafters, the rafters represent around 20% of the volume, while the air gap accounts for the remaining 80%.

Table 3. Decomposition method for building components of Case 05: façade wall of the ground floor.

Component	Layers	Layer Description	Layer Thickness	Sublayers	Materials	Proportion in the Layer
Front façade Ground floor Fa Fr Gf	Li	Internal finishing	0.03	1	Plaster coating	1
	Ls	Structural	0.36	2	Brick masonry	0.9
				3	Lime mortar	0.1
	Le	External finishing	/	4	/	/

For case studies constructed after 1830, façade components, particularly solid brick masonry, were further analyzed by floor level, as per historical regulations [73,74], indicating that wall thickness varies according to building height and number of storeys (Table 4). These thickness values were subsequently verified and validated in the field through numerous case studies [14,76,77] used by the authors in previous research. For case studies built before 1830, the thickness of the facade walls was measured on site, floor by floor.

Table 4. Façade wall thickness according to floor level, based on requirements of the building regulations of the City of Liège (1839 and 1879).

Front Façade	Basement	Ground Floor	First Floor	Second and Attic Floor
Thickness of the wall according to the floor level	48 to 60 cm	36 to 48 cm	36 cm	24 cm

For each identified material, one of two statuses was assigned: original material (implemented during the construction of the building) and contemporary material (implemented more recently in the building). The quantities of each material were then calculated based on *Material density*, *Wall surface area*, *Layer thickness*, and the *Material proportion within the layers*, as presented in Table 5, based on the following formulas:

Material quantity in mass [kg]

$\text{Material density} \times \text{Wall surface area} \times \text{Layer thickness} \times \text{Material proportion in the layer}$

Quantity in volume [m³]

$\text{Material surface area} \times \text{Layer thickness} \times \text{Material proportion in the layer}$

Table 5. Materials quantities estimation method—front façade of Case 05.

Material	Material Status	Density kg/m ³	Surface Area m ²	Thickness m	Proportion in the Layer
Plaster coating	Original	1500	18	0.05	1
Brick masonry	Original	1800	18	0.48	0.9
Lime mortar	Original	1600	18	0.48	0.1
/	/	/	/	/	/

Finally, the total material stock was established by summing the quantities of each type of material identified in the walls.

This decomposition method enables results to be expressed both in mass (kg) and volume (m³), at the level of individual materials (brick, structural wood...), individual walls (roof, slab, façade...), and the whole building.

In addition, to support the estimation of waste flows generated by the rehabilitation scenarios, each material was characterized in terms of waste according to four criteria (Table 6).

Table 6. Waste characterization—front façade of Case 05.

Material	Material Nature	Waste Fraction	Waste Class	Eurocode
Plaster coating	Gypsum/Lime	Plaster	2	17 08 02
Brick masonry	Clay brick	Inert brick	3	17 01 02
Lime mortar	Lime	Mortar	2	17 05 04
/	/	/	/	/

The results of these inventories were extrapolated, for some case studies, to the urban scale of the city of Liège, enabling the estimation of buildings' material deposits, which could potentially result from rehabilitation operations and be reused or recycled by 2050 (cf. Section 2.3.5).

2.3.3. Descriptive Sheets of the Main Buildings Materials Encountered

The most encountered materials in the case studies, such as brick, roof tiles, timber framing, and natural stone, were then documented in descriptive sheets. These sheets follow the structure outlined in the Interreg FCRBE project [78] and detail the type, species, and nature of each material (homogeneous or composite), as well as its dimensions, color, texture, state of conservation, quantity, and location within the case study. They also assess the reversibility of material assembly within the wall using four criteria (Table 7) and the reuse potential based on five criteria (Table 8). These two criteria were elaborated relying on the literature [79,80] and previous research works [81]. They were evaluated using a qualitative approach based on a graphical scale ranging from green (very good score) to red (very poor score), given that no quantitative method currently exists in Europe for assessing reuse potential. This approach is quite consistent with methods used in other research projects such as H2020 BAMB [82] and FEDER BBSM.

Table 7. Assessment of the reversibility of various building materials assembly.

Type of Assembly	Reversibility	Simplicity of Disassembly	Speed of Disassembly	Ease of Handling
Connection by lime mortar	Reversible with small damages	Simple	Rather slow disassembly	Very easy for brick and small elements
Connection by cement mortar	Non-reversible	/	/	/
Glued or coated	Non-reversible	/	/	/
Mechanical connection with screws	Reversible with small damages	Simple	Speedy, but time required for connection removal	Very easy in general, but dependent on the material
Mechanical connection with nails and staples	Reversible with damages	Simple		
Free-standing, without connection	Reversible	Very simple	Very speedy	

The assessment uses a qualitative approach based on a four-color graphic scale, ranging from green (reversible assembly, very simple, very speedy and very easy of handling) to red (non-reversible assembly).

Table 8. Reuse potential—examples for some existing materials and elements in case studies.

Material or Element	Nature	Lifetime (Year)	Robustness to Disassembly	Size, Mass, and Modularity	Existence of Reuse Sector
Brick	Homogeneous	>100	Very robust	Small size, light, modular	Yes
Wood beam	Homogeneous	>100	Robust	Large size, heavy, modular	Yes
Wood lathing	Homogeneous	60 to 120	Not robust	Small size, light, modular	No
Sill, natural stone	Homogeneous	>100	Very robust	Large size, very heavy, not modular	Yes

The assessment uses a qualitative approach based on a four-color graphic scale, ranging from green (homogeneous, long lifetime, very robust, compact, lightweight, modular, and with an established reuse sector) to red (composite, short lifetime, not robust, bulky, very heavy, non-modular, and lacking a reuse sector).

Additionally, information on technical specifications, conventional end-of-life treatments, and key considerations for material reuse was also provided.

2.3.4. Rehabilitation Scenarios and Theoretical Accounting of the Waste Flows

The fourth step aimed to quantify and anticipate the flows of waste generated by traditional historic residential buildings' energy rehabilitation, considered as potential resources for reuse in an urban mining approach. The three rehabilitation scenarios were

developed based on the reflexive rehabilitation framework, the decision-making tools, and the strategies provided by the P-Renewal research project [83,84] and aligned with the standard EN 16883 on conservation and energy renovation performance of cultural heritage [85]. Indeed, the authors considered that, despite the absence of formal classification, Cases 04, 05, and 06 also exhibit specific heritage features to be preserved.

First, a diagnostic of the state of conservation and an assessment of the energy performance of each envelope wall were carried out to identify rehabilitation and insulation needs. For the assessment of energy performance, the existing walls were modeled in the tool “TOTEM” (Tool to Optimize the Total Environmental impact of Materials) [86], a Belgian decision-support software program that enables the comparison of materials, constructive systems, and renovation scenarios based on their energy performance and environmental impact. For instance, the existing envelope walls modeled in TOTEM and their U-value estimation, for Case Study 05, are illustrated in Table 9.

Table 9. Cases 03 and 05: description of wall composition, state of conservation and U-value estimation.

	Front Façade	Rear Façade	Pitched Roof	Windows	Slab on Cellar
Case 03					
Description	Brick masonry with lime mortar. Presence of natural stone.	Brick masonry with lime mortar. Presence of natural stone.	Wooden structure (oak) of five trusses and rafters Wooden battens Slate	Wood frames Single glazing	Wooden floor on joists (ground-supported) Concrete slab beneath the floor in some areas
State of conservation	Listed façade with normal aging state, without degradations.	Listed façade with normal aging state, without degradations.	Listed original wood frame in good condition (some woods show wear and deformation), lack of watertightness	Single glazing, window frames in poor condition, lack of airtightness	Floor with normal aging state, without degradation
U-value (W/m ² K)	1.26 <i>For a thickness of 0.38 m</i>	1.26 <i>For a thickness of 0.38 m</i>	4.5	5.38	2.63
Case 05					
Description	Brick masonry with lime mortar. Presence of natural stone.	Brick masonry with lime mortar.	Wooden structure and rafters Rain-proof layer Wooden lathing Clay roof tiles	Wood frames Simple glazing	Vaulted brick floors. Leveling layer with lime mortar and sand. Cement tile flooring
State of conservation	Façade with normal aging state, without degradation.	Façades frame with small degradations.	Wooden structure and covering in good condition	Single glazing, window frames in poor condition, lack of airtightness	Slab with normal aging state, without degradation
U-value (W/m ² K)	1.30 <i>For a thickness of 0.36 m</i>	1.30 <i>For a thickness of 0.36 m</i>	4.5	5.38	1.00

In addition, a heritage significance assessment was carried out. For unlisted case studies, the evaluation was based on four criteria (authenticity, integrity, rarity, and representativeness) and eleven indicators proposed by the assessment method of the Walloon Heritage Administration [87]. These data were collected and analyzed on site, then summarized in a table using a qualitative evaluation system based on “+” and “−” scores for each heritage interest. For the listed case studies, the assessment considered the various elements identified in the official classification order.

