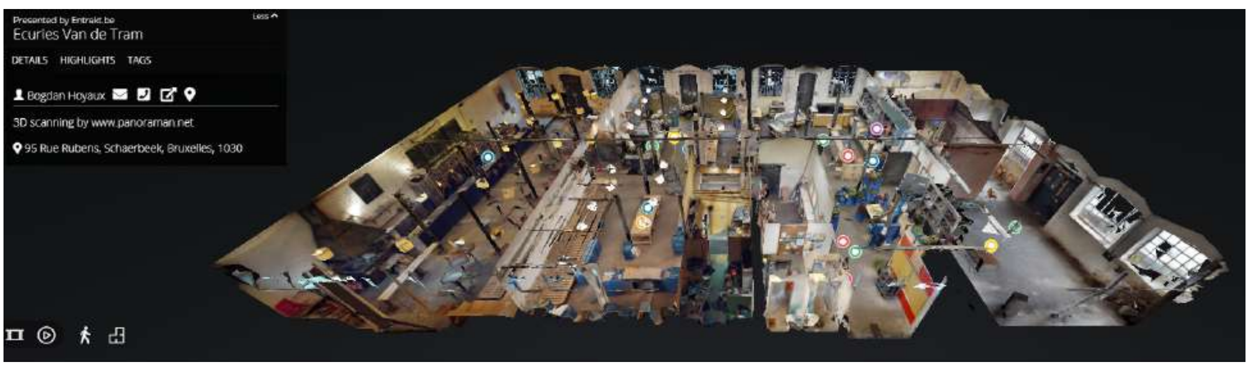
Digital tools for Reuse

Linking reuse and contemporary trends in the construction industry



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1. Introduction

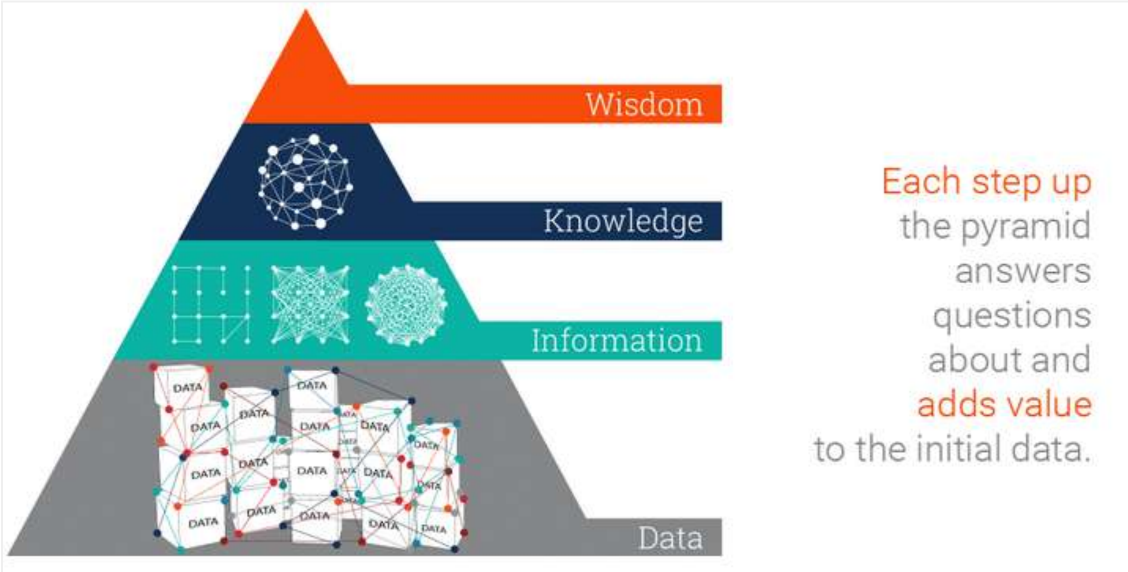
1.1. Circular economy & digitalisation : emerging trends in the construction sector

Different trends are emerging in the (de)construction industry. On the one hand, there is a strong and growing interest in the circular economy, with focus on maintaining value of building materials, products, elements and complete buildings, by design choices, but also in the end-of-life phase of a building, by trying to reclaim and reuse as many products as possible.

On the other hand, digitalization and the use of digital tools in the construction sector is growing, and is believed to be one of the major steps forward to a more efficient and more productive construction sector.

The idea behind digitalization is that data can be made available, and processed into information, knowledge and wisdom[1]. Through digitalization, data can be shared to provide better insights and to make better decisions; data and information can be put available to others, to allow more transparency and cooperation; data allows to measure and evaluate certain parameters and to do calculations; and data and information allow to optimize certain processes, eg. by automatization of repetitive tasks.

