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Development of a 3D Digital Model of End-of-Service-Life Buildings for Improved Demolition Waste Management through Automated Demolition Waste Audit

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Abstract: This paper presents the development of a 3D digital model of end-of-service-life buildings to facilitate a step change in preparation of pre-demolition protocols that can eliminate problems of inadequate documentation and extensive time spent in preparing pre-demolition audits. The 3D digital model consists of the following four main components: (i) digitization of paper-based drawings and their conversion to CAD; (ii) automated generation of a 3D digital model from CAD; (iii) corrections to the 3D digital model to account for changes in the lifetime of a building; (iv) a sub-model for performing pre-demolition audit. This paper proposes the innovative approaches of incorporating a minimal amount of human intervention to overcome numerous difficulties in automated drawing analysis, application of augmented reality (AR) in corrections to the 3D digital model, and data compatibility for pre-demolition audit. These processes are demonstrated using one building as case study. Using the digital model, a pre-demolition audit can be prepared in minutes rather than the many days required in current practice without a digital model. The accurate quantification of the quantities and locations of different demolition waste materials and products in buildings to be demolished will enable a systematic and quantitative evaluation of potentials of material and product reuse and eliminate contamination of different demolition waste streams (which may contain hazardous waste), which is the main cause of environmental degradation and downcycling of demolition waste materials.

Keywords: construction and demolition waste; digital modeling; artificial intelligence; augmented reality; pre-demolition audit; end-of-service-life building; circular economy; sustainable demolition

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1. Introduction: The Need for a Digital Approach

The construction industry is the main consumer of mineral and other non-renewable resources and generates staggering amounts of waste all over the world (e.g., 35.7% of the total waste in the European Union in 2018 [1]; 107 million tons of waste in the US in 2020; 120 million tons per year in China [2]; up to 50 million tons per year and growing in India [3]; 30 and 25 million per year in Japan and Germany, respectively [4]).

Although there have been a number of initiatives to tackle the enormous quantities of CDW arisings [5,6], landfilling or downcycling is still prevalent, with low rates of recovery and low values of recycled materials [7]. The primary reasons are the suboptimal quality of recycled materials made of CDW arisings and a general lack of confidence of the end-customers in the quality of recycled materials. A large contributing factor to these issues is the contamination of CDW arisings in current demolition and waste sorting practices. Not only does the current practice of waste management exacerbate resource depletion, it also causes adverse environmental impacts in instances where burning or exposing CDWs to weathering generates airborne pollutants and releases particulate matters into the atmosphere [8,9], posing significant health and safety and ecological problems.

To drastically reduce the aforementioned problems associated with CDWs, solutions have to be found to vastly reduce the discharge of materials entering the CDW stream [10]. At the same time, the qualities of the remaining CDW arisings have to be controlled and enhanced to provide high-quality recycling materials for subsequent construction projects to minimize the need for using new materials. To ensure wide uptake to reach the expected future EU target of high CDW recovery (to be set by the EC in 2024 or beyond) and, most importantly, the status of zero avoidable CDW by 2050 [11], such solutions have to be easily adoptable by all stakeholders involved in processes of CDW generation and management.

The current practices are ill suited to the ambitious goals set above, as explained below.

In the traditional approach of construction demolition waste management, a large number of stakeholders are involved [12], including the property owner, the contractor, the national administration (building authority), the auditor, the waste manager, the products manufacturer, the designer/consultant planning the demolition or renovation works, and the designer/consultant planning new buildings or infrastructures.

In the entire demolition waste management cycle, there are many work items associated with several stages of the process, as summarized in Figure 1. The different aforementioned stakeholders may be engaged at different stages of the process.

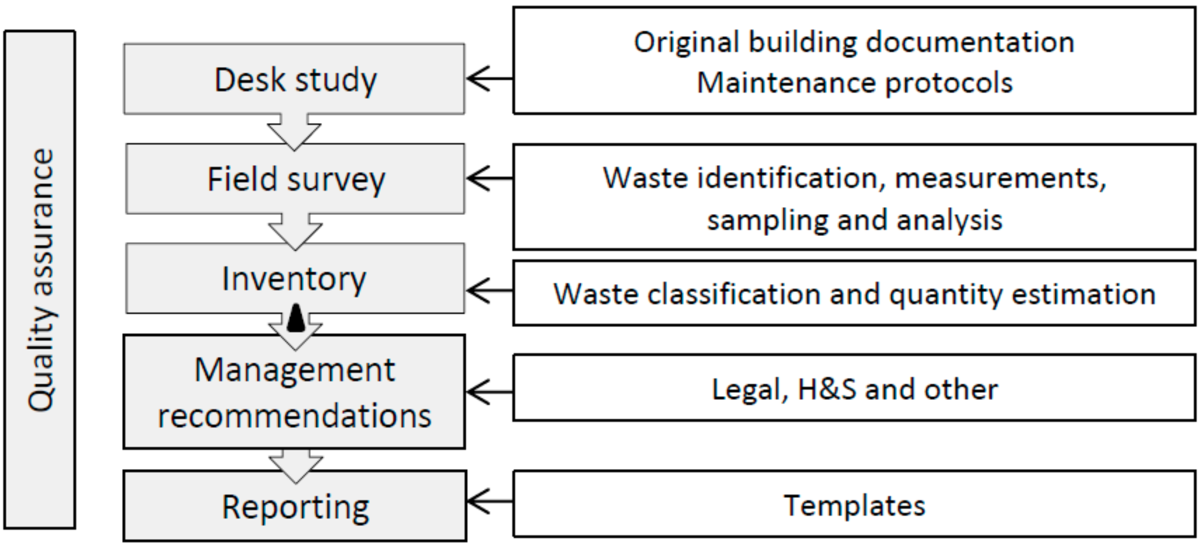


Figure 1. Summary of a waste audit process [13].

Throughout the different stages of the process, a large amount of data and information should be collected. They include the age of the building or infrastructure; design documents; documentation of use; a list of hazardous substances; aggressiveness of the surrounding area; location, volume, quantity, and waste code of materials; details of construction elements (e.g., structural loadbearing members such as columns, beams, walls, slabs, and non-loadbearing elements such as floor coverings, lighting units, interior walls, false ceilings) in a systematic manner (e.g., on a room by room basis on different floors, or the total amount of the different types of materials and their current quality [14,15]); non-destructive and destructive test results on samples of materials and construction elements [16,17].

The above features of the construction industry lead to fragmentation, a lack of close cooperation among different stakeholders, a lack of consideration on how to minimize CDWs during the whole life cycle of buildings and infrastructure among some of the stakeholders, reliance on personal knowledge and manually operated processes, conflicting demands, and slow processes of manually dealing with different requirements of different stakeholders. As a result, the current practice of conducting a pre-demolition audit is time-consuming and inefficient, with ineffective data capture [18]. There is little transparency in the project. It is difficult to evaluate retrospectively for effectiveness because inadequate project documentation makes it challenging for designers to easily incorporate audit results. There is also no standardized and normalized pre-demolition audit methodology, and different regions and countries may apply different techniques [19,20]. Depending on the knowledge of the pre-demolition team, the demolition decision-making process and results are different. It is inevitable that the end results of current construction waste management are suboptimal [21].

As a consequence of the above problems, prediction of demolition waste is grossly inaccurate and the contamination of CDWs makes the downstream activities of waste identification and sorting very difficult.

Only an integrated digital platform can overcome the above challenges of construction waste management. Theoretically, precise identification of the location of construction materials has the potential to accurately predict the number of different streams of demolition waste. However, since the 3D model described in this paper is the first step of this development, the results of the complete digital platform will only be known after implementation in practice.

Although construction wastes and demolition wastes are often included together in CDW management, their management processes are different. This paper will focus on demolition wastes when dismantling end-of-service-life (EoSL) buildings.

In order to create a demolition scenario (pre-demolition planning), the first step is to carry out an audit of the potential demolition waste. The 3D model will provide all the necessary information to facilitate efficient and systematic identification and examination of different streams of demolition waste to enable automated creation of a demolition scenario.

Depending on the pre-demolition plan, some materials may be reused and thus are taken out of waste stream, while others are discharged as construction demolition waste. Not only is the 3D model able to predict their amounts, but it is also able to facilitate a demolition plan that allows the discharged waste to be better identified and separated to minimize contamination and hence to benefit downstream waste management activities.

2. Proposed Digital Approach

To allow for integrated decision-making, considering all aspects of demolition waste management, the digital model must ensure that knowledge of the history of the EoSL building is permeated through the entire process of demolition waste management, rather than in isolated personal knowledge. As with building information management for new builds, a digital model of the EoSL building will enable transparent and traceable records to be kept to enhance confidence and trust of the users in recycled materials.

2.1. Main Components of the Digital Model

The digital model of an EoSL building consists of the following three main components: (i) a 3D model of the building, (ii) material characteristics of the various members of the building, and (iii) an audit of the members and their materials.

The main goal of a pre-demolition audit is to provide high quality information to reduce waste and allow higher valorization rates [22]. According to the European guidelines for waste audits [23], currently under review, the materials assessment for waste auditing and demolition should include basic information about the types of materials and future classification as inert, non-hazardous, or hazardous waste, together with the Eural code from the European list of wastes, as well as the estimate of quantities in mass and volume [14].

The audit report should include output information [12] as follows:

1. An inventory of elements recommended for deconstruction and reuse;
2. Location of the waste materials in the building;
3. Quality of the material and any impurities;
4. Reusability, considering a number of parameters such as safety in operations, time required, economic feasibility, space on site for sorting, proximity of recycling facilities, weather conditions, standardized details, age of the building/component, etc.;
5. Required testing methods for further investigation;
6. Recommendations for the deconstruction work procedure.

To achieve this aim, the 3D digital model must include the geometrical information of the different members of the building and assign material properties to the different components of the members. The more accurate and more detailed the data for materials/elements are, the better the outcome of the pre-demolition decision will be with regard to achieving the highest value of CDWs [24].

After establishing a 3D digital model of the EoSL building, an automated audit should be developed to inform and guide an effective demolition plan, in order to minimize material contamination and maximize the value of recycled materials.

2.2. Basis of Digital Model

2.2.1. Point-Cloud-Based Model

For the vast majority of end-of-service-life buildings, drawings are either non-existent or paper-based. In cases where EoSL buildings lack paper drawings, digital scanning and a point-cloud-based method can be employed to establish a 3D digital model of the building [25–27], an example of which is shown in Figure 2.

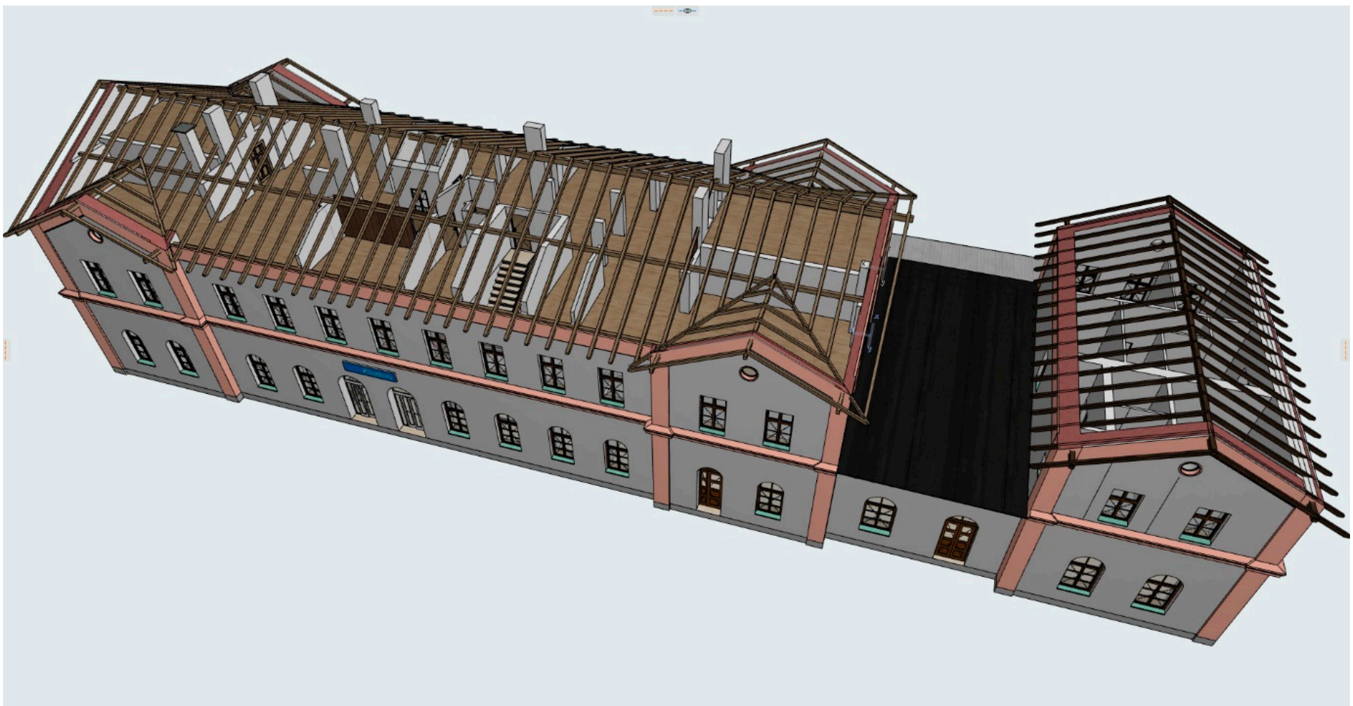


Figure 2. A 3D digital model after digital scanning of a railway station building in Prague destined for demolition.