Based on these three analyses, various energy improvement solutions were identified and categorized wall by wall. Then, three rehabilitation scenarios or strategies were proposed, following the same principles as the strategies of the P-Renewal project on the envelope. For unlisted case studies, the rehabilitation strategies pursue more ambitious energy performance improvements and allow greater flexibility regarding demolition interventions. For listed case studies, the strategies seek to preserve the protected elements as much as possible while accommodating necessary interventions, including the partial replacement of structural roof components. For all case studies, the main objective is to enhance comfort and living conditions while maintaining the buildings’ heritage significance and distinctive features to the greatest extent possible. The improvement solutions and scenarios were selected based on both the literature [88–90] and previous research projects conducted by S. Trachte [83,91] on energy rehabilitation of existing buildings, analysis of exemplary case studies [92–94], and current Belgian renovation practices [94]. The insulation solutions preferably integrate biobased insulation produced in Wallonia and comply with the Walloon EPB requirements in terms of U-value. For instance, the three rehabilitation scenarios for Cases 03 and 05 are illustrated in Table 10.

Table 10. Rehabilitation scenarios for Cases 03 and 05, by walls.

Walls	Scenario 01	Scenario 02	Scenario 03
Case 03			
Front façade	No works	Removal of external finishes Internal insulation (spandrel height) and new finishes	Removal of external finishes Internal insulation (full height) and new finishes
Rear façade	No works	Removal of external finishes Internal insulation (spandrel height) and new finishes	Removal of external finishes Internal insulation (full height) and new finishes
East façade	Removal of external finishes Internal insulation (full height) and new finishes	Removal of external finishes Internal insulation (full height) and new finishes	Removal of external finishes Internal insulation (full height) and new finishes
Pitched roof	Removal of the roof covering (reused). Removal of the wooden lathing Insulation between rafters, with vapor barrier and new layer, rain-barrier membrane, and internal finishes	Removal of the roof covering and wooden lathing. Removal of the wooden structure (30%) Insulation between rafters with vapor barrier and new covering, lathing, rain-barrier membrane, and internal finishes	Removal of the roof covering and wooden lathing. Removal of the wooden structure (50%) External insulation between the wooden frame and the new covering, lathing, rain-barrier membrane, and internal finishes
Windows	Replacement of existing frames with high-performance double-glazed wood frames	Replacement of existing frames with high-performance double-glazed wood frames	Replacement of existing frames with high-performance double-glazed wood frames
Slab (on ground)	No works	No works	Removal of the wood floor (reused) Insulation between joists + vapor barrier

Table 10. Cont.

Walls	Scenario 01	Scenario 02	Scenario 03
Case 05			
Front Façade	No works	No Works	Removal of internal finishing and internal insulation (spandrel height) with new finishes
Rear Façade	Removal of external finishes External insulation and new finishes	Removal of external finishes Window bay enlargement (30%) External insulation and new finishes	Complete demolition of the rear façade and new façade with wood frame and finishes
Pitched Roof	Removal of the roof covering (reused). Removal of the wooden lathing Insulation between rafters, with vapor barrier and new layer, rain-barrier membrane, and internal finishes	Removal of the roof covering and wooden lathing. Removal of the wooden structure (30%) Insulation between rafters with vapor barrier and new covering, lathing, rain-barrier membrane, and internal finishes	Removal of the roof covering and wooden lathing. Removal of the wooden structure (50%) External insulation between the wooden frame and the new covering, lathing, rain-barrier membrane, and internal finishes
Windows	Replacement of existing frames with high-performance double-glazed wood frames	Replacement of existing frames with high-performance double-glazed wood frames	Replacement of existing frames with high-performance double-glazed wood frames
Slab (on cellar)	No works	No works	Removal of floor finishes and leveling mortar and rigid insulation with new dry screed board

The wall decomposition method, with three distinct layers, enables a precise analysis of rehabilitation interventions, facilitating the application of different levels of demolition to each layer.

Finally, the main waste flows generated by the renovation scenarios were then calculated, extrapolated at the urban scale, and analyzed in relation to available reuse and recycling systems (collect, reuse, and recycling) near the city of Liège.

2.3.5. Extrapolation of the Results to the Urban Scale (Existing Deposit and Waste Flows)

The extrapolation of existing material stocks and rehabilitation-induced waste flows at the urban scale was carried out based on Case Study 05. This methodological choice is based on the prevalence of this house type within Liège's traditional historic residential building stock, as well as the easier correlation between their dimensional and volumetric characteristics and the cadastral dataset. This extrapolation is consistent with previous work conducted within the framework of the B³RetroTool [95] (Brussels) and P-Renewal [76] (Wallonia) projects, as well as the COZEB [96] studies in Wallonia. It was developed through a two-step methodological approach.

The first step involved identifying and quantifying bourgeois terraced houses within a cadastral dataset provided by the Federal Public Service Finance (Data Delivery Division) [97], which initially comprised 38,958 parcels. A series of successive filters based on property type, construction period, number of storeys, floor area, and degree of shared ownership was applied to progressively refine the dataset and isolate buildings corresponding to this house type. The selection first retained parcels classified as houses or mixed-use buildings combining residential and commercial functions. It then focused on buildings constructed between 1850 and 1918. The dataset was further refined by limiting the number of storeys to two or three and restricting the building footprint and floor area to between 40 and 200 m². Finally, only parcels with one or two shared party walls were retained. This step-by-step filtering process reduced the dataset to 11,130 parcels. Their distribution by

construction period reveals a strong concentration in the late nineteenth and early 20th centuries, with the largest proportion dating from 1900 to 1918.

In the second step, the extrapolation was performed using a more restrictive subset to ensure consistency with Case 05. Buildings constructed between 1875 and 1899, with two façades and three storeys, were retained, resulting in 1347 parcels (Table 11). Although this subset represents only about 12% of all identified bourgeois houses and 3% of the total cadastral dataset, it provides a sufficiently coherent basis for a first estimation of potential material stocks and rehabilitation-induced waste flows. The aim is not to produce a precise value but to outline a consistent order of potential flows derived from the specific characteristics of Case 05.

Table 11. Identification of cadastral parcels corresponding to the bourgeois house type based on cadastral matrix data. The gray area represents the 11,130 parcels classified as bourgeois houses.

Built Area		40 < m ² < 85			
Construction period		bef. 1850	1850–1874	1875–1899	1900–1918
Nb of facades	Nb of floors				aft. 1918
2 facades	+2			3755 parcels	
	+3		1145 parcels	Case 05 1347 parcels	5452 parcels
3 facades	+2		139 parcels	274 parcels	365 parcels
	+3				

The material and waste quantities identified in Case 05 were then extrapolated to this homogeneous group of parcels, enabling an initial assessment of the materials available in existing bourgeois terraced houses in Liège and of the waste volumes their rehabilitation could generate by 2050. These results also underline the need to evaluate whether current treatment and recovery systems should be reinforced, to anticipate the logistical demands of sorting and removal, and to consider the impacts associated with transporting materials between urban rehabilitation sites and peripheral processing facilities.

2.3.6. Development of the Digital Method for Rapid Data Acquisition

Based on theoretical material deposits inventories, this step aims to establish a digital method for rapidly acquiring qualitative and quantitative data on material deposits in traditional old buildings. This approach combines both digital survey methods and artificial intelligence to enhance data collection, processing, and analysis. It aims to use computer vision models (artificial intelligence) to autonomously detect selected materials from orthophotos generated through photogrammetric surveys and to calculate their corresponding surface areas on the façades of the bourgeois house typology.

“Structure-from-Motion” photogrammetry is used as the primary survey method, motivated by its ability to produce high-resolution and geometrically accurate orthophotos while only requiring consumer-grade photographic equipment [98]. In addition to ensuring sufficient precision for material identification and quantification, the equipment and method selected are consistent with the requirements of AI-based workflows, as the same type of imagery can be used both for model training and for analysis. Furthermore, photographic equipment is widely accessible, relatively low-cost, and easy to use compared to other surveying technologies, which require specialized expertise and significant financial investment (Table 12). Other digital survey methods, such as lasergrammetry, can be applied in large-scale case studies to improve the accuracy of orthoimages, but they demand specialized and costly equipment.

Table 12. Presentation of data-acquisition tools and their specific features.

Type of Tools	Speed, Precision, and Cost	Raw Data Collected	Data Processed	Information Obtained
Image sensor Drone and camera	Medium speed High precision Low cost	Images Videos	High-precision mesh, orthophotos, and a 3D model.	A precise view of the materials used and an understanding of the wall's overall relief and texture.
Terrestrial LiDAR sensor Leica BLK	Low speed High precision Medium cost	High-precision point cloud	Image showing reflected-light intensity and sectional views within the point cloud for generating plans and cross-sections.	Visualization of the materials present and production of plans and sections for potential quantity surveys.
Image and SLAM sensor NAVVIS VLX	High speed Medium precision High cost	Point cloud 360° panoramic images	Color or intensity images, model navigation, and generation of sections and cross-sections.	Lower-accuracy visualization of materials and assemblies, and production of plans and sections for potential quantity surveys.