[1] https://www.ontotext.com/knowledgehub/fundamentals/dikw-pyramid/

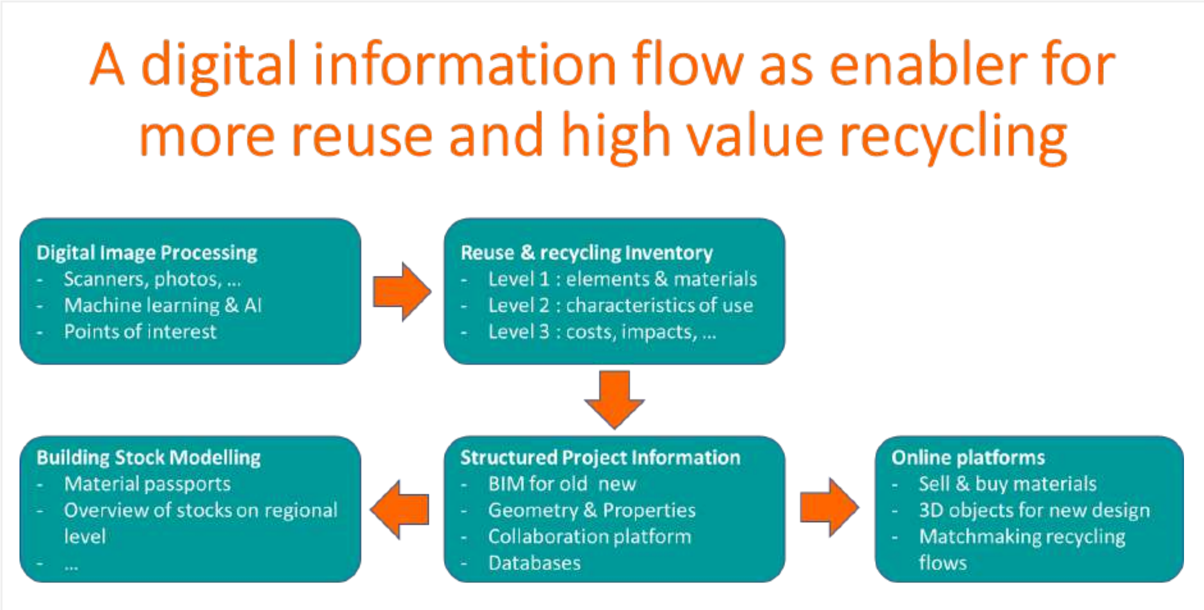


1.2. Exploring the use of digital tools for reuse of materials

This report explores the possibilities and the potential of digital technologies and tools that can help to improve reuse. Based on the state-of-the-art developed within the FCRBE project (and later complemented by the work in Interreg-NWE Digital Deconstruction) several interesting technologies and tools were selected by BBRI, in order to explore and exploit (through try-outs) the way digital information and instruments can help fostering reuse strategies.

Focus is put on the first phases of the 'reuse process', namely the inventory phase (conducting reclamation audits) and making the collected information available to inform the market, reuse & reclamation dealers, designers, other concerned parties, and to make better informed decisions based on a digital inventory. This means the work has focused on :

- How digital tools can help to acquire information in the inventory process, eg. 3D scanners, photogrammetry, automatized material recognition using AI/Machine Learning, ...
- How inventories can be standardised for easier use afterwards using BIM and other ways of information structuring
- How software & apps can help to create a better process and information flow



2. Methodology & approach

2.1. Methodology

The methodology to explore the potential of these digital instruments and approaches was to first foresee a general description of the tools and their use cases, based on the State-of-the-art (WP_T2 – D_1.1[2]). This allows for interested parties to gain sufficient basic knowledge in order to start developing their own interest and knowledge and practical experience with these tools.
In the second instance, the most interesting use cases per technology were identified, and a try-out or demo was elaborated, in collaboration with the actors in the field (e.g. Rotor) to validate the possibilities and evaluate the actual potential of the tools. The results of these tests are described in the report.

Finally, where possible and applicable, some general rules and guidelines are given for further work (in research, in development and in practice) for each of the explored technologies.