The process necessitates specialized equipment, such as digital photogrammetry and laser scanning technologies, which are crucial yet demand substantial financial investment.

Moreover, preparing the building for scanning involves extensive cleaning and clearing of the space to ensure accurate data capture, a step that can be both time-consuming and labor intensive.

In this method, the expertise of skilled surveyors becomes indispensable, as accurate interpretation and manipulation of the point cloud data requires a high level of proficiency in using advanced software tools [28,29]. This complexity is underscored by the Scan-to-BIM process, a critical step in converting point-cloud data into usable models, which is often a lengthy endeavor demanding significant expertise. The need for computational power and memory is another significant hurdle, as the handling and processing of large volumes of point-cloud data to convert them into a 3D digital model are resource-intensive tasks.

Recent advancements aim to alleviate some of these challenges, for example, developments in both semi-automatic and fully automatic solutions that focus on enhancing the efficiency and accuracy of the scan-to-model process. Nonetheless, the adoption of these technologies and processes requires careful consideration of their implications on project timelines, budgets, and overall feasibility [30].

2.2.2. Paper-Based Drawings

Most EoSL buildings usually have some format of paper drawings, and this is the starting point of the process developed in this paper. Developing a 3D digital model from paper-based drawings involves two principal steps: converting the paper-based drawings to digital CAD and developing a 3D digital model from the CAD.

There have been a number of research studies that have investigated how to automate the process of directly extracting detailed information from scanned paper drawings to develop digital CAD. However, for various reasons, these existing developments are not suitable to the requirements of the digital platform of this research.

One of the key problems of converting paper-based drawings to digital CAD is recognition of many geometric patterns and symbols in drawings and associating them with building objects, and in understanding text attributes to identify the object's material, element type, and locational information. Because both sets of data are required to completely draw the digital CAD of an object with properties; the process of distinguishing them as separated layers takes priority [31,32]. Multiple text and line extraction methods using heuristic rules to separate data in one image from another are proposed [33], but the application of these methods is difficult when line drawings and text overlap or touch each other.

Another approach is to use geometric features and symbols to identify building components. Line segments, being the most common features in 2D building drawings, have been employed to identify walls [34–36], columns [37], and rooms [38]. Symbols have also been used to detect grid lines, enabling further identification of building elements such as columns, beams, and walls [39]. However, with multiple meanings of some symbols and possible lack of completeness of drawing features and text (e.g., due to damages), this method is prone to false matches. Furthermore, these methods are not suitable for building components with irregular shapes.

With rapid advancement of artificial intelligence (AI), there has been a substantial increase in the application of AI in drawing analysis using Convolution Neural Networks [40,41]. However, this is still at the early stage of fundamental research and development. Not only does this require advanced expertise and sophisticated supporting tools, the scale of any application is severely limited.

The limited progress in development from paper-based drawing to digital CAD is a result of the existing research investigations aiming to develop the digital CAD of an existing building or its components to the high level of quality and complexity of the CAD as if for new design of the building.

The aim of converting from paper-based drawing to CAD for pre-demolition audit is different from that of the above-mentioned existing research studies. The level of detail required for the above developments far surpasses that that is required for the purpose of this research, for which simplicity of use and large scale application are essential but the need for precision in many details is modest.

An alternative approach is possible. In this alternative approach, a professional's ability to quickly understand and identify the important information in paper drawings is combined with computer's raw power to process information. In this way, human intervention eliminates the need to deal with different drawing conventions, damaged drawings, recognition of symbols and text, so that computer processing can be done quickly to convert paper-based drawing to digital CAD. Although the authors have not fully implemented this approach, Section 4.3 of this paper will present the preliminary work by the authors to demonstrate feasibility of this approach.

2.3. Correction of Mistakes in Digital Model

Whether the CAD of an EoSL building already exists or is generated from converting paper-based drawings, the CAD can contain many mistakes because the EoSL building may have undergone many changes throughout its life and this information is not captured in the CAD. Therefore, it is necessary to carry out extensive corrections to the 3D digital model that is developed from the CAD, so that the 3D digital model is a sufficiently faithful representation of the EoSL building for effective pre-demolition waste audit. This is the main focus of this paper.

Thus, the key objectives of the paper are: (i) outlining a method of digitization of paper drawings for the purpose of generating a digital CAD of an EoSL building, based on minimal human intervention; (ii) automated generation of 3D digital model from the digital CAD; (iii) corrections to the 3D digital model; and (iv) development of a pre-demolition audit.

To illustrate the development process, the George Begg building of the University of Manchester is used as case study. It should be pointed out that even though the case study focuses on a small footprint of the building, the method developed in this paper is intended to be easily scalable. Nevertheless, in some cases when the building is small, using this technology may not be necessary. This is at the discretion of the user.

Furthermore, the 3D model of this paper has been developed with usability in mind. However, this paper has only presented the methodology of the 3D model. Application of the 3D model to real buildings will be demonstrated as part of the entire Horizon Europe project RECONMATIC. The results and lessons learned from the demonstrator will be reported in due course.

3. A Description of the George Begg Building

Figure 3 shows the entrance to the George Begg Building of the University of Manchester, UK. It was built in 1974. It is a two-storey academic building, consisting of offices, lecture theatres, laboratory, student workspaces, computer labs, etc. The structure of the building is mainly reinforced concrete. There are many non-loadbearing members, including many types of internal walls, doors, and windows. Whilst the structural member grids are regular, the internal space layout is highly irregular.

Furthermore, throughout the life of the building, many changes were made to arrange the interior space, with removal of many original non-loadbearing elements of the building and also many additions. Therefore, there are numerous mistakes in the raw 3D digital model of the building after conversion from the existing CAD. Figure 4 shows the plan view of the ground floor of the building as built in 1974; the portion highlighted in green is used as a case study in this paper.

Figure 3. Image of the George Begg building, University of Manchester.

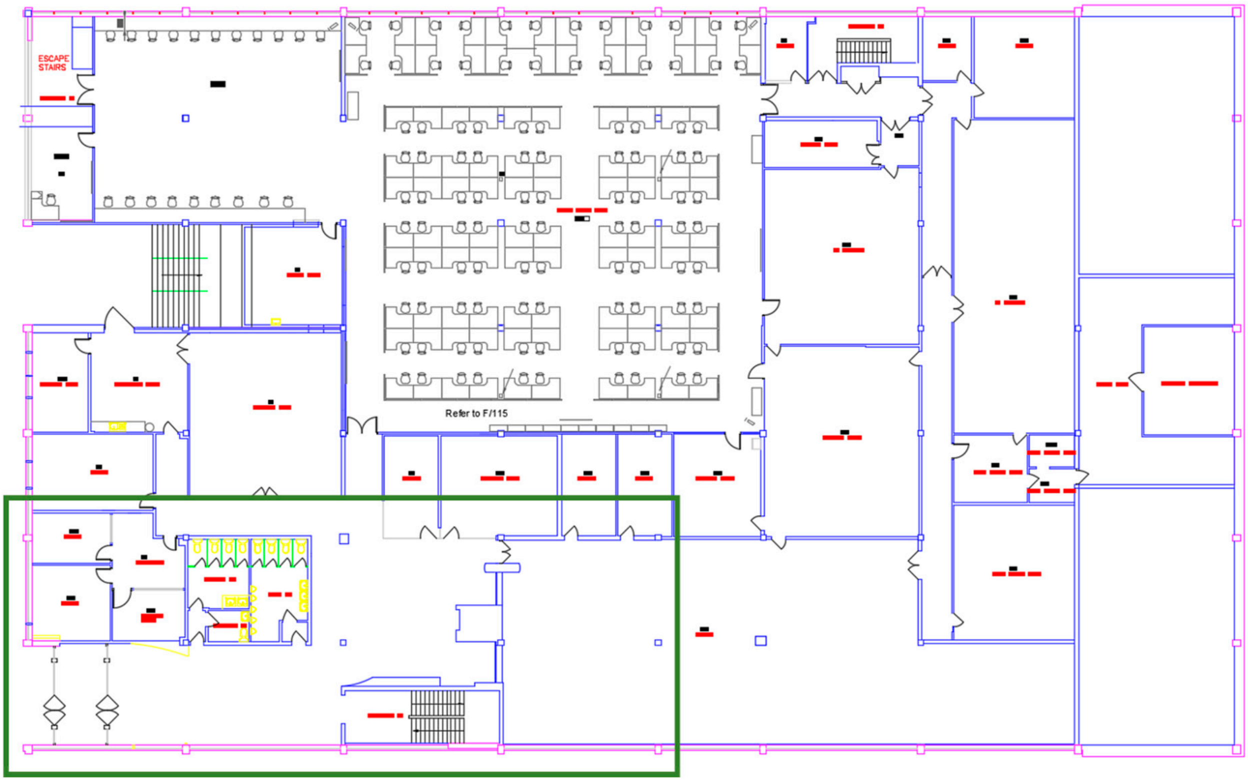


Figure 4. Ground floor plan of the George Begg building (case study part in green box).

4. Methodology of Creating 3D Digital Model

4.1. Overview

Figure 5 summarizes the four main steps of developing a faithful 3D digital model. These steps will be described in detail in Section 4.3 (step 1 and step 2), Section 4.4 (step 3), and Section 4.5 (step 4), with Section 4.6 providing a critical review of the process and outcomes.

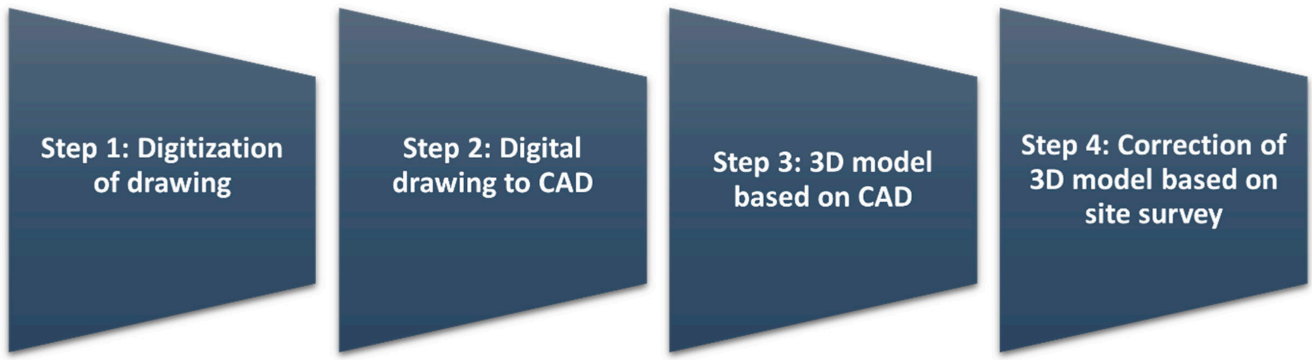


Figure 5. A summary of the main steps of developing a 3D digital model.

4.2. Hardware and Software

To ensure that the digital platform developed in this paper can be widely used, the requirement for hardware and software must be modest. In this research, the following hardware and software were used:

A standard scanner to scan paper-based drawings.

A commonly used windows operating system, for example core i5.

An AR app commonly available in low spec Android or IOS smartphones with a camera, and a microUSB 2.0 port for connectivity to the laptop.

MS Office applications such as PowerPoint (version 2022 or above) to post-process scanned images of paper-based drawings.

Autodesk AutoCAD (version 2022 or above).

Autodesk Revit (version 2022 or above) to convert CAD to 3D digital model.

4.3. Automated Conversion of Paper-Based Drawings to CAD

This section explains the first two steps of the process shown in Figure 5: (i) digitization of drawings; and (ii) creating from digital drawings.