The decision to develop and test this digital method on the terraced bourgeois house typology is based on its prevalence in Liège, making it both a representative and strategically relevant case study. This choice also meets the requirements of AI-based learning processes, which depend on the availability of sufficiently large and coherent datasets for effective training. By focusing on a well-defined typology, the model can learn and detect distinctive architectural features more effectively, such as doors, windows, the division of openings and proportions (height-to-width ratios), as well as recurring façade compositions. This typological consistency facilitates the detection of architectural elements, the classification of buildings, and the segmentation of materials. As terraced bourgeois houses share similar construction principles, material palettes and façade layouts, this enhances the model's ability to recognize, differentiate and classify materials. The focus on façades is further justified by their accessibility from public space, allowing many façades to be surveyed without prior authorization. In contrast, the inspection of other building-envelope components generally requires either drone-based surveys (for rear façades and roofs) or access to interior spaces (for floor slabs).

The proposed methodology is structured into five main stages (Figure 5): (1) data acquisition for AI training, (2) data processing, (3) model training for material recognition and surface estimation, (4) AI-based predictions, and (5) validation of predicted results.

1. Data collection for AI model training and evaluation

The process begins with the acquisition of training data and the construction of a structured dataset designed to support both model development and evaluation. Three complementary datasets were developed, each serving a specific role within the methodological framework. The first one was acquired for the images to be annotated and to train the AI model to recognize materials, while the two others served to create scaled orthophotos under various conditions to test the model's performance.

The primary dataset consists of façade photographs collected in the Outremeuse and Vennes districts of Liège. The dataset remained consistent with the typological characteristics of the 19th-century bourgeois houses under study. The acquisition was carried out using a Nikon Z6 camera with the following parameters: ISO 400, focal length of 24 mm,

aperture set to $f/8$, and a shutter speed of $1/100$ s, producing images with a resolution of 6048×4032 pixels. In total, 454 façade images were collected and subsequently annotated to constitute the training dataset.

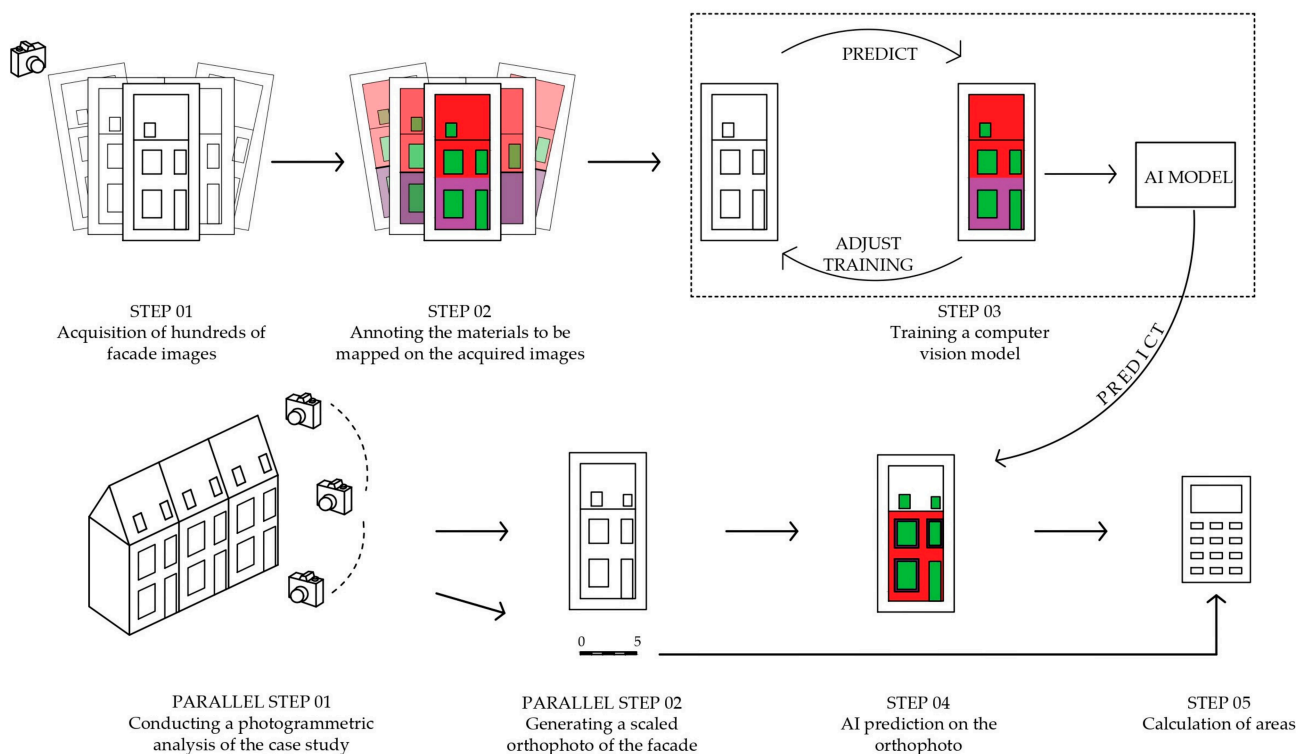


Figure 5. Methodological steps in the development of the digital method for rapid data acquisition. © S. Boutet and O. Noël.

Using the same camera equipment and similar parameters, a second dataset was generated from photogrammetric surveys of selected façades. Due to the dense urban context and the height of the surveyed buildings, a 10 m telescopic pole camera tripod was employed to ensure consistent image overlaps across the entire façade surfaces during the surveys, which is necessary for correct photogrammetric reconstruction. These surveys were used to produce high-resolution orthophotos, which provide geometrically corrected and metrically reliable representations of building surfaces. This dataset is primarily intended for model evaluation, allowing the assessment of the model's ability not only to identify materials but also to quantify their surface areas with precision after training (cf. points 4 and 5).

A third dataset was produced using a fisheye lens on the same Nikon Z6 camera (Tokyo, Japan), allowing wide-area coverage with fewer images while maintaining sufficient overlap for orthophoto generation, thereby exploring an alternative acquisition method. This characteristic is particularly advantageous for photogrammetric processing, as it reduces the number of images required to generate orthophotos while maintaining sufficient coverage and geometric consistency. This approach therefore aims to accelerate the data acquisition process by reducing the need for numerous high-detail photographs while still maintaining the quality required for subsequent analysis. It also offers the opportunity to explore alternative acquisition strategies in terms of efficiency and scalability (cf. steps 4 and 5). Having already proven effective in small, confined spaces, it should significantly improve the data acquisition phase in narrow streets, particularly when capturing hard-to-reach upper sections of buildings [99,100]. It should be noted that fisheye image distortion is corrected during the Structure from Motion and orthophoto generation process.

2. Data processing for AI training

The collected data of the primary dataset is subsequently processed to construct the training dataset. Images are manually annotated for semantic segmentation using specialized online tools (Roboflow Universe), with six predefined classes: glazing/openings, brick, rubble stone, non-relevant elements, cut stone, and wood (Figure 6). These are the predominant materials found on the studied facades and were chosen for an even representation of each class in the dataset.

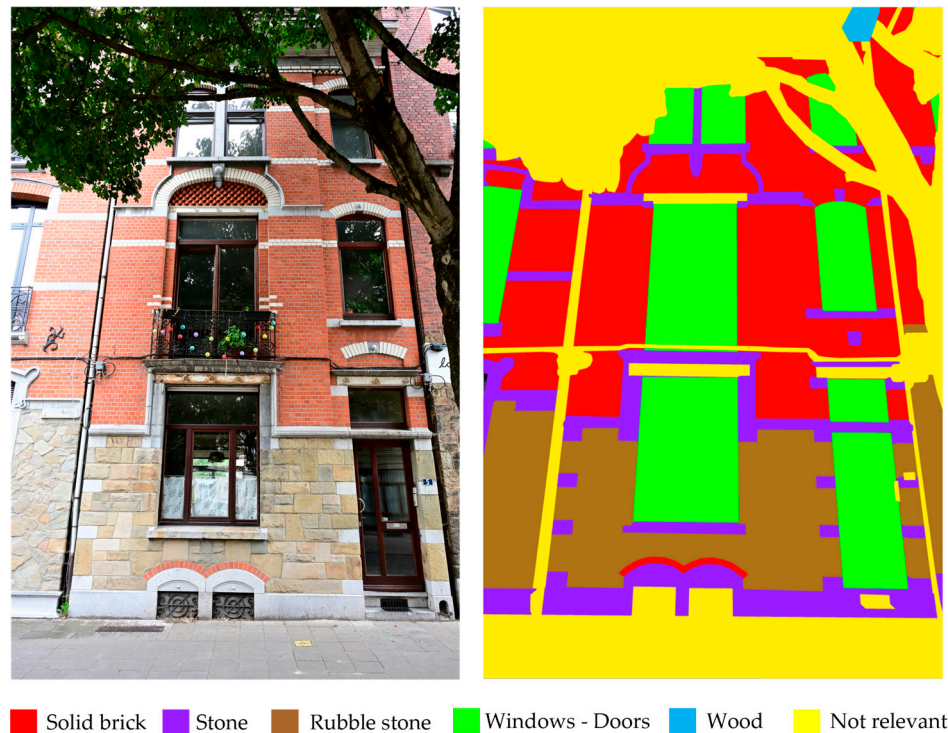


Figure 6. Facade image of the Outremeuse neighborhood annotated using the Roboflow platform. © S. Boutet and O. Noël.