2.2. How to read this report

Each of the following chapters covers extensively the work done on each technology selected by BBRI :

[2] https://www.nweurope.eu/media/8917/fcrbe_wpt2_d11_20190927-for-publication.pdf

Chapter 3 : Reality capture : the use of 3D scanners, photogrammetry, ...
Chapter 4 : The use of Artificial intelligence in support of building material reclamation
Chapter 5 : Building Information Model (BIM) in support of reuse in the demolition industry
Chapter 6 : Applications (software) and Material databases in support of reuse in the deconstruction industry.

The final chapter gives an outlook towards future evolutions and steps in this very interesting and quickly evolving domain.

3. Reality capture & scanning technologies

3.1. Introduction

3.1.1. Context

Old buildings represent an important part of European cities' real estate stock. To increase the rate of renovation, it is now necessary to develop new tools to optimise and facilitate the renovation process and to develop strategies for demolition and deconstruction. Even if going faster seems paramount here, there is a risk of losing quality, intrinsic heritage values[3], as well as missing significant reuse potential. Understanding the nature and the condition of buildings is thus crucial to choose the better adapted solutions. This is where the new digital technologies have much to offer, and where innovative surveying tools may be the key to more 'responsible' retrofitting strategies and well-thought demolition and deconstruction.

The digitization of existing buildings is key to support the emergence of sustainable renovation models and accelerate the transition to a circular economy. The term 'digitalization' includes innovative recording technologies, with which data regarding the composition, state and use of the building can be compiled and shared between retrofitting actors. Those recording efforts are already well-advanced in new constructions where the BIM approach is becoming the norm, but various obstacles are encountered in the renovation and deconstruction of the existing building stock. The difficulty in establishing the bases of a digital model of existing buildings is one of the major obstacles that currently limits the development of digital potential in renovation & demolition. The BIM methodology developed for new construction is often unsuitable. Firstly, because it does not allow the full complexity of the existing built environment to be integrated. Secondly, because using BIM imposes significant modelling efforts and costs, not always adapted to the retrofitting/demolition world where many small businesses coexist.

[3] 'Heritage values' is considered here in the broad sense, not only for listed buildings

Surveying the existing condition of a building is a crucial step for every well-thought retrofitting or demolition project. Developments in 3D digital survey tools now make it possible to facilitate this step and easily capture a significant amount of information (not necessarily possible with manual recording methods). This qualitative geometric and visual information can be used as a basis for the creation of various 3D digital mock-ups suitable for renovation or reuse and deconstruction strategies. Scanning technologies represent a major opportunity for design offices specialising in the conservation, renovation or restoration of existing buildings, particularly old buildings. There exist various technologies that meet various needs, with solutions for every scale and level of technological expertise.

3.1.2. What exactly is reality capture?

In a broad meaning, 'reality capture' designates the process of digitising an existing building, its environment, or its components. It could be defined as

"translating the appearance and dimensions of a building, its components or its environment, 'as it is', in the form of a virtual representation, ideally in 3D."

Indeed, the term is often specifically linked to 3D scanning technologies. In this report, we chose to give a wider meaning and include innovative technologies related to 2D capture (see Figure 1). This choice is not trivial as such two-dimensional technologies are often more accessible and can provide a quicker access to key data. For example, 360 cameras can provide a quick representation of all rooms of a building at low cost but the actual dimensions of those rooms will not be captured with such devices. For reuse potential assessments it is thus clear that the level of technological deployment will depend on the requirements of the inventory missions as well as contextual parameters, such as the available budget or the timeframe of the study.

Recent high-definition technologies have revolutionised the building surveying and recording processes, which are crucial when working on existing buildings. The documentation process is now benefiting from an extremely high level of details offered by such automatic 3D digitalisation technologies. Some limitations factors remain, such as the complexity of the involved data transformation processes or the significant requirements in terms of resources. Here the two main challenges are identified to be answered:

(1) Access barriers to innovative scanning technologies: Getting into 3D scanning represents a significant investment, both in human and in material point of view. The obsolescence of technological instruments, the need of constant software upgrades and powerful machines to read the files represent big challenges to access scanning technologies. Moreover, these techniques need high specific knowledge that differs between the various techniques. Often smaller enterprises cannot afford to invest in constant training or in the latest technologies. This explains why the scanning technologies are nowadays not yet largely used in the renovation field. The possibility of subcontracting scanning missions is thus crucial, but it still requires applicants to be able to express their needs in a clear and technical way.