4.3.1. Digitization of Paper Drawings

Scanning Paper-Based Drawings

While the scanning process is straightforward, it is important to ensure high quality scanning to avoid any errors at later stages by following these steps: (i) use clean paper drawings that are devoid of any creases to prevent shadows or distortions in the scan, if the original paper drawing is not this quality, a photocopy of the original should be used; (ii) use a minimum 300 DPI scan quality, which is readily available off the shelf; (iii) use grayscale or black and white scan to differentiate between active and passive elements (explained later) and to reduce the file size; and (iv) use JPEG or PNG image output format. The paper drawing must be properly aligned and framed on the scanner bed.

Figure 6a shows a scanned image of the highlighted part of the George Begg building as indicated in Figure 4.

Post-Processing Scanned Image

After completing the scan, the scanned image is cropped, straightened, and brightened using MS Office PowerPoint tools. A key difference between the methodology of this research and others is that a small amount of human intervention is incorporated so as to eliminate the vast array of challenges associated with automated recognition of paper drawings by computers, as previously described in Section 2 of this paper. In this intervention, a qualified professional who understands architectural and structural drawings highlights the main elements of the building on the scanned image in red using rectangular shaped boxes. Different types of elements are drawn separately on a copy of the scanned image to ensure proper detection of all types of elements. Figure 6b–d show the images for columns, beams, walls, and slabs, after digital processing of the same scan in Figure 6a.

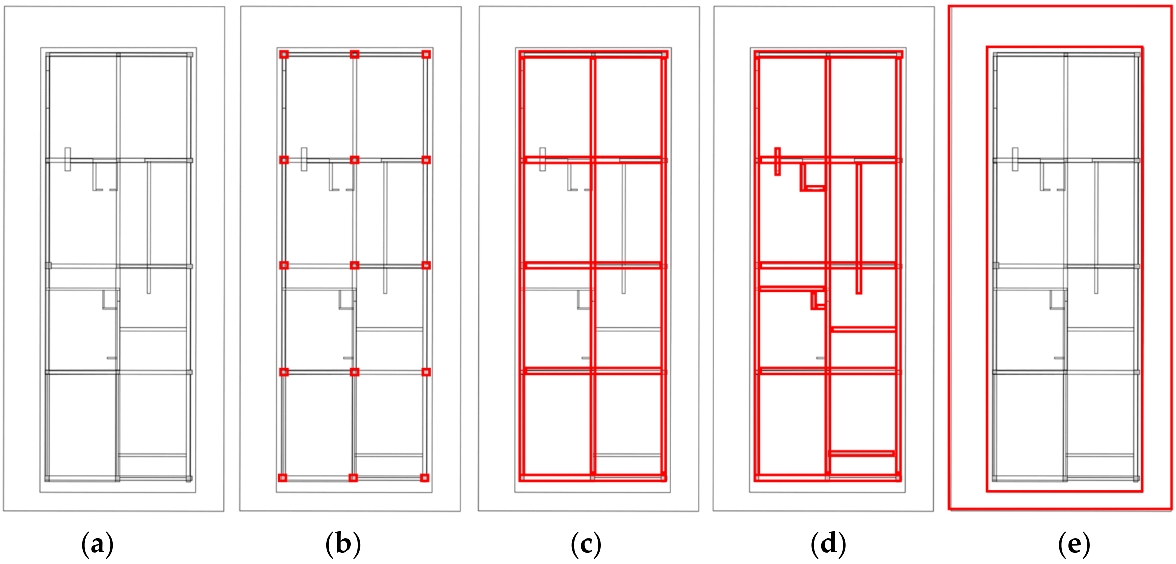


Figure 6. Post-processed scanned copy with elements in digital form highlighted in red. (**a**) Scanned copy. (**b**) Columns. (**c**) Beams. (**d**) Walls. (**e**) Slab.

4.3.2. Creating Digital CAD

Assigning Coordinates to CAD

For each type of element that has a specific image, on successful detection of an element, the coordinates of the element with reference to the scale of the image, which is entered by the user, are automatically output as a text file for the type of element, which is then read into an AutoCAD script reader for automatically drawing these elements in a layer of CAD for this type of element. Figure 7a shows a snapshot of the overall CAD, built by merging the separate layers (Figure 7b–d) for columns, beams, walls, and slab.

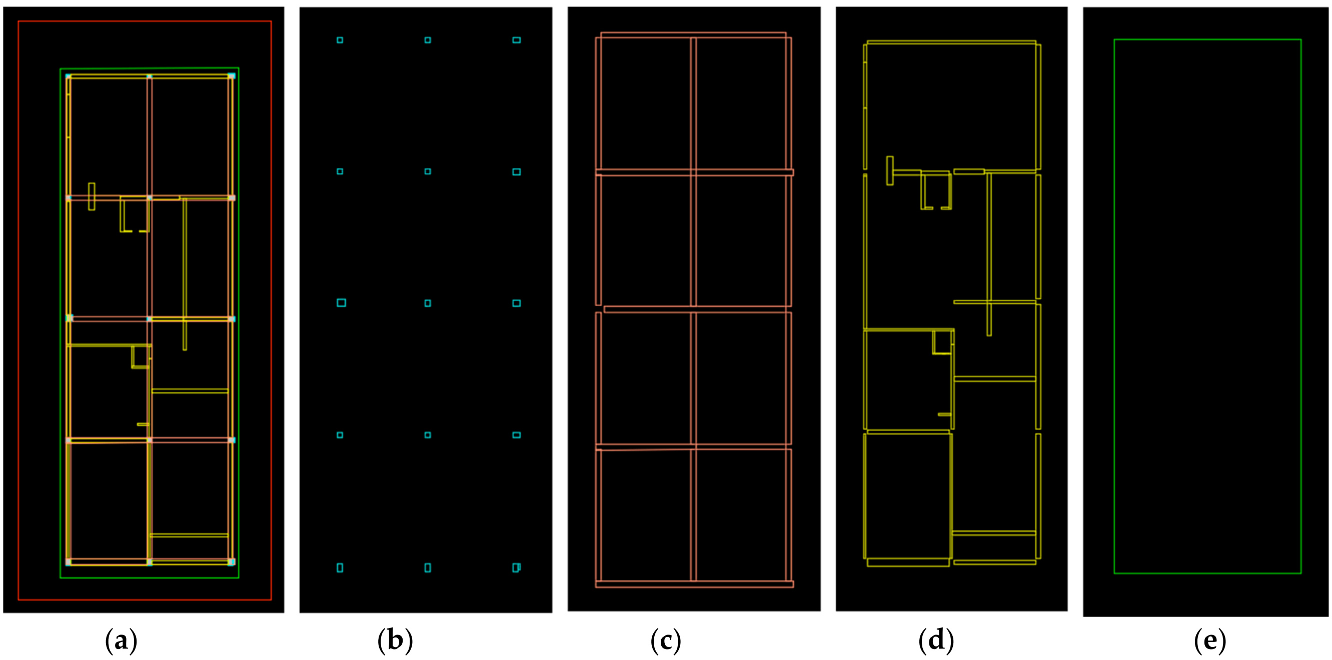


Figure 7. CAD converted from paper-based digital images in different layers (based on red highlights in Figure 6). (**a**) All elements. (**b**) Columns. (**c**) Beams. (**d**) Walls. (**e**) Slab.

Assigning Properties to CAD

The CAD generated from paper drawings includes the length and width of all the elements, but their height and material properties are missing. It is crucial to embed the missing geometric parameters and material properties in CAD before conversion to a 3D digital model. Figure 8 summarizes the process of incorporating these parameters into CAD. This process has to be carried out manually by the professional, based on their understanding of the paper drawings.

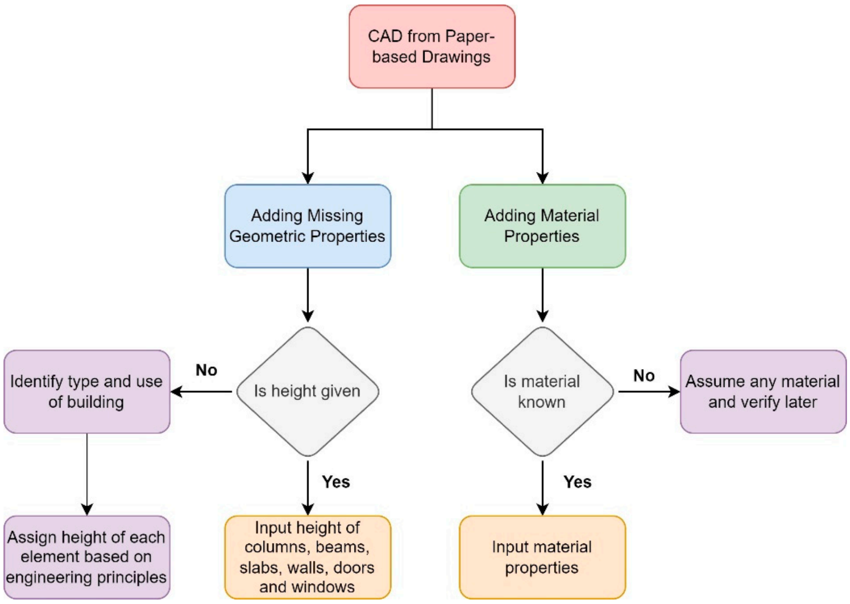


Figure 8. Process of incorporating missing parameters into CAD before conversion to 3D model.

4.4. Automated Conversion of CAD Drawings to 3D Model

4.4.1. Importing CAD into 3D Modeling Software

The process of converting CAD drawings (whether after processing paper drawings or using existing CAD) into a 3D digital model is developed using Autodesk Revit alongside its visual programming extension Dynamo [42]. The CAD drawing, with different types of elements and material properties of every element are automatically imported into the Revit environment using the "Link CAD" or "Import CAD" feature, which serves as the base reference upon which the 3D digital model is constructed.

4.4.2. CAD to 3D Model Framework

Different types of construction elements require different processes. For example, architectural CAD elements such as walls are line elements, while doors and windows are point-based elements. Similarly, structural elements such as beams are line elements, while columns are point-based elements, and slabs are area elements. Figure 9 summarizes the different procedures for converting CAD drawings to a 3D digital model for different types of construction elements.

The conversion process progresses from one floor to the next. On each floor, the different types of construction elements in Figure 9 are in individual layers with associated layer names for their identification.

Figure 10 shows a screenshot of the final output of the 3D digital model after conversion from CAD drawings, including: (i) the 3D model in .obj format and (ii) an excel sheet with detailed information of all the elements including their distinctive ID, materials, area, volume including parametric dimensions (length, width, and height), and location. The detailed information is arranged according to: (i) different levels of the building; (ii) nature and composition of the material; (iii) quantity of each material.

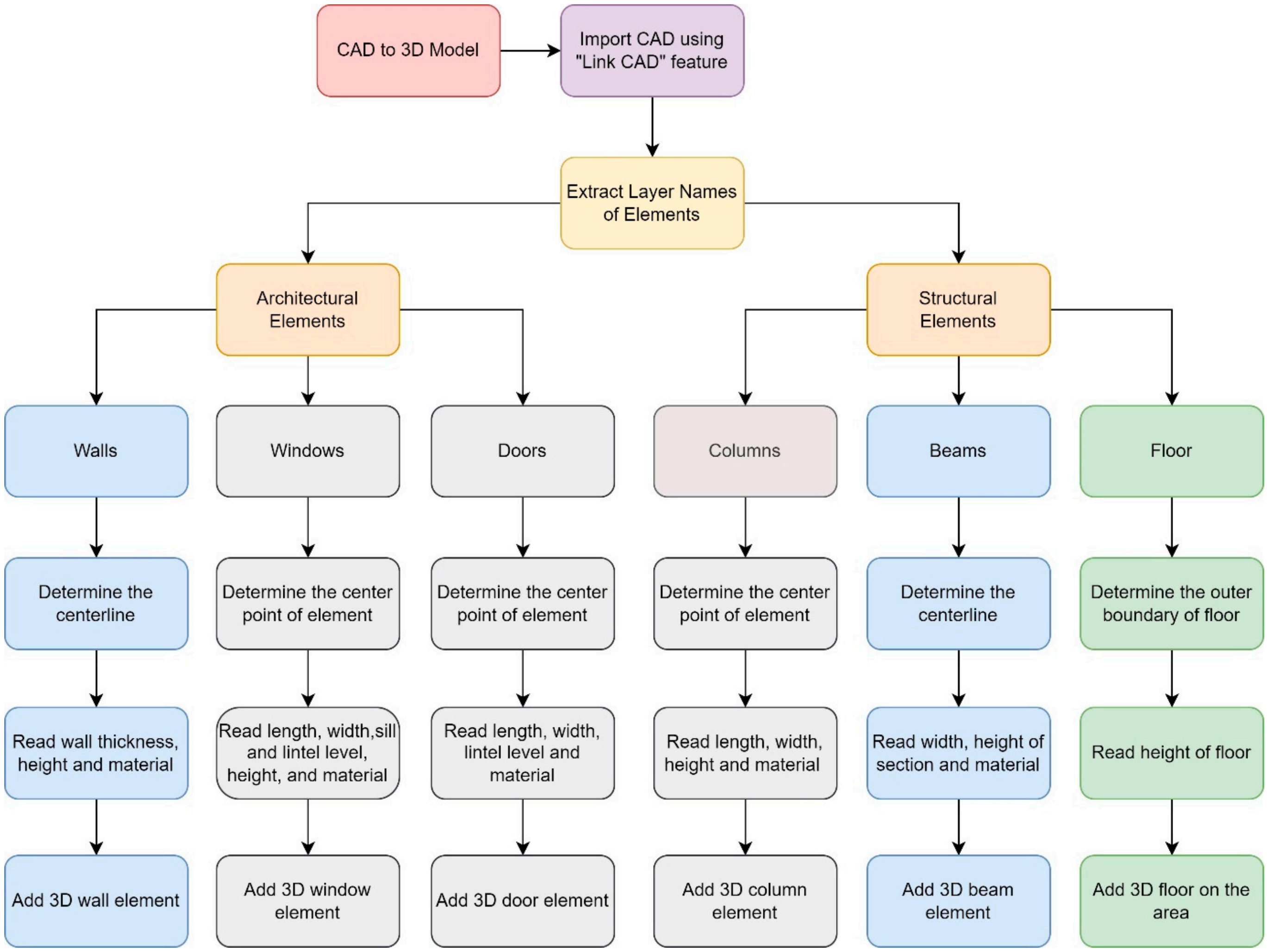


Figure 9. Summary of conversion processes from CAD elements to 3D elements.