The annotation process was carried out by three annotators who shared the dataset labeling task. To ensure consistency across the dataset, several coordination meetings were held throughout the annotation period to align interpretation rules and reduce inter-annotator variability. A systematic quality control procedure was then applied to detect potential errors or incomplete annotations, with problematic images systematically returned to the annotation stage for correction until full validation was achieved. In total, 426 out of 454 images were retained after this process.

To ensure full coherence of the annotation framework, a final validation step was conducted by a single annotator who reviewed and harmonized the entire dataset. Annotation rules were also strictly defined: shutters were included within the glazing/openings class, while non-relevant façade elements such as vegetation, street furniture, and cars were systematically annotated over the intended target classes as background to avoid ambiguous learning and ensure consistent model supervision. The validated dataset was then partitioned into training, validation, and test subsets. While a distribution of 70%, 20%, and 10%, respectively, is commonly used, there are no fixed optimal ratios. Thus, priority can be assigned to the training and validation subsets to maximize model learning capacity in cases where the dataset size is limited [101]. Under such constraints, the test set may be supplemented or replaced by images originating from external, non-annotated datasets. In

our work, the dataset of 426 images was divided into two sets using an 82%/18% split: a training set (346 images) and a validation set (80 images).

Preprocessing operations, including automatic orientation and resizing to 640 pixels, were then applied to standardize the inputs and fit the model's architecture, while data augmentation techniques, such as horizontal flipping and variations in hue and brightness, were used to increase dataset variability and improve model robustness by creating duplicated variations of the original annotated images. This resulted in an augmented training set consisting of 1038 images (3×346). In addition to expanding the size of the training subset, this step remains crucial in adding variability to the data and serves to improve robustness by simulating changes in lighting, framing, exposure, etc. Due to the structure of the annotation tool we employed, the validation subset was not augmented. The final dataset is then exported in a semantic segmentation format, including images, masks, and class metadata.

3. Training the AI model to recognize materials and calculate surface areas

The AI training phase was then carried out using DeepLabv3+ (ResNet50V2 backbone), a semantic segmentation model chosen for its performance on our dataset and its ability to capture multi-scale information through atrous convolutions. While no benchmarking of segmentation architectures was conducted for this study, both SegFormer and DeepLabV3+ were evaluated during preliminary testing, where the latter achieved better performance. The model was implemented in Google Colab, a cloud-based environment, to allow access to a remote L4 NVIDIA GPU. The model was trained on the prepared dataset to classify the six defined material categories using a DeepLabv3+ architecture with a ResNet50V2 backbone. Training was performed with the Adam optimizer, a fixed learning rate of 1×10^{-4} , a batch size of 8, and SparseCategoricalCrossentropy as the loss function. A maximum of 300 epochs was defined, with early stopping configured with a patience of 20 epochs based on the validation mean IoU. Training stopped after 109 epochs, and the weights from epoch 89, corresponding to the highest validation mean IoU, were retained. Model performance was assessed at the end of each training epoch by computing metrics such as Intersection over Union (IoU (Figure 7) and loss on the validation set, which provided an estimate of prediction accuracy on unseen validation data. When training was completed, the model achieved a mean validation IoU of 0.789. Class-specific IoU values were 0.867 for windows and doors, 0.660 for wood, 0.860 for brick, 0.684 for rubble stone, and 0.732 for stone. It was then deployed to generate predictions on test images to validate training beyond metrics. This stage involved both the visualization and qualitative analysis of the predicted outputs. The original images were systematically compared with their corresponding predicted segmentation masks to assess the accuracy and consistency of material recognition. This visual inspection enabled the identification of potential misclassifications or imprecisions and helped determine whether further refinement of the annotation and training processes was needed. Steps 2 and 3 were repeated until all annotations and training hyperparameters showed the best results. Once results were considered satisfactory and further training did not achieve better performance, the model was deployed for the final stage.

4. AI model predictions and surface verification

In the final stage, scaled orthophotos from datasets 2 and 3 were produced at a spatial resolution of 5 mm/pixel. As the real-world dimensions of each pixel are known, the visible surface area of each material class can be manually derived. However, the trained model is designed to automate this quantification process. To do so, the orthophotos were subsequently downscaled to 640 pixels to match the input requirements of the DeepLabv3+

architecture and then processed by the model. The resulting output segmentation masks were finally upscaled back to the original orthophoto resolution.

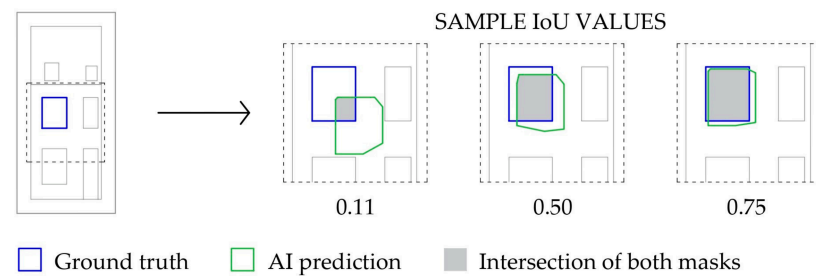


Figure 7. Visualization of the IoU metric. © S. Boutet and O. Noël.

5. For each image, we then calculated the surface area of every detected class.

First, the predicted segmentation mask was loaded, and pixel counts were computed per class, while all material-related pixels were summed to obtain the total visible façade material area, excluding background. Total façade surface was then derived by multiplying this global pixel count by the pixel area defined from the spatial resolution, ensuring a consistent conversion from image pixels to real-world units. The same pixel-to-area conversion was applied to each material class to obtain class-specific surface areas. In parallel, relative proportions were calculated by dividing each class pixel count by the total number of material pixels, producing percentage distributions per façade. Finally, all quantitative results were stored per image and exported as a structured table containing pixel counts, absolute areas in square meters, and percentage values, enabling direct comparison of façade material compositions across case studies (Figure 8).

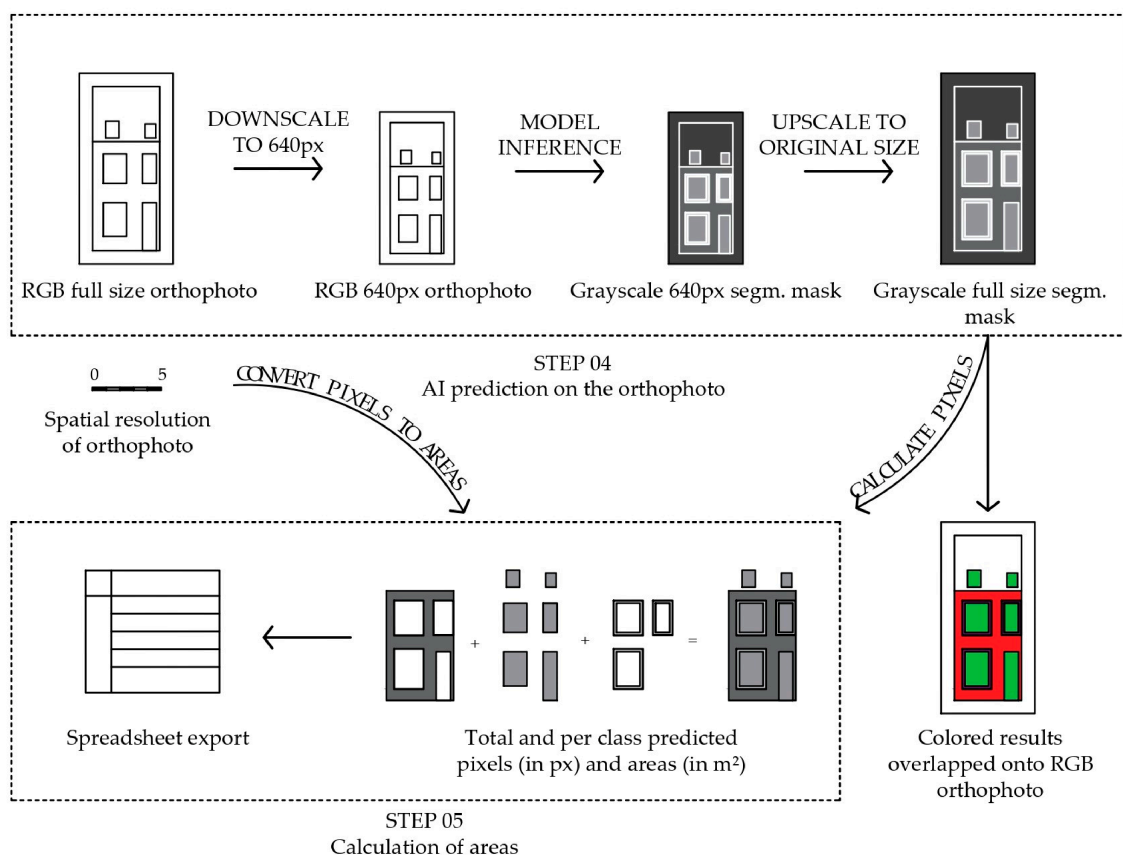


Figure 8. Methodological steps for calculating areas by the AI model. © S. Boutet and O. Noël.