(2) Lack of guidance for appropriate collection, processing, and valorisation of data : High resolution geometric data is extremely heavy, requiring large processing and storage capacities and high-end computers to manipulate them. Beyond their size, the 3D datasets are often monolithic and do not have a sufficient level of segmentation or semantization to create meaningful data. **Only adequate post processing workflows** can guarantee an efficient valorisation of the resources spent upstream to collect the data. Finally, even if the way of transforming digitised 3D data to extract useful data would be well-defined, the software solutions to do so are often very complex, expensive, and not building-oriented. Many processing workflows remain repetitive and could be automated. All those reasons explain the observed high prices for the realisation of complex digitising missions, where not only the geometry of the building is sought after, but also building features and pathologies. It makes them rather uncommon in the context of small projects.

This report discusses the meaningful potential of reality capture technologies for reclamation audits and reuse inventories without setting aside the barriers to a massive appropriation.

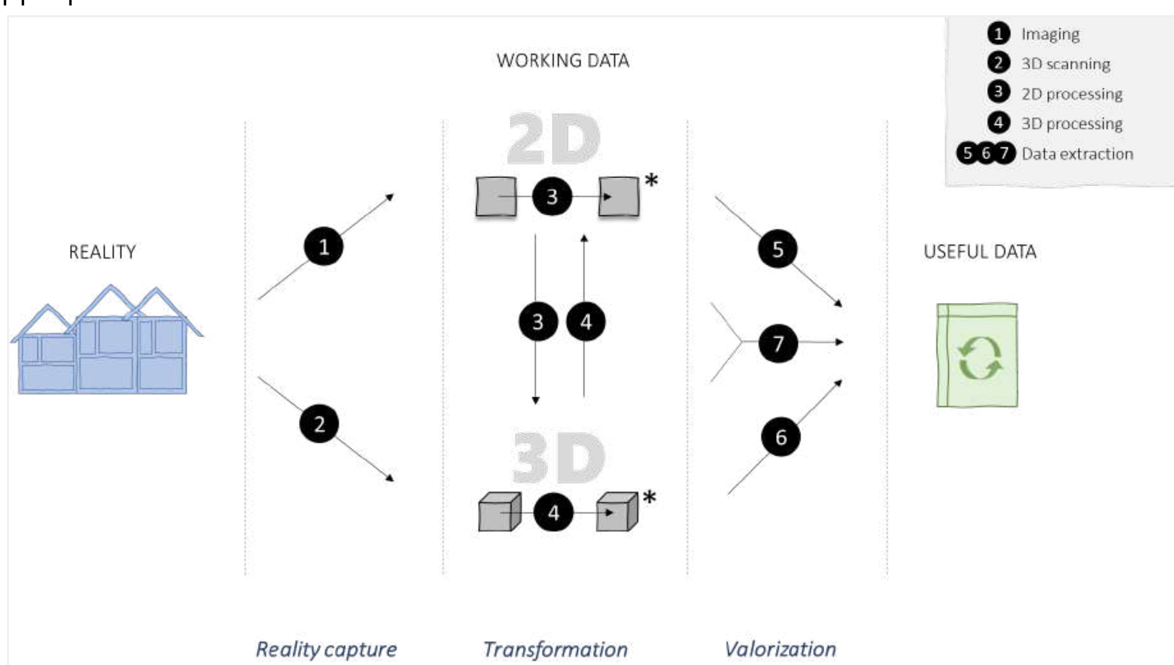


Figure 1. Reality capture and data processing up to useful information (source: BBRI)

3.1.3. The object of interest, ‘as it is’

For each capture mission, one first important question to be asked is the object of interest. The scale of study is the central parameter here (Figure 2). On a small scale, it is possible to digitise small or very small architectural elements such as ornaments, small mouldings or carved elements located at a height. On a larger scale, reality capture technologies can be used to create models related to the entire building. In some cases, the surveyor will want to focus on a specific part of the building, such as a facade or roof. Here too, the possibilities offered by 3D digitization to the various experts are immense. At the city scale, entire districts could be digitised, often in the framework of more strategic thinking (e.g., material stock in the city, flows of materials). In fact, specific needs can be expressed at each scale.