4.5. Corrections to the 3D Digital Model (from CAD) Based on Site Survey

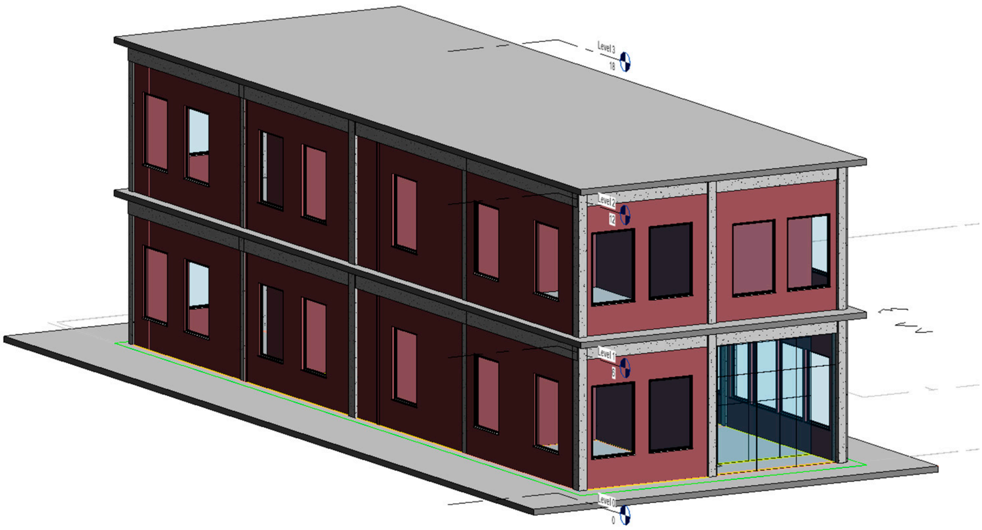
This is the key stage of the process. As already mentioned, the raw 3D digital model will inevitably contain many mistakes due to changes to the building throughout its lifetime. It is vital that these mistakes are corrected, and this can only be done by site survey in which the raw 3D digital model is compared against the real construction and any mistake is corrected. Figure 11 summarizes the correction process, with the aid of an augmented reality (AR) APP that is used to quickly record on-site measurements.

This correction process is described in detail in the following sections.

4.5.1. Navigation and Detection of Element

To start the correction process, the surveyor measures distances to the adjacent elements, one by one, in the x–z plane of the floor (the y direction is perpendicular to the floor plane) in real-world using the ARPlan app from a local origin. The surveyor then navigates the same distances in the digital model by inputting the same local distances, entering the distances in the panel in the top right of the model, highlighted in red in Figure 12, and then pressing the “Move” key.

For example, in the case of the George Begg building, the first element, a glass wall, is at 8.60 m from the local origin in the real world. When the same distance of 8.60 m is moved in the digital model using the navigation panel, the same glass wall is identified as shown in yellow in Figure 12. This means that this element and its location in the 3D model are correct. If necessary, to further verify the identity of the element, the surveyor can view the element from different angles and freely navigate around it in the 3D model, as explained in the next sub-section.



(**a**)

	A	B	C	D
1	Name	Category	Volume	Material
2	location <Not Shared> 309082	Element		None
3	Floor_Timber_22Cbd-225Joist 309091	Floors	2829.896319	Wood Sheathing, Chipboard Structure, Timber Joist/Rafter Layer
4	Floor_Timber_22Cbd-225Joist 309100	Floors	4544.546512	Wood Sheathing, Chipboard Structure, Timber Joist/Rafter Layer
5	Beams 1 309135	Structural Framing	18	Concrete - Cast-in-Place Concrete
6	Beams 2 309138	Structural Framing	18	Concrete - Cast-in-Place Concrete
7	Beams 3 309141	Structural Framing	18.58676795	Concrete - Cast-in-Place Concrete
8	Beams 4 309144	Structural Framing	18.58676795	Concrete - Cast-in-Place Concrete
9	Beams 5 309147	Structural Framing	18.58676795	Concrete - Cast-in-Place Concrete
10	Beams 6 309150	Structural Framing	18.58676795	Concrete - Cast-in-Place Concrete
11	Beams 7 309153	Structural Framing	18.58676795	Concrete - Cast-in-Place Concrete
12	Beams 8 309156	Structural Framing	104	Concrete - Cast-in-Place Concrete
13	Beams 9 309159	Structural Framing	24	Concrete - Cast-in-Place Concrete
14	Beams 10 309162	Structural Framing	28.49619116	Concrete - Cast-in-Place Concrete
15	Beams 11 309165	Structural Framing	17.33333333	Concrete - Cast-in-Place Concrete
16	Beams 12 309168	Structural Framing	26.17047551	Concrete - Cast-in-Place Concrete
17	Beams 13 309171	Structural Framing	24	Concrete - Cast-in-Place Concrete
18	Beams 14 309174	Structural Framing	28.49619116	Concrete - Cast-in-Place Concrete
19	Beams 15 309177	Structural Framing	17.33333333	Concrete - Cast-in-Place Concrete
20	Beams 16 309180	Structural Framing	26.17047551	Concrete - Cast-in-Place Concrete
21	Wall-Ext_215Bwk 309183	Walls	165.0590551	Brick, Common
22	Wall-Ext_215Bwk 309184	Walls	165.0590551	Brick, Common
23	Wall-Ext_215Bwk 309185	Walls	170.4396864	Brick, Common
24	Wall-Ext_215Bwk 309186	Walls	170.4396864	Brick, Common
25	Wall-Ext_215Bwk 309187	Walls	715.2559055	Brick, Common
26	Wall-Ext_215Bwk 309188	Walls	165.0590551	Brick, Common
27	Wall-Ext_215Bwk 309189	Walls	195.9814328	Brick, Common
28	Wall-Ext_215Bwk 309190	Walls	119.2093176	Brick, Common
29	Wall-Ext_215Bwk 309191	Walls	179.986415	Brick, Common
30	Wall-Ext_215Bwk 309192	Walls	165.0590551	Brick, Common
31	Wall-Ext_215Bwk 309193	Walls	195.9814328	Brick, Common
32	Wall-Ext_215Bwk 309194	Walls	119.2093176	Brick, Common
33	Wall-Ext_215Bwk 309195	Walls	179.986415	Brick, Common
34	Columns 1 309221	Structural Columns	60	Concrete - Cast-in-Place Concrete
35	Columns 2 309223	Structural Columns	60	Concrete - Cast-in-Place Concrete
36	Columns 3 309225	Structural Columns	60	Concrete - Cast-in-Place Concrete
37	Columns 4 309227	Structural Columns	60	Concrete - Cast-in-Place Concrete
38	Columns 5 309229	Structural Columns	60	Concrete - Cast-in-Place Concrete

(**b**)

Figure 10. Auto-generated 3D model with material characteristics from CAD. (**a**) 3D model. (**b**) Excel sheet.

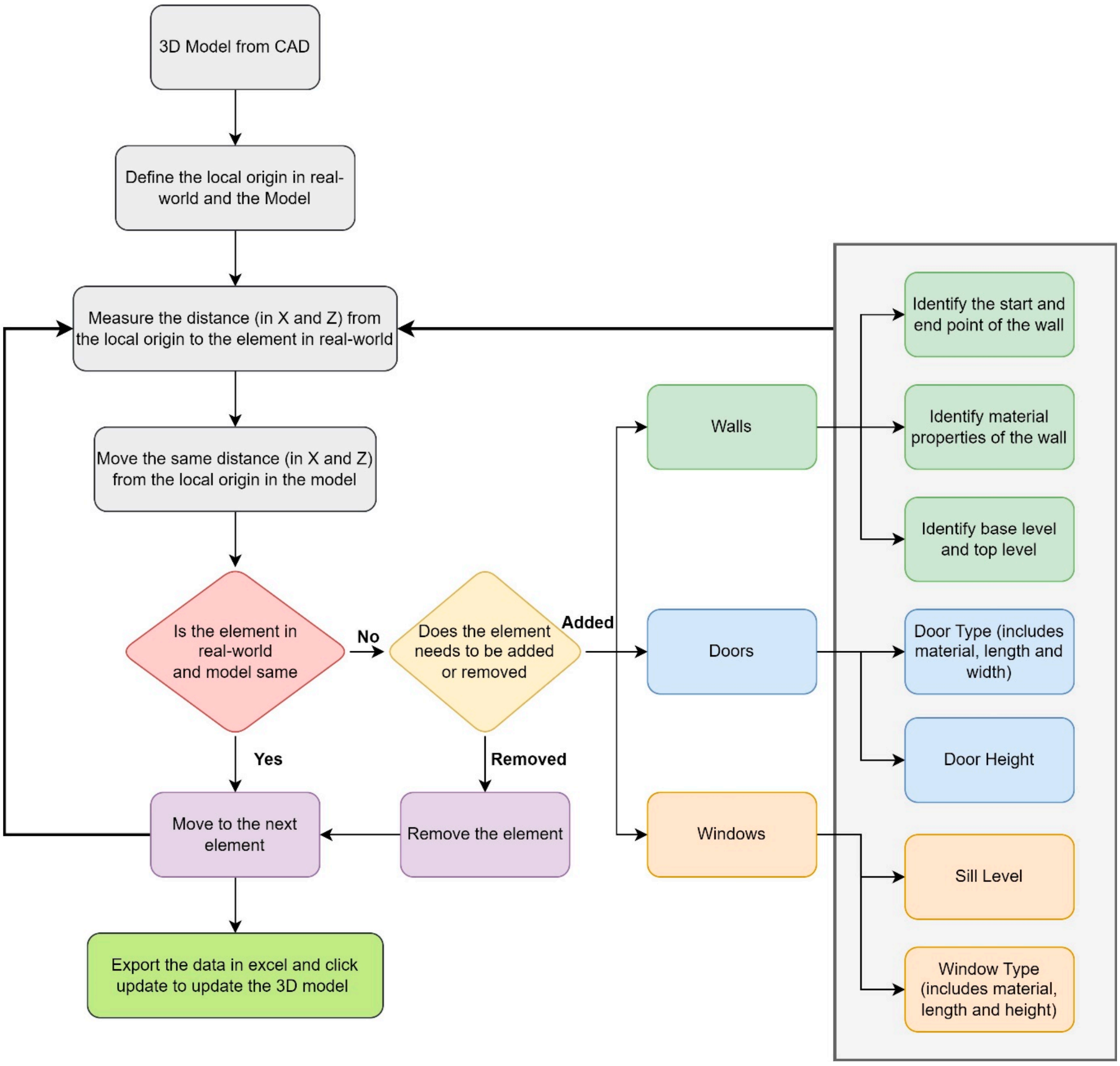


Figure 11. A summary of the process of identifying and correcting mistakes in raw 3D digital model.