Subsequently, a validation phase was conducted by comparing the AI-derived surface measurements with manually calculated reference values. For each material class, a percentage difference was computed to quantify the deviation between automated and manual estimations. This comparison provided a quantitative assessment of the consistency and accuracy of the model outputs. Overall, this dual evaluation approach, combining qualitative visual analysis and quantitative comparison, offers a comprehensive measure of the model's reliability and supports the identification of potential improvements in the training procedure when necessary.

3. Results

The results presented below focus mainly on the theoretical inventories of existing material deposits, the waste flows estimation, and the data acquired through the developed digital method.

3.1. Inventories of Existing Material Deposits

As presented in Figure 9, theoretical inventories enable a detailed assessment of materials, in mass and volume, by both wall and material type, while also allowing for overall building-scale estimations.

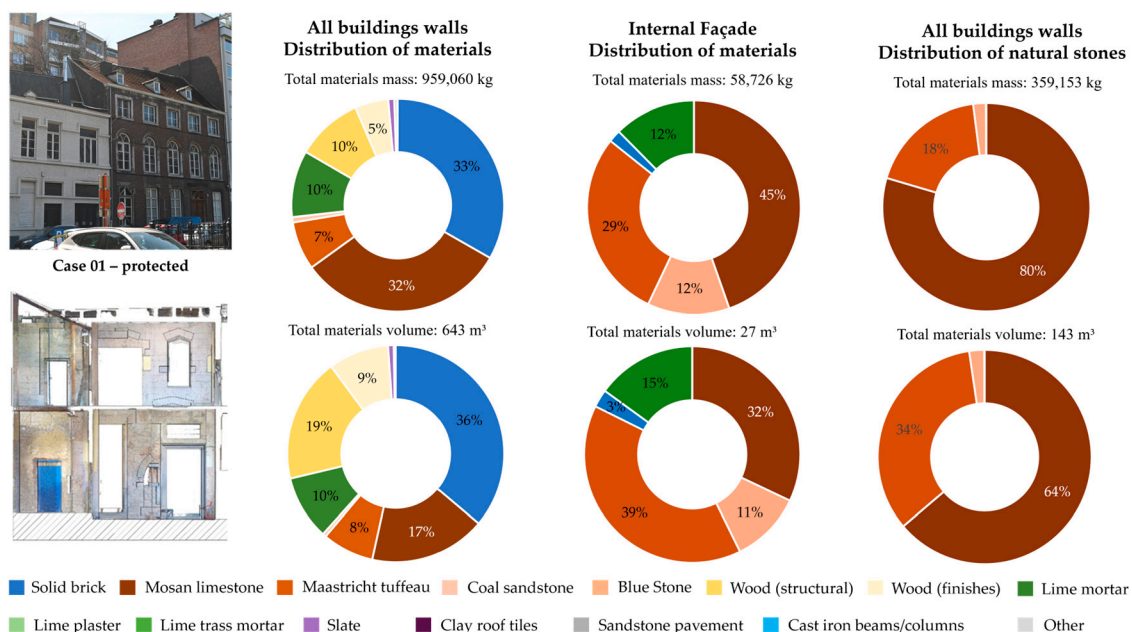


Figure 9. Case 01—Materials distribution for the whole building and for the internal façade, and natural stones distribution of the whole building. Sources: O. Noël and S. Trachte.

The theoretical inventories exhibit some uncertainties due to the lack of comprehensive iconographic documentation and precise data on certain original wall compositions and/or more recent modifications, as well as the exclusion of certain components and materials (See Section 2.3.2). These limitations also do not affect the development of the digital method, which focuses exclusively on the materials of the main exterior façade. Nevertheless, despite these limitations, the results reveal a clear predominance of brick masonry, accounting for more than 30% of the total mass and volume, particularly in the three 18th-century cases (Figure 10).

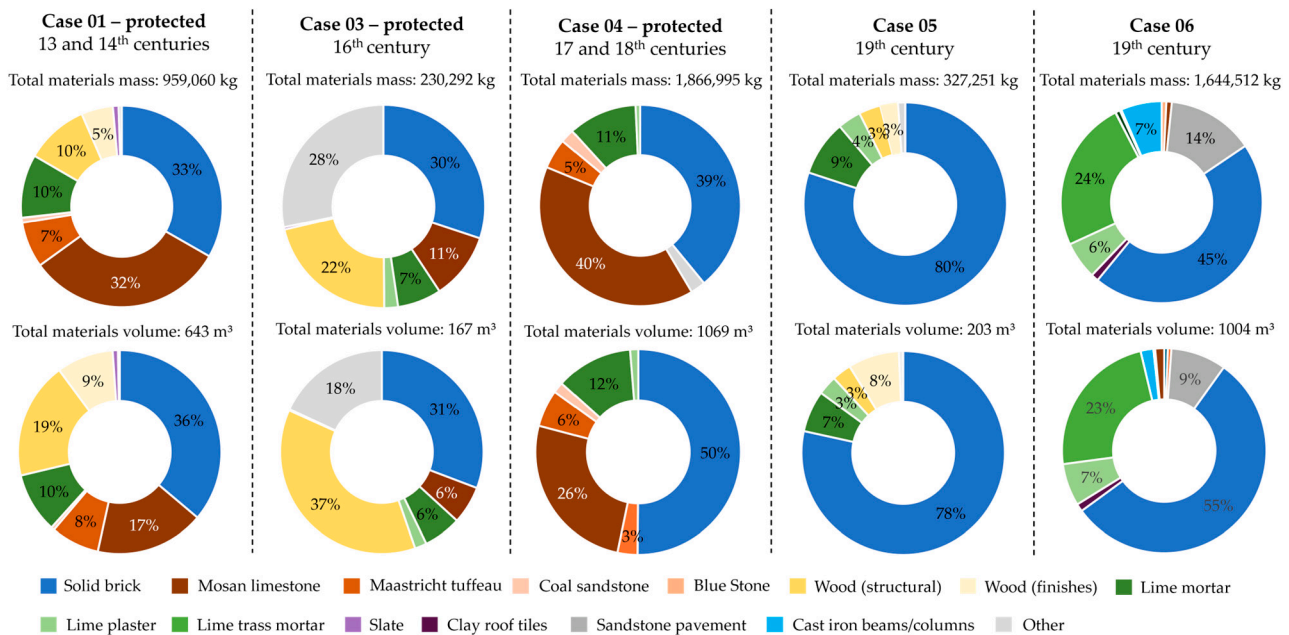


Figure 10. Material deposits, in mass and volume, for Cases 01, 02, 04, 05, and 06. Sources: O. Noël and S. Trachte.

In the cases built prior to the 18th century, the results also highlight the dominant use of natural local stone, either in masonry or as a decorative element. These differences are consistent with the historical evolution of construction techniques. The inventories further indicate that wood—whether used for structural elements or interior finishes—represents a relatively small share of the material stock in both mass and volume. However, in the oldest Cases 01 and 03, it accounts for approximately 15–20% of the total mass and up to 30–35% of the volume.

Finally, they highlight how a specific building's function can influence material use. While the first four cases were residential, the last, originally a military structure for horses, required reinforced load-bearing elements and vaulted floors, resulting in a higher presence of cast iron, steel, and lime filling mortar in the vaulted floor.

3.2. Waste Flow Estimation

Thanks to the wall decomposition method, waste flow can be presented by scenario for the entire building as well as for each envelope wall (Figure 11).

As shown in Figure 12, the estimation of waste flow reveals some variability across case studies and scenarios. In general, given the scale of the work, rehabilitation Scenarios 02 and 03 generate greater amounts of waste, both in terms of mass and volume. This is particularly evident in Cases 03 and 05: in Case 03, waste quantities double between Scenarios 01 and 02, while in Case 05, they triple between Scenarios 01 and 02 and quadruple between Scenarios 02 and 03. In Case 06, the increase in waste quantity is more pronounced between Scenarios 02 and 03.

The proposed scenarios for listed buildings (Case 03) are generally less invasive in terms of demolition and tend to generate mainly windows and finishing waste, such as wood and lime plaster, along with smaller amounts of roof covering. Most wooden elements, such as frames, structural components, and finishes, are sent to energy recovery facilities. However, it would be worthwhile to examine the potential for reusing structural timber from floor and roof frameworks, especially structural timber from 18th and 19th century buildings, since they present a variety of wood species.