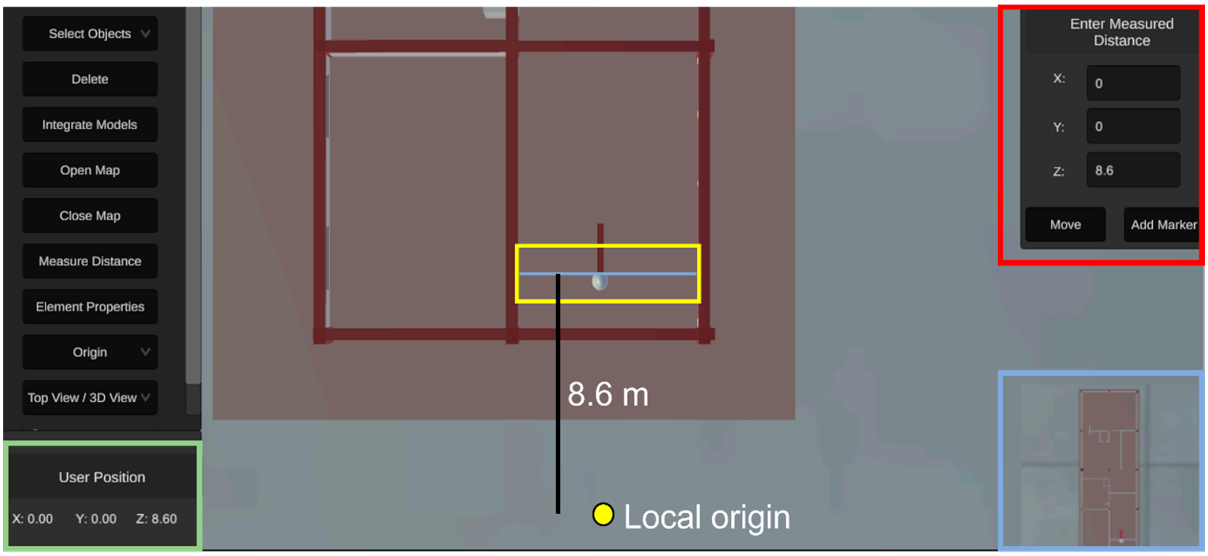


Figure 12. Navigation panel. The pointer in the model moves the distance entered in the panel highlighted in red when the "Move" button is pressed. At coordinate (0, 8.60) m, a glass wall (in yellow) is detected.

Once the identity of the element is confirmed, the surveyor can move to the next element. For the next element, the origin is updated as the previously confirmed position, which is (0 m, 8.60 m) in this case. This eliminates any problem (such as accumulation of errors in measurement) associated with using a fixed point of origin when measuring distances in the real world and when navigating in the digital model. The position of the surveyor relative to the initial origin is continuously tracked in the model and is shown in the green panel in the bottom left of Figure 12. The position of the surveyor is also displayed with respect to the overall plan of the building in the model as shown as the red point in the bottom right blue panel in Figure 12, to help and remind the surveyor of their location in real world on the floor of the building.

4.5.2. Toggle Views to Confirm the Identity of Elements from Different Angles

If the surveyor has any doubt and wants to check the identity of an element, they can navigate freely in the digital model and check the digital model of the element against real world observation. For example, Figure 13 shows the same glass wall in Figure 12 in 3D view, and Figure 14 enables the surveyor to zoom in or out by using the slider bar.

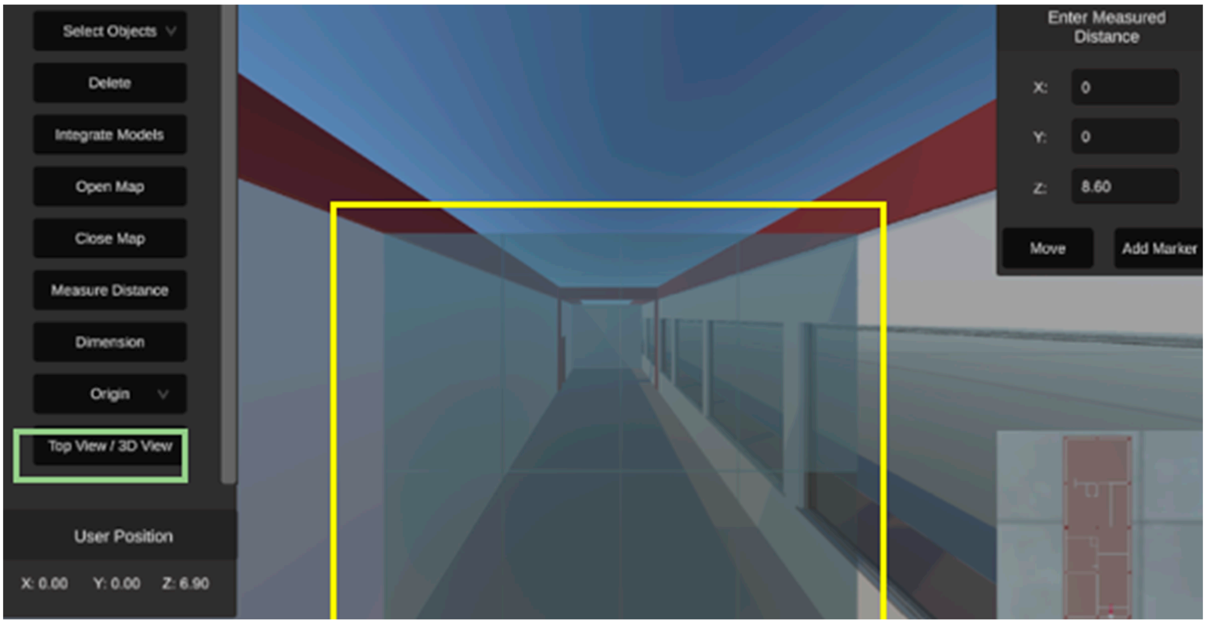


Figure 13. 3D view of the same glass wall (in yellow) shown in Figure 12 in 2D.

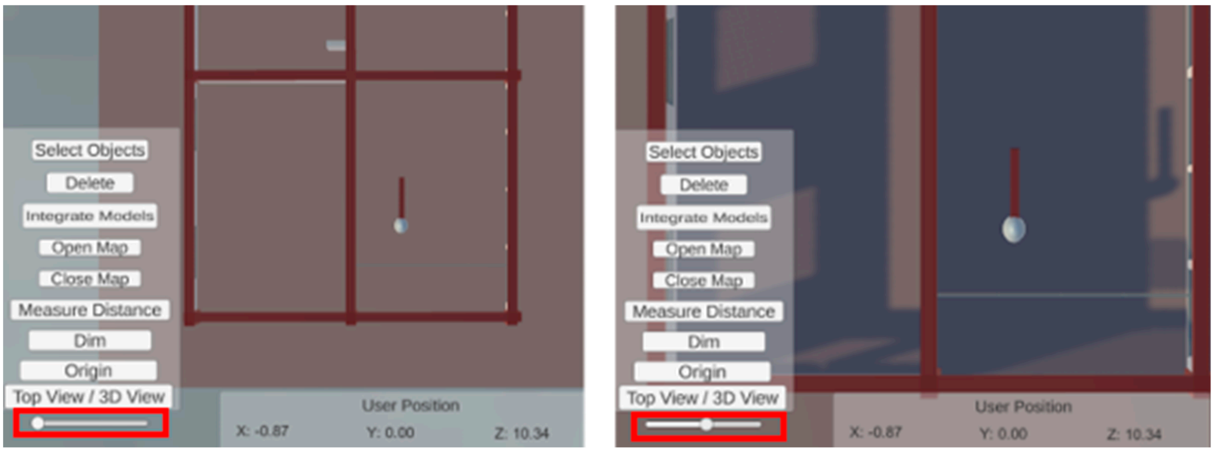


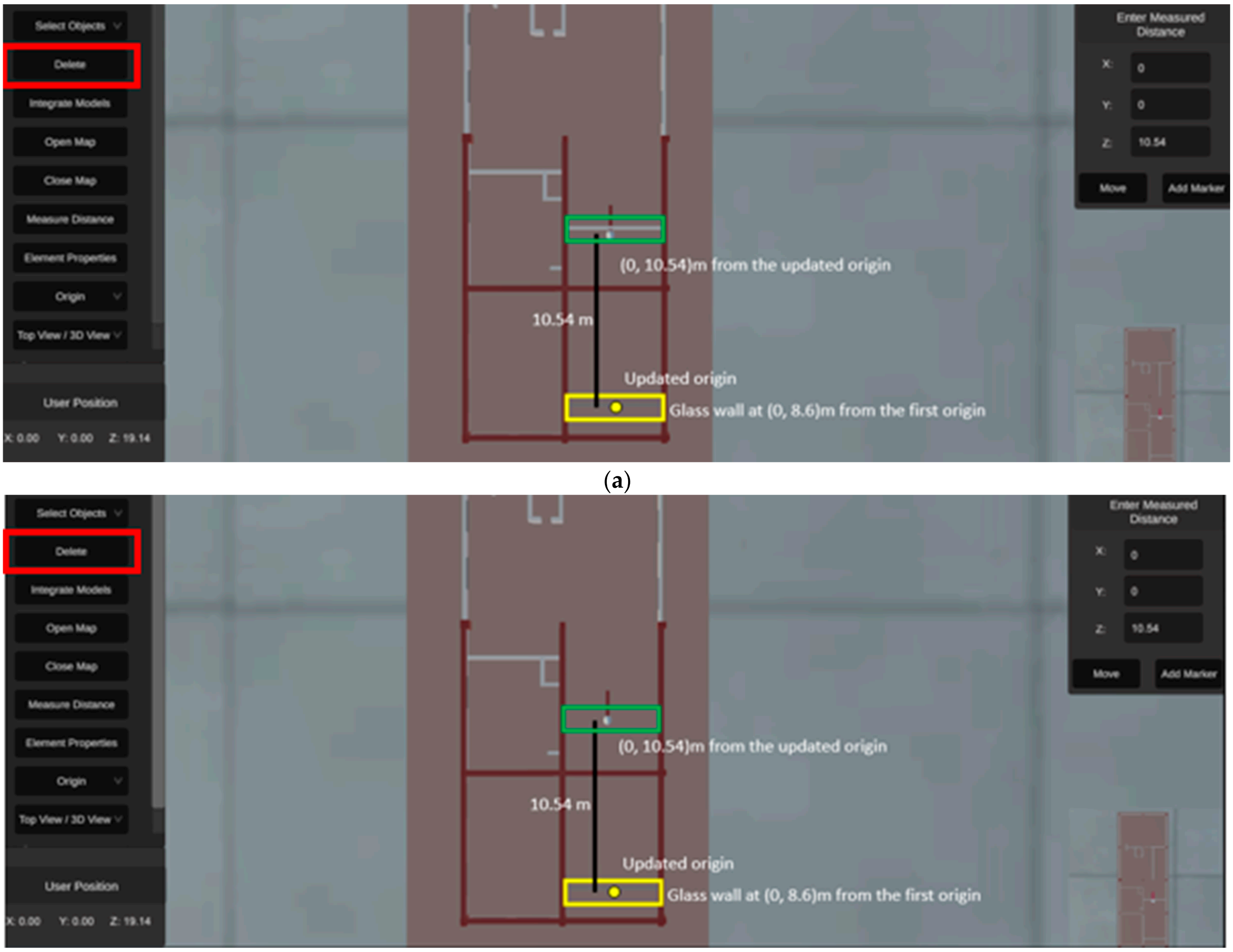
Figure 14. Zoom out/in views using the slider bar shown in red. (**a**) Overall picture in zoomed-out (normal) view. (**b**) Zoomed-in view to focus on a particular area.

4.5.3. Removing Elements

When the surveyor moves a distance in the x–z plane in the digital model from the updated origin (located at the glass wall shown in Figure 12) to the next element, this element exists in the digital model. However, if the distance moved by the surveyor in the digital model is less than that measured by the surveyor to the next element in the real world in the same direction, then this element does not exist in the real world and this non-existent element must be deleted from the digital model.

Removal of a Wall

For example, in the digital model of George Begg building, a wall is found in the digital model after moving from the updated local origin (0 m, 8.6 m) by moving 10.54 m in the z direction from the updated origin, as shown in Figure 15a. In contrast, the surveyor measures a distance of 16m to the next element in the real world. This means that the wall in the digital model does not exist in the real world. The surveyor then selects this wall in the digital model and presses the delete button highlighted in red in Figure 15 to give the result in Figure 15b.



(a)

(b)

Figure 15. Digital model before and after the removal of a wall (in green). (**a**) Wall identified at coordinate (0, 10.54) m. (**b**) Highlighted wall in (**a**) deleted.