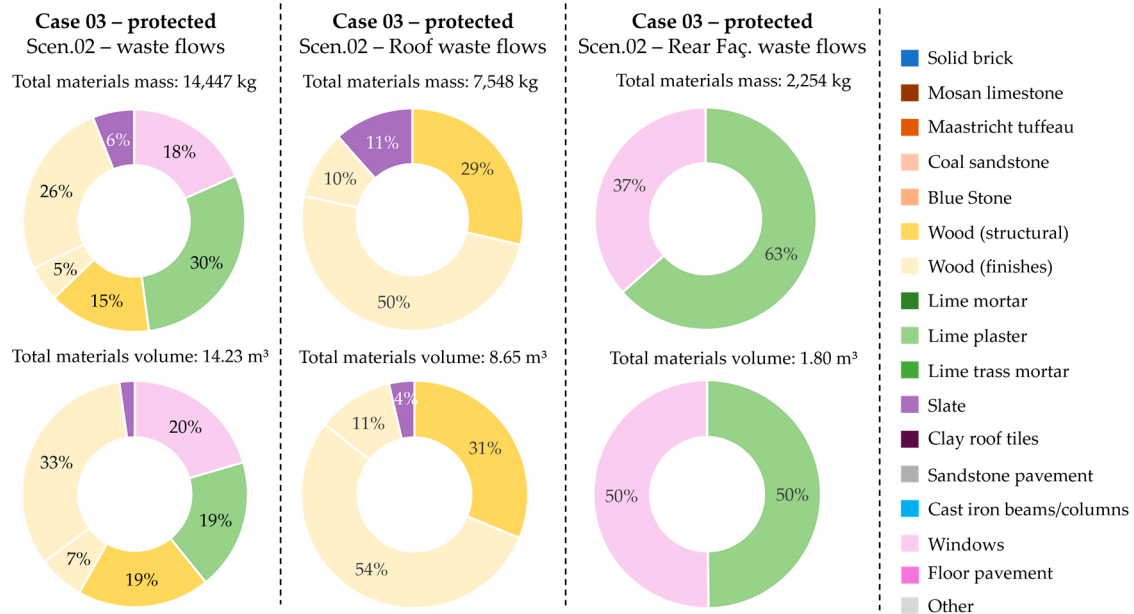


Figure 11. Case 03, energy rehabilitation Scenario 02—waste flows estimation for the entire building, roof, and rear façade. Sources: O. Noël and S. Trachte.

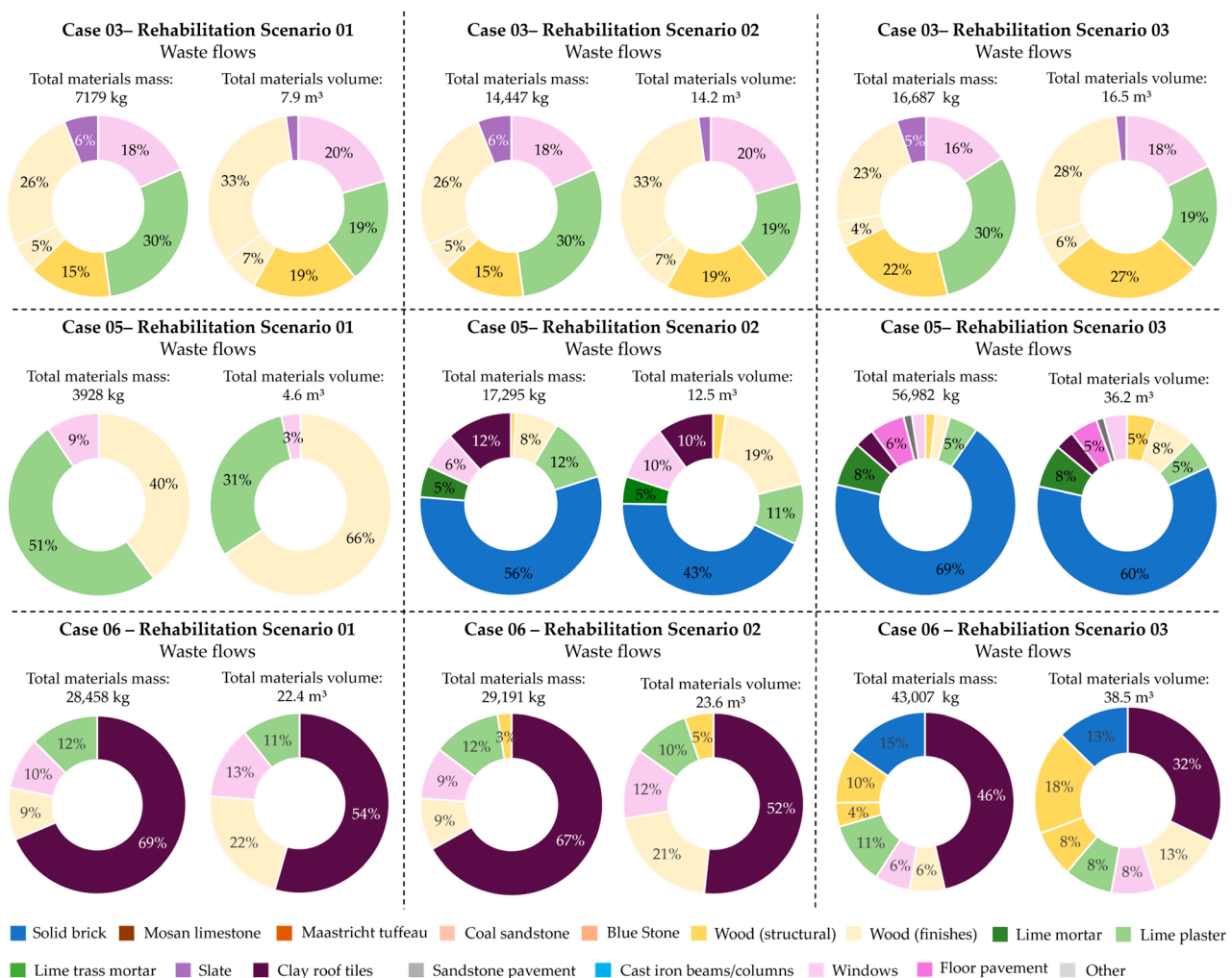


Figure 12. Estimation of waste flow, following the three rehabilitation scenarios, for Cases 03, 05, and 06. Sources: O. Noël and S. Trachte.

In contrast, the scenarios for unlisted buildings produce a large amount of structural waste, including brick masonry in Case 05 and timber roof framing in Case 06. The three scenarios in Case 06 also generate a large volume of roof covering waste due to the extensive area covered with terracotta tiles. Overall, the results for Scenario 1 are quite similar across all case studies in terms of waste type generated, unlike the more contrasting Scenarios 2 and 3. These latter scenarios also produce a more diverse range of waste, with a predominance of inert materials (bricks, clay roof tiles, natural slates). This waste is currently sent to crushing facilities, where it is downcycled and processed into aggregates used primarily for road construction and building foundations.

3.3. Extrapolation at the Urban Scale for Case 05

The results extrapolation at the urban scale was only made for Case 05, both in terms of material deposits and waste flows. They are presented in Figures 13 and 14.

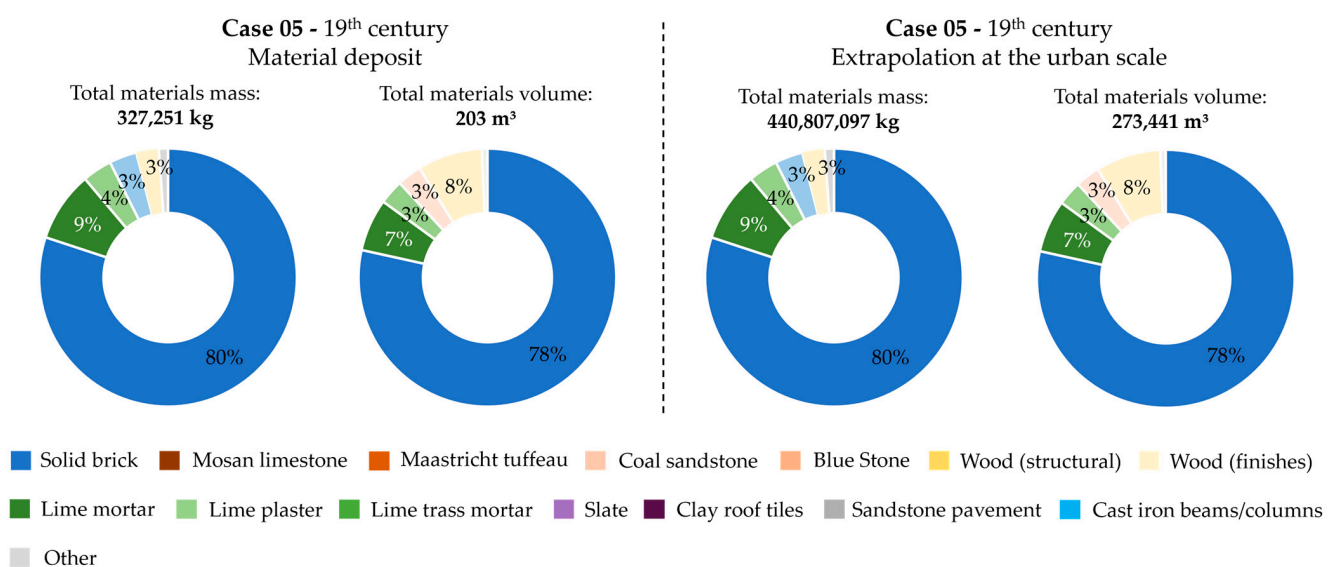


Figure 13. Extrapolation of material deposits, in mass and volume, for Case 05. Sources: O. Noël and S. Trachte.

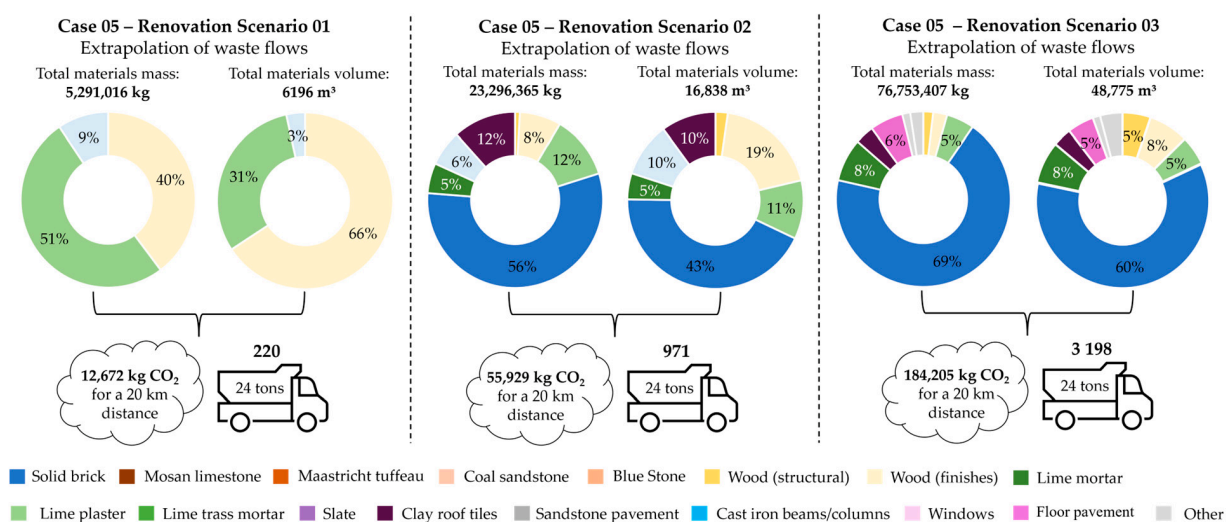


Figure 14. Extrapolation of waste flow across the three rehabilitation scenarios for Case 05. This highlights the number of trucks required to transport the waste, as well as the associated carbon emissions. An average emission factor of 0.12 kg of CO₂ per ton-kilometer and an average load of 24 tons per truck were used to estimate these emissions. Sources: O. Noël and S. Trachte.

Considering an Urban Mining approach, the results in terms of material deposits indicate that the city of Liège has a substantial deposit of brick masonry within its built environment, much of which may be reusable, as it is predominantly constructed with lime mortar. By contrast, the proportion of wood and natural stone is considerably smaller.

The results for waste flows extrapolation (Figure 14) also show variation across scenarios in terms of waste types. If we consider Scenario 02 as the most frequently applied to this type of building, extrapolation also indicates a predominance of brick, alongside a higher share of wood and natural stone. As these three materials have significant potential for reuse, they could be directly incorporated into rehabilitation works in place of new materials, thereby reducing carbon emissions associated with transport.

3.4. Data Acquired from the Digital Method

From the dataset generated for each case study, orthophotos were produced and used as input for the AI model. The primary objective was to enable the model to automatically identify façade materials and compute their corresponding surface areas.

Overall, as shown in Figure 15, the results are promising: the model achieves an average accuracy of approximately 80%, and the predictions are generally consistent and sufficiently reliable for material quantification. In most situations, the model successfully recognizes façade materials, including achieving a detailed distinction between stone and brick masonry.

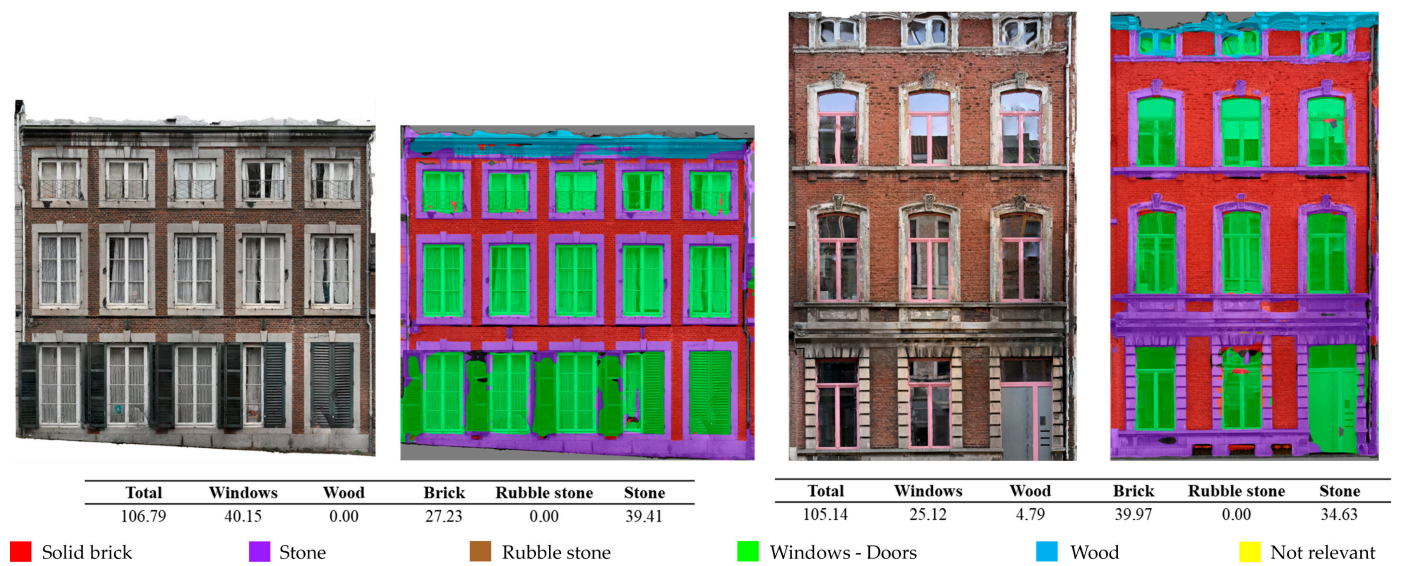


Figure 15. Predictions of materials and surfaces using AI for Cases 03 and 05. Sources: S. Boutet and O. Noël.

However, several limitations were observed. The model still encounters difficulties in specific areas, such as the detection of wood cornices, where geometric complexity leads to occasional misclassifications. More systematic errors occur for materials that were underrepresented in the training dataset, particularly wood elements and rubble stone, which remain more prone to confusion. Additional challenges were identified in the recognition of glazed openings. Reflective surfaces sometimes produced visual artifacts, causing the model to incorrectly interpret reflections of opposite façades as brick surfaces. Similarly, the presence of vegetation partially obscuring the façade can reduce detection performance by masking relevant features.

To address these limitations, further refinement of the model is required, particularly through the enrichment of the annotated image dataset. Increasing the number of annotated

examples, especially for underrepresented materials such as wood and rubble stone, would likely enhance the model's ability to distinguish these elements with precision.

4. Discussion

4.1. Limits of Theoretical Inventories

While theoretical inventories, carried out using Excel metrics and spreadsheets, have enabled the development and validation of the digital method, they also reveal certain limitations, particularly in terms of time and data accessibility. Indeed, for most case studies, graphic documents are generally insufficiently detailed and do not provide comprehensive information on the construction techniques used or the materials present in the building. The use of photographic records, 3D scanning, or photogrammetry requires access to buildings and entry into private, often occupied and furnished, spaces. This intrusion into private areas may raise privacy concerns, and the occupation of these spaces can limit access to the walls and materials that constitute the building. In addition, the analysis of graphic documents and in situ surveys requires significant time to collect data and integrate them into Excel spreadsheets, which are then used to establish inventories. This limitation encourages narrowing the analysis to the most significant or representative elements, which can lead to biased estimates and the overlooking of elements with high reuse potential, such as decorative features. The developed digital method was designed to overcome these limitations by reducing both the challenges associated with accessing the building and its components and the effort required for data collection and integration.

4.2. Comparison Between Theoretical and Digital Data

To assess the reliability of the generated data and validate the model's outputs, the results produced by the AI-based material quantification were systematically compared with manually computed surface measurements for all materials visible on the façades represented in the orthophotos. This verification step, summarized in Table 13, provides a reference baseline against which the performance of the AI-based quantification can be evaluated.

Table 13. Comparison between inventory areas and those obtained using AI.

		Total	Windows	Wood	Brick	Rubble Stone	Stone
Case 03	Areas from inventory	106.79	40.15	0.00	27.23	0.00	39.41
	Areas calculated by the AI model	110.30	44.61	6.15	22.44	0.00	37.05
	Difference in %	−3%	−11%	100%	18%	/	6%
Case 05	Areas from inventory	105.14	25.12	4.79	39.97	0.00	34.63
	Areas calculated by the AI model	103.59	27.76	4.54	35.46	0.03	35.8
	Difference in %	1%	−11%	−6%	11%	/	−3%

The comparison confirms the trends previously observed (Section 3.4). Significant discrepancies were found for wood elements, particularly in Case 03, where the difference reached 100%. This error is explained by the presence of a stone cornice on this façade, whereas cornices in bourgeois-style houses are typically made of painted wood. Since the wood class in the training dataset was largely represented by painted wooden cornices, the

model may have learned a contextual association between the cornice position/geometry and the wood class, therefore incorrectly classifying the stone cornice as wood. Smaller deviations were also observed for glazed surfaces and brick masonry. In the case of brick, the discrepancy is largely due to open shutters in the orthophotos, which obscure portions of the brickwork and therefore affect both manual and automated calculations.