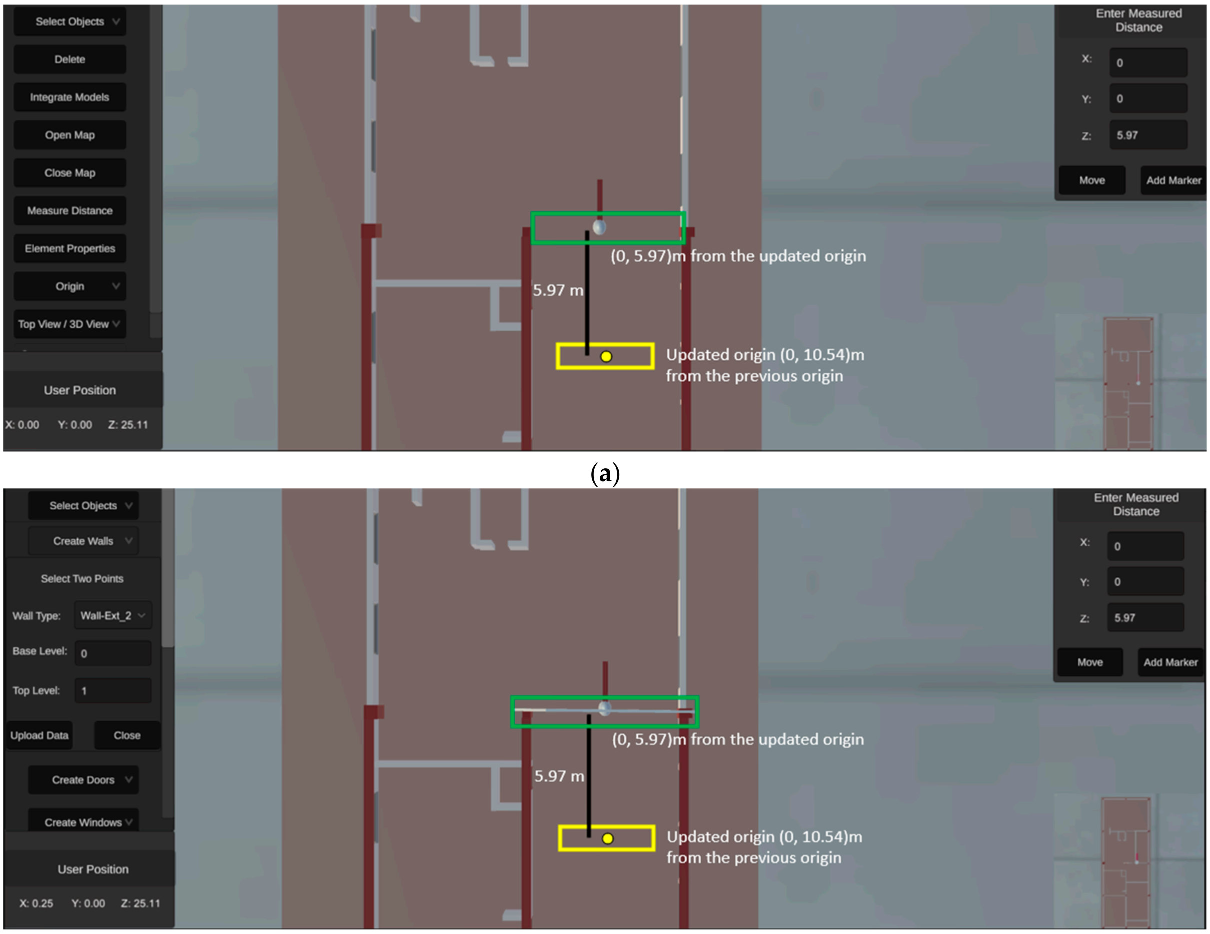
The same removal process can be applied to any other element (door, window).

4.5.4. Adding Elements

In contrast to element removal, if the surveyor detects an element in the real world, but the distance measured by the surveyor in the real world is less than the distance in the same direction in the digital model until the next element, then this element exists in the real world, but not in the digital model. This element must be added.

Adding Walls

In the case of George Begg building, after moving 5.97 m in the z direction from the updated origin (0 m, 10.54 m) (position of the wall that was removed in the previous step, shown in Figure 15a,b), a wall is identified in the real world but this wall does not exist in the digital model because the distance measured by the surveyor to the next element in the digital model is longer, as shown in Figure 16. A new wall must be created at this location in the digital model. To create a new wall at this location, the user clicks the 'Select Objects' button to launch a panel for the user to input data. To create a new wall, the user selects the 'Create Walls' button to display another panel, which will ask the user to input the following data: (i) wall type (from a list of options based on [43]), (ii) base height, and (iii) top level of the wall. The user then enters the start and end coordinates of the wall, being (−1 m, 5.97 m) and (2 m, 5.97 m), respectively, in this example, measured in the real world using the ARPlan 3D app. A wall is created when the user clicks the upload data button. The material of the wall, its geometrical information such as area, volume, and dimension (length, width, and height), and location are then added.



(**a**)

(**b**)

Figure 16. A snapshot of the model before and after adding a wall (in green). (**a**) Wall not present in the digital model. (**b**) Wall added in the model.

Figure 16 shows the wall before and after its creation.

Adding Doors and Windows

The same process as above is followed to add doors and windows. For example, at location (0 m, 8.42 m), from the last origin in the real George Begg building, the wall has a door and a window, but they are not present in the digital model as shown in Figure 17 (highlighted in red). They are added at location (0 m, 8.42 m) from the updated origin (shown in Figure 16a,b), as shown in Figure 18.

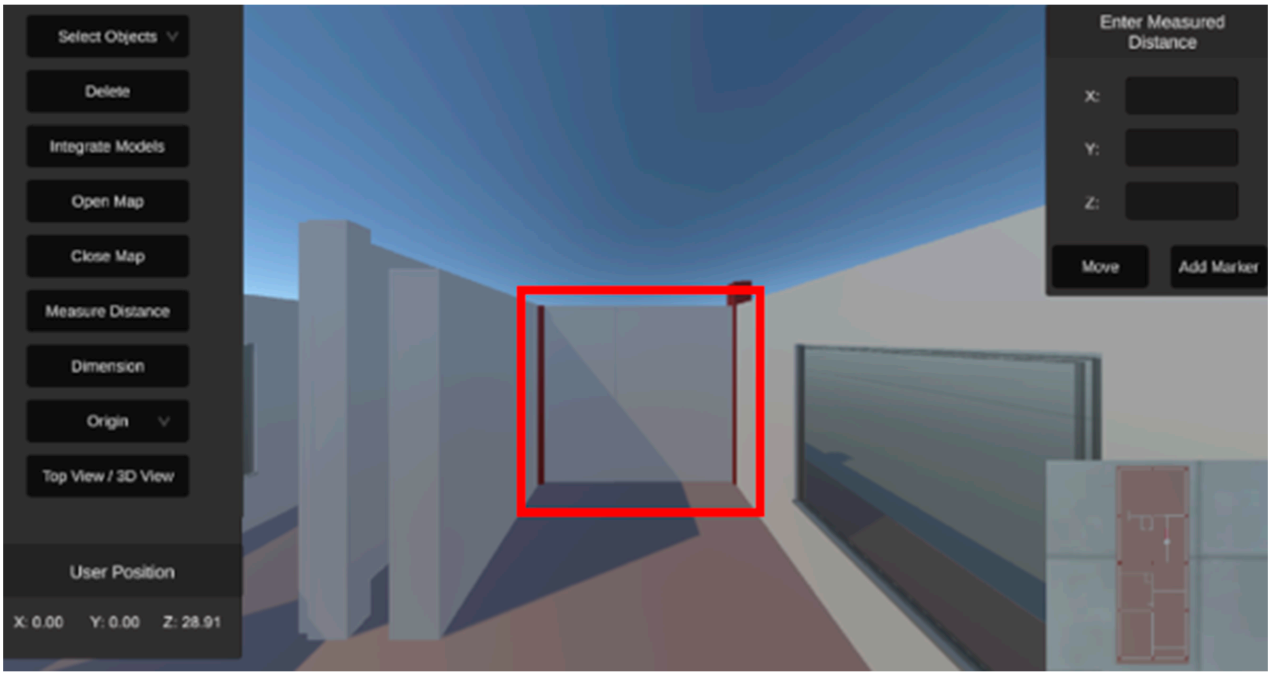


Figure 17. A wall in the George Begg building missing a door and a window.

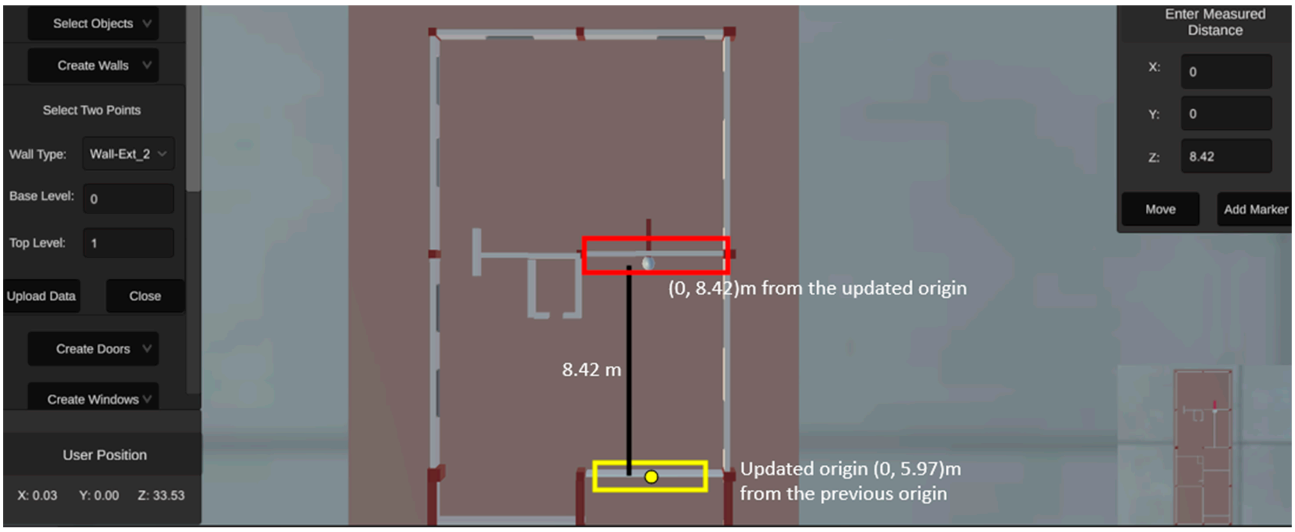


Figure 18. A wall with missing door and window.

The user follows the same steps as for creating a wall, including clicking the 'Select Objects' panel, and then clicking the 'Create Doors' or 'Create Windows' button appropriately. Afterward, the user enters relevant information for doors, i.e., (i) door type selected from the drop down manual according to [43] and (ii) door height. Door width and length is already incorporated in door type. The exact location of the door in the wall is not important because, for pre-demolition audit, only the type and quantity are needed. Figure 19 shows the added door highlighted in green. Figure 20 shows an added window in the same wall.

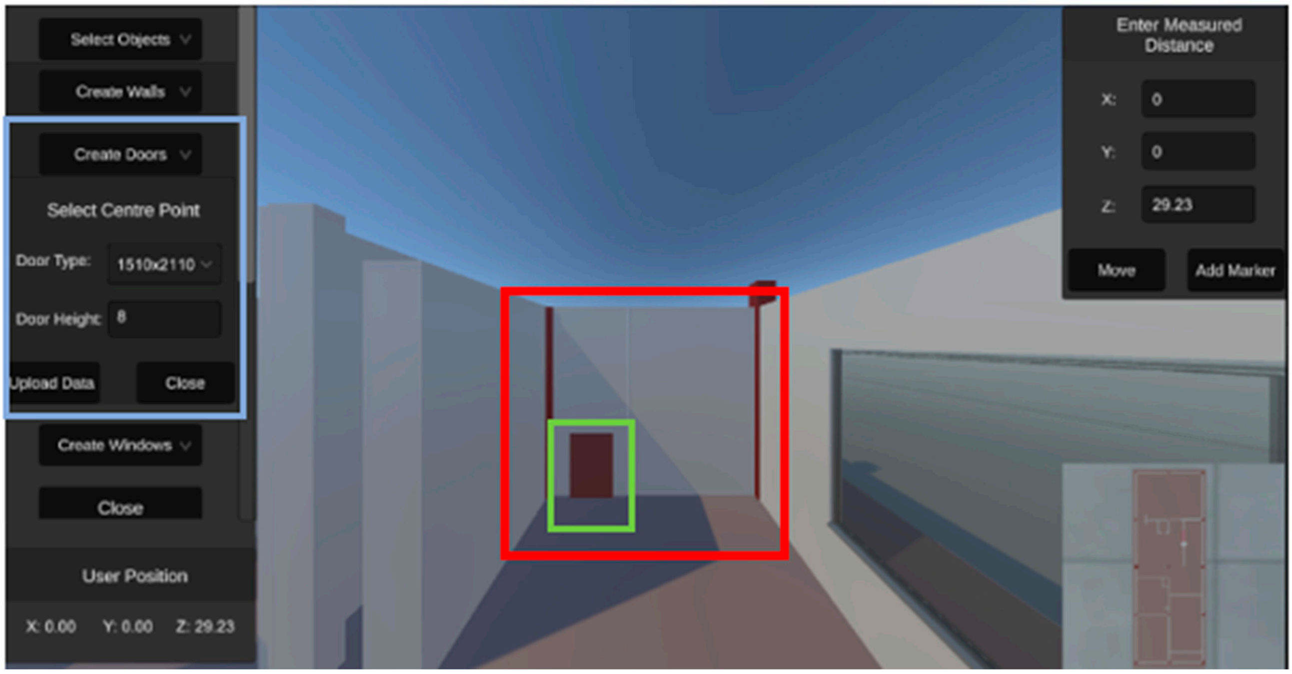


Figure 19. Creating a new door (shown in green) in a wall (shown in red) using the door creation panel (shown in blue). The size of the door is 1510 × 2110 cm.