Despite these differences, the comparison shows that the numerical method developed as part of this project is effective and promising for the rapid identification and quantification of façade materials. This approach provides a solid foundation for the large-scale assessment of materials, where further refinement, particularly of the training dataset, would improve accuracy.

4.3. Transferability of the Digital Method to Other Building Types

The developed method was then tested on Case 02, which is characterized by a more enclosed façade and a predominantly horizontal rather than vertical configuration. As presented in Figure 16, the results show that the AI model successfully identifies key materials such as brick, stone, and windows and provides reliable surface estimations.

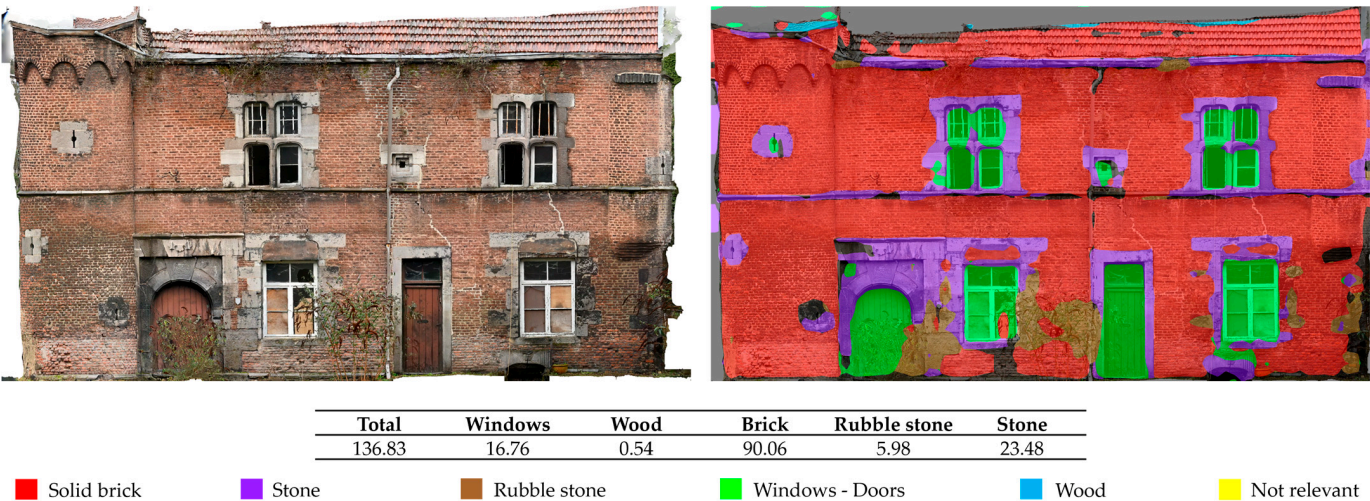


Figure 16. Predictions of materials and surfaces using AI for Case 02. Sources: S. Boutet and O. Noël.

However, performance decreases when the model is applied to heavily eroded brick walls (misclassified as rubble stone) and red terracotta tile roofs (misclassified as brick). The method also fails to correctly identify wooden roof cornices, which are instead classified as stone. These inconsistencies lead to systematic errors, particularly in the detection of roof elements and wooden components. This issue is especially evident when wood is painted, as in window frames, or when roof coverings exhibit wear, discoloration, or partial vegetation growth.

Despite these limitations, the results remain promising. Expanding the training dataset to include a wider variety of façade typologies and material conditions could significantly enhance the model’s generalization ability and overall performance.

Moreover, the method was originally developed exclusively using street-facing façades, primarily for reasons of accessibility and to ensure coverage of a wide range of buildings. However, its scope should now be extended to other building components, including roofs, interior floor walls, and partition walls. This extension would enable a more comprehensive representation of building materials and construction typologies and would likely improve the robustness and generalization capacity of the model.

4.4. Future Research Perspectives

The objective of the URMIBALI project was to develop a digital method enabling the rapid acquisition of data on the materials composing traditional residential buildings constructed before 1919. As these data are currently unavailable in Wallonia, the objective was also to reduce the amount of human labor required for their collection and integration, particularly through case studies necessary for the development of theoretical inventories.

The digital method developed based on the façade of the bourgeois house has shown promising results that could be further strengthened through future research projects investigating other building typologies, whether historic or contemporary, and broadening the range of materials studied. To support this development, remote sensing tools based on spectral measurements and signatures [49] acquired with portable spectrometers, such as the ASD FieldSpec, could improve and refine the collected data by providing a finer level of granularity. Such studies could be carried out in Wallonia in collaboration with the Remote Sensing and Geodata Unit of the research center ISSeP [102].

Moreover, although the current method enables the identification of materials present on a façade and the calculation of their surface areas, human intervention is still required, on the one hand, to estimate thicknesses and determine the volume of each material layer and, on the other hand, to identify material pathologies and signs of deterioration. These developments could be further advanced by leveraging digital tools currently used in the heritage sector to detect and analyze various pathologies [99], as well as to assess wall thickness.

Finally, the data acquired on each building material composing traditional historic residential buildings, translated into technical datasheets, could ultimately feed a dedicated database accessible to professionals in the sector, helping them overcome legal and regulatory barriers and strengthen their reuse practices.

5. Conclusions

Aligned with Wallonia's objectives for building energy efficiency and circular construction, the URMIBALI research project aims to advance knowledge of traditional historic residential buildings in Liège through the combined use of theoretical analyses and digital technologies. Specifically, the project seeks to improve understanding of these buildings' material composition, including material types, characteristics, quantities, and reuse potential. This information, currently absent from existing building databases in Wallonia, is essential for developing renovation strategies tailored to the specific characteristics of the historic building stock. By supporting informed energy renovation practices, the project contributes to carbon neutrality objectives while promoting circular construction, material reuse, and greater sustainability within the construction sector. It also anticipates the waste streams likely to result from future energy renovation interventions.

Based on six case studies sufficiently representative of the traditional residential building stock in Liège, the research is structured around two complementary components. The first focuses on identifying existing material stocks, estimating waste streams generated by energy renovation works, and assessing the reuse potential of the resulting waste fractions. The second develops a digital methodology for the rapid and efficient acquisition of façade material data.

The project makes significant contributions to the field of urban mining. By adopting a comprehensive multi-material approach encompassing all building components, it provides previously unavailable data on the material composition of traditional historic residential buildings in Wallonia and evaluates multiple rehabilitation scenarios to estimate future waste flows. The inventories reveal a predominance of brick across the building stock, while the oldest buildings also contain substantial quantities of wood, primarily hardwood

species, and locally sourced natural stones such as Mosan limestone, Coal sandstone, and Maastricht tuffeau. These materials exhibit considerable reuse potential owing to their reversible connections, durability, and resilience during disassembly. The waste flow estimates support these findings, while also highlighting, for some rehabilitation scenarios, a substantial contribution from finishing materials, particularly coatings and wood-based products, which generally present limited reuse opportunities. The extrapolation at the urban scale, established based on Case 05 “Bourgeois house”, indicates substantial reuse potential for bricks and, to a lesser extent, for wood and stone. Recovering and reusing these materials could significantly reduce carbon emissions associated with waste transport, processing, and disposal, while limiting the demand for new construction materials.

From a digital perspective, the project introduces an innovative and accessible workflow that leverages readily available tools to train an artificial intelligence model capable of identifying façade materials from images of varying quality. This flexible methodology facilitates large-scale material data acquisition while significantly reducing the time, cost, dependence on specialized equipment, and level of expertise typically required for such assessments. Although the digital methodology requires further refinement, the results demonstrate its considerable potential for accelerating the collection of reliable information on the nature and quantity of materials contained within historic buildings. However, the results also highlight that the workflow should currently be considered as a preliminary method for assessing overall proportions of material surfaces, rather than as a fully automated and precise tool. Further validation on a broader range of case studies, additional annotated data for underrepresented material classes, namely wood and rough stone, and the definition of class-specific error thresholds will be necessary before practical deployment.

Such data is fundamental to advancing the circular economy by improving knowledge of building composition, supporting the management and reuse of construction materials, enabling projections of renovation-related waste streams up to 2050, and facilitating the monitoring of material flows at the urban scale. Furthermore, the methodology offers valuable applications in geographic information systems, heritage documentation, and building archaeology, thereby strengthening the knowledge base required for the sustainable management of the built environment. Overall, the URMIBALI project demonstrates how the integration of urban mining principles and digital technologies can enhance understanding of historic building stocks and support the transition toward a more circular construction sector. By enabling scalable material characterization and improving the anticipation of future resource and waste flows, the project provides practical tools and knowledge that can inform renovation policies, heritage conservation strategies, and resource management practices in Wallonia and beyond.

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