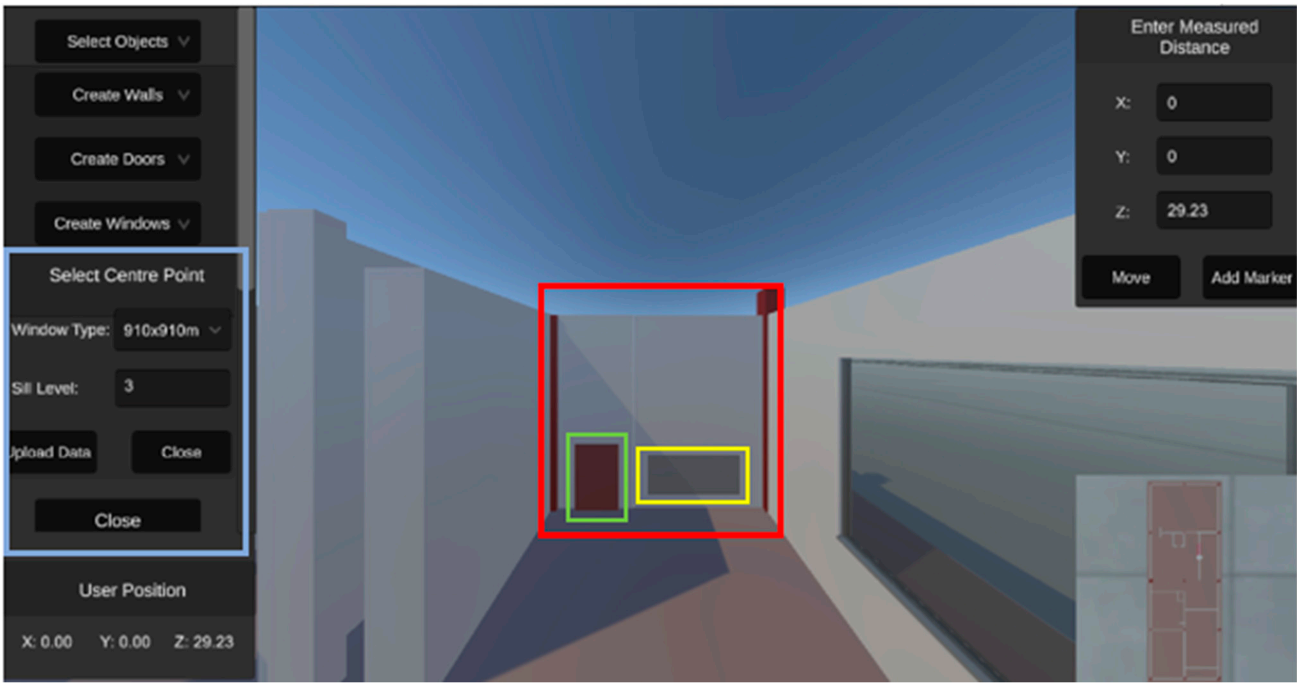


Figure 20. Creating a new window (shown in yellow) in a wall (shown in red) using the window creation panel (shown in blue). The size of the window is 910 × 910 cm.

4.5.5. Exporting the Data for Pre-Demolition Audit

After each iteration of corrections, the Excel file generated from the original 3D model (as shown in Figure 10) is automatically updated. All the elements deleted from the model are tagged "deleted" and all the elements added are recorded. From a practical point of view, if the scale of the building is large, it is impossible to verify the entire model at once. In this case, the surveyor can save the last correct coordinate and directly resume from the same point of origin next time. The final Excel sheet, after all corrections are made, is then imported into Autodesk Revit code (developed by the authors), which collects all the changes and updates the 3D digital model. In case any element (added during the correction process) is offset from the grid, the script intelligently snaps the element onto a grid. The corrected model is now exported for pre-demolition audit.

4.6. Critical Review of the Process and Outcomes

The key to development of the 3D digital model of this paper is to take advantage of a small amount of human intervention to solve numerous problems associated with automatic recognition of information by computer. This is mainly manifested in digital location of structural members during the paper drawing to CAD conversion process and in correcting mistakes in the 3D digital model.

For the former, notable challenges in the process of creating a digital CAD from paper-based drawings are the extraction of coordinates of different structural members, the sensitivity of their dimensions to the thickness of lines drawn for them, and the inadequacy of using lines (or other simple shapes such as rectangles) to communicate complex details (such as profiled steel section size). This will be solved by creating an option to input the information in a text box on screen, next to the image showing locations of the structural members for easy referencing. This step is being implemented and the results of this development will be further evaluated.

For the latter, the authors have developed the correction process (which is inevitable due to changes in the lifetime of the building) to ensure that any human intervention is intuitive and minimal. One particular problem with quick measurement of distances is lack of precision, even with inclusion of an intelligent snapping algorithm in the model. Fortunately, for demolition purposes, this lack of precision is generally inconsequential because this would not affect identification of the waste stream and would at most only cause a few percentages in error in prediction of the amount of waste. Nevertheless, this digital model has the potential to be expanded to be very accurate for applications where detailed information is necessary, for example in structural strengthening or refurbishment. This will be the next phase of development of the digital model.

5. Pre-Demolition Audit

5.1. Overview

A pre-demolition audit is a specific task in the project planning stage of demolition and the first step of demolition waste management. It is concerned with making an inventory of the type and quantities of elements and materials in the building for later decisions about reuse, recovery, recycling, or landfilling.

In this research, the pre-demolition audit is developed based on the Eural guideline. In this project, the web application of the Eural guideline is created in React [44], which has emerged as the preferred tool to optimize the demolition processes, including making the pre-demolition audit. As an introduction, this software is designed to evaluate structures prior to demolition, identifying materials that can be recovered, recycled, or reused, and assessing the environmental impact of demolition. The use of a 3D digital model in this software allows the user to perform detailed and accurate audits in minutes.

However, this software has unique requirements for how the data is presented in the 3D digital model. This section will detail how the 3D digital model described in the previous section is integrated into the web platform, including the following three phases: (i) uploading and management of IFC files in web applications; (ii) processing of this data; (iii) reporting.

5.2. IFC File Management and Uploading in Web Applications

The first step in the pre-demolition audit process involves the user uploading a 3D digital model that must use the Industry Foundation Classes (IFC) format [45] for outputting material and product information of the building. From the user perspective, this task is simple: a menu will appear in the platform's interface and the user will select the 3D digital model to be uploaded. However, from the programmer perspective, correct transfer of data is critical, which is achieved by ensuring compatibility of data between the 3D digital model uploaded by the user with a web application. To address this challenge, the IFC.js library is used, which is an advanced tool designed to interpret and translate IFC files (as outputted by the user's 3D model) into a format that can be efficiently managed and displayed in web environments.

IFC.js [46] is based on the Three.js [47] geometry system, a recognized framework for creating 3D graphics in the browser. This library is essential for handling the complexity and density of data present in 3D digital models, enabling efficient and dynamic visualization. It uses Instanced Meshes, an advanced technique for drawing sets of repeated geometries.

In addition, IFC.js implements flatbuffers for data persistence in an efficient binary format, which minimizes memory usage and ensures agile data management. One of the highlights of this library is its ability to prevent memory leaks, ensuring a smooth user experience.

5.3. Evaluation of Materials for Sustainable Waste Management

Once the model has been uploaded, the elements of the building and their materials can be evaluated to determine their recyclability and reusability. This evaluation can be undertaken either individually (Figure 21) for each element or collectively (Figure 22) based on groups such as columns, slabs, windows, and doors. Each component is analyzed by its specific properties, such as the type of material (concrete, wood, metal, etc.) This information is visualized in the application interface where all the details are shown in the associated menu (Figure 23).

This dual approach, considering both individual components and groups of components, allows for a holistic understanding of recycling and reusing opportunities (Figure 24) within the project, which will be developed in the pre-demolition protocol, taking the pre-demolition audit output of the digital model. By processing the data with advanced algorithms, the potential for material reuse is maximized, thus facilitating a more efficient and environmentally friendly management of available resources from demolition wastes.

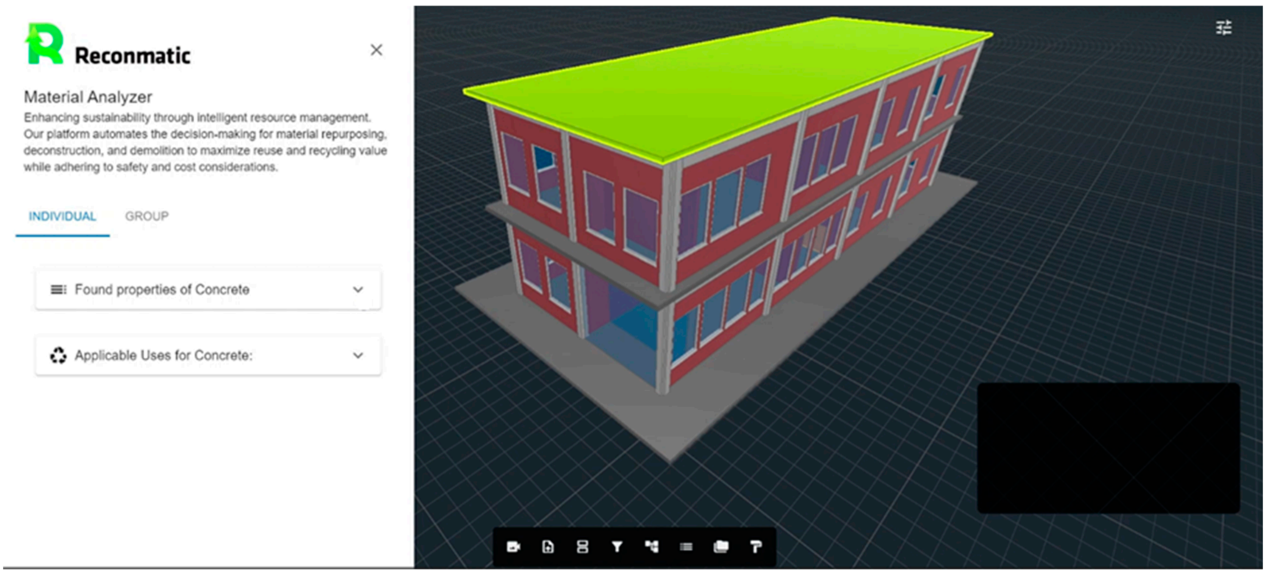


Figure 21. Display of properties by individual element.

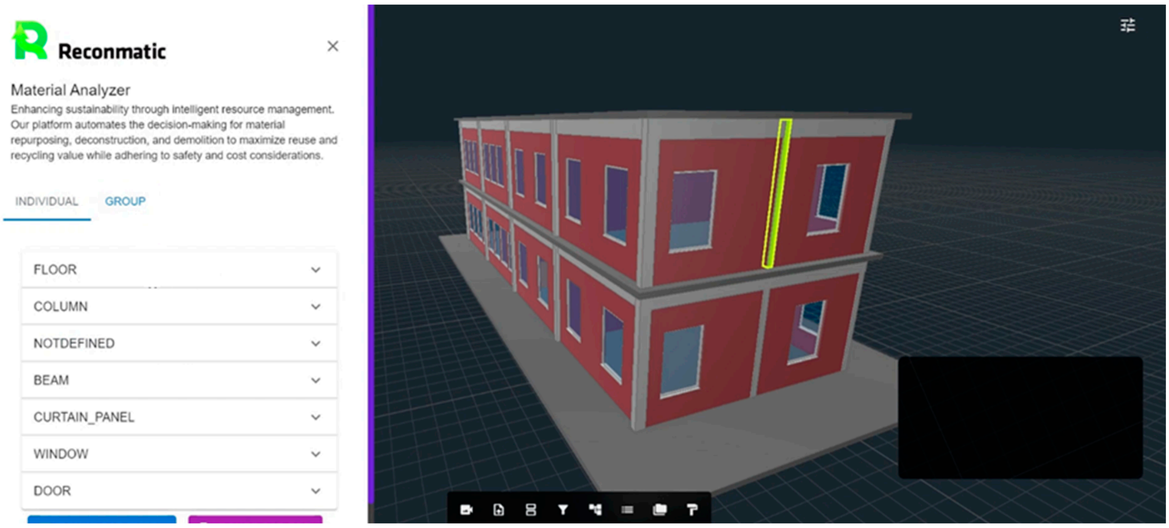


Figure 22. Display of properties by a group of elements.

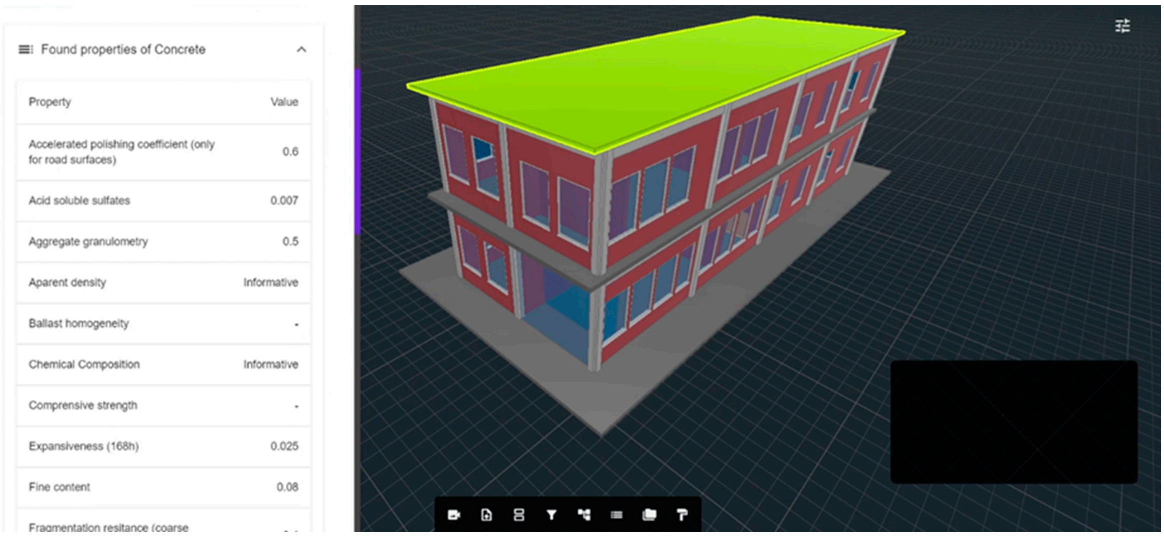


Figure 23. Specific properties of a roof.

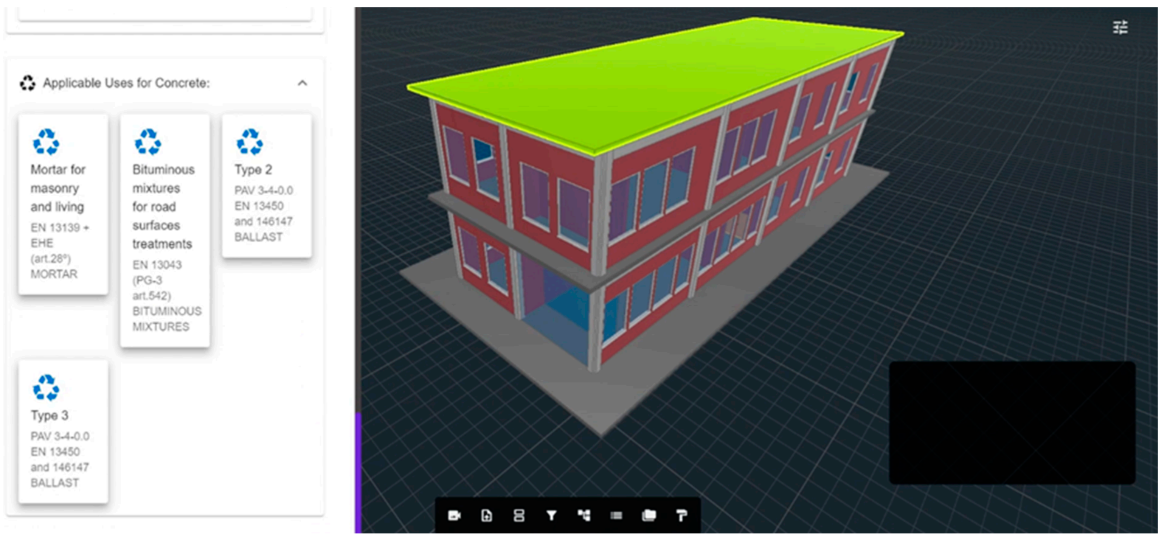


Figure 24. Reuse opportunities.

5.4. Reporting

As results of the pre-demolition audit, graphic outputs such as PDF reports (Figure 25) or CSV files (Figure 26) are generated. With these outputs, the auditor can visualize the demolition management by inspecting, both individually and as a group, how the structural components or their individual parts will be processed in demolition. The digital platform is the repertoire of all the relevant information of the building, thus including all the relevant knowledge of the stakeholders acquired from the different stages of their work related to demolition and waste management of the building. This ensures that no relevant information is lost.

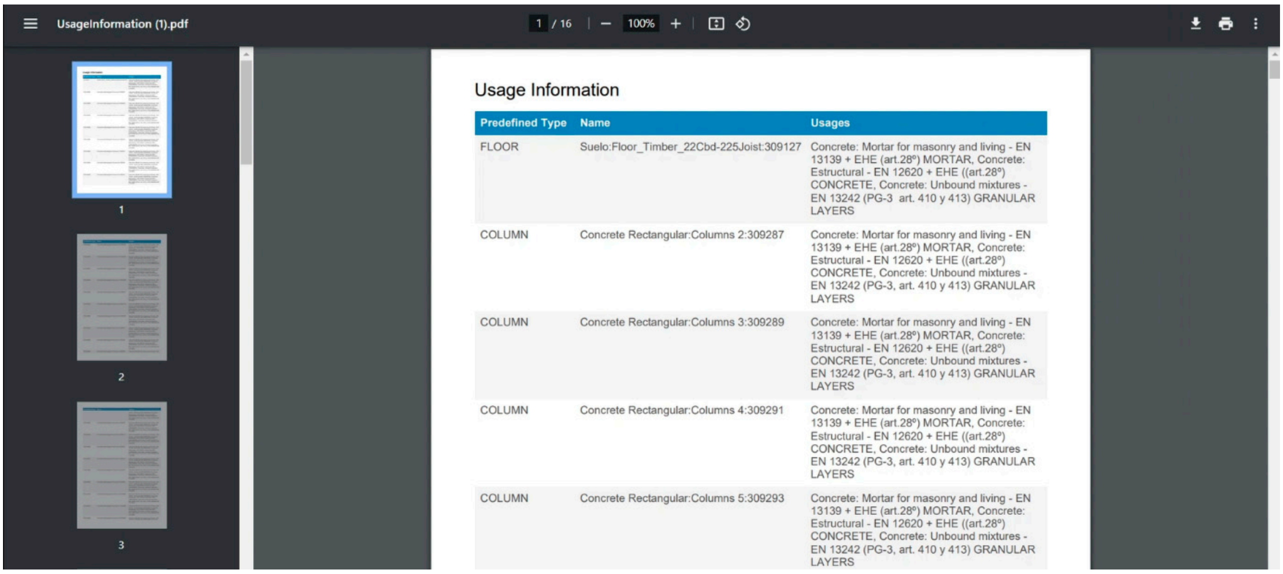


Figure 25. An example of PDF report.

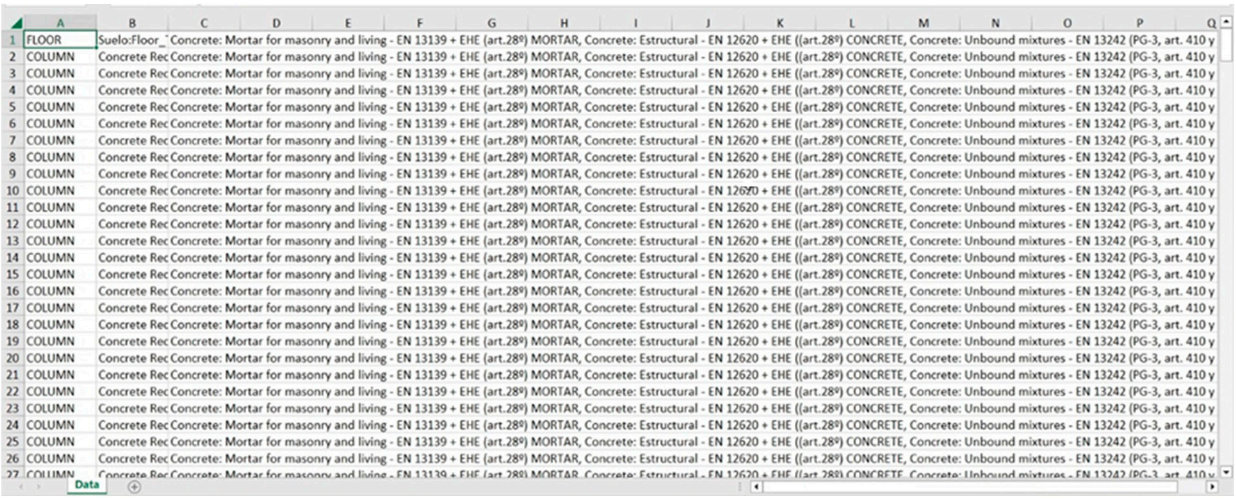


Figure 26. CSV files.

It is important to mention that the effectiveness of the digital model depends on the model having the correct material and product/element information for the pre-demolition plan, e.g., with regard to material/product reuse, and on correct extraction of the information for pre-demolition audit. At this stage, the RECONMATIC project team is still defining the required material/product information. However, whatever the required material/product information, this paper has demonstrated that they are correctly extracted in the digital model described in this paper.

6. Conclusions

This paper describes a novel method that integrates artificial intelligence (AI), computer-aided design (CAD), and augmented reality (AR) to automatically develop a 3D digital model for end-of-service-life (EoSL) buildings from paper-based drawings, in preparation for automated development of a pre-demolition protocol to facilitate high-value recycling and reuse of materials from significant waste generated by the construction industry, particularly from demolition activities.

The main contributions of this paper are as follows:

It proposes and demonstrates an approach that takes advantage of a very small amount of human intervention to overcome numerous challenges associated with automated recognition of paper-based information by computer.

It describes in detail an intuitive approach that incorporates augmented reality for correcting mistakes in the digital model that are a result of changes in the lifetime of buildings.

It demonstrates the implementation of a pre-demolition audit that allows building materials and products to be examined in detail in different ways (individually, collectively either by locations such as floor or by groups such as beams/columns/walls/floors).

The developed digital model is an essential part of a digital platform that allows for integrated decision-making for optimal demolition waste management by minimizing or eliminating problems brought about due to fragmentation of the construction industry and scattered knowledge of the history of the EoSL building. The digital platform will enable demolition contractors to drastically improve onsite operations, including waste classification and sorting, so as to minimize waste contamination. It will inform downstream product manufacturers in order to achieve the highest reuse of materials and products and to extract the highest possible values for the recycled materials.

The integrated digital model is ideal for transparency and quality assurance of demolition waste management.

However, the digital model presented in this paper is the first stage of developing the digital platform. Its application in planned demonstration cases of the Horizon Europe project RECONMATIC will test its effectiveness and advantages compared to existing models of demolition waste management.

The development reported in this paper is for the purpose of dismantling buildings at the end of their service life. Therefore, the required precision of information (such as element dimensions and their connectivity) is not particularly high. Although this development has the potential to be used for other purposes, such as structural strengthening and refurbishment, further research is needed to investigate how to efficiently gather more detailed information.

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