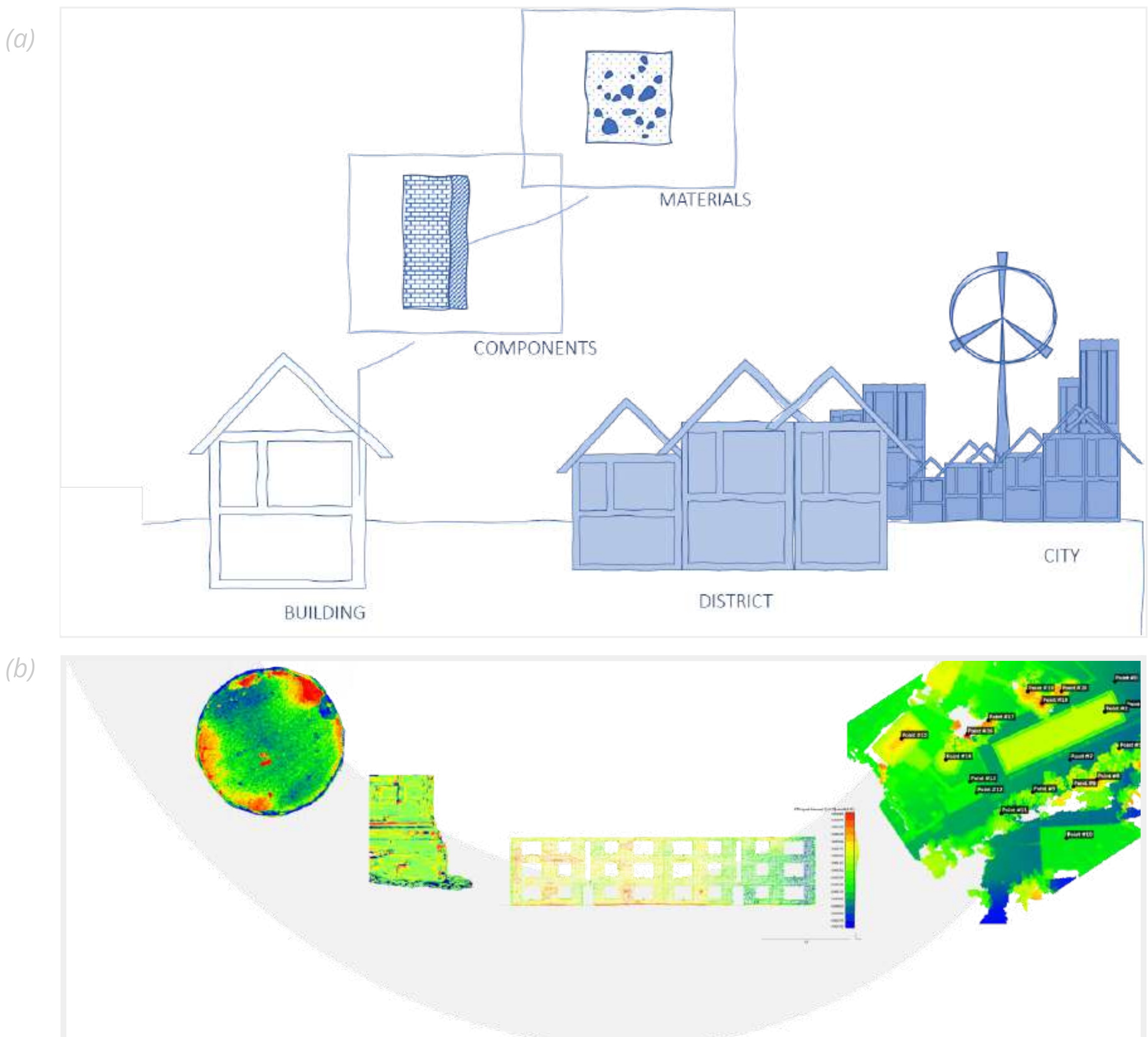


Figure 2. *The object of interest varies from case to case, from microscopic scale up to city scale.*
(a) *Schematic representation;* ***(b)*** *actual studies of planarity, performed on various scales (source: BBRI)*

3.1.4. Real life needs and digital answers

Beside the scale of study, the final goal of the reality capture mission ('useful information') will allow defining the right means and the right technologies. Generally, the means should be expressed in terms of 'deliverables', i.e., the digital file that will answer the need. Let us imagine that the goal of a mission is drawing up inventory of the construction materials at building scale, then the key deliverables could be annotated CAD plans, pictures, or a wide range of digital views extracted from realistic 3D models. All those files could allow a specialist to access the needed information in a pre-processed way. One must keep in mind that the range of possible deliverables depends on the technologies mobilised. Not every technology can produce every possible deliverable, and there, understanding the key technologies and their 'working data' is crucial.

3.1.5. Useful information

What exactly is the 'useful information' when it comes to a reclamation audit? In fact, it can vary a lot from case to case. Globally, two general categories of information can be found: (1) which building materials present a reuse potential and (2) How can they be reclaimed for reuse?

What to reuse : Often, construction materials and products will be at the heart of all reality capture initiatives. Both qualitative and quantitative information will then be sought after. The qualitative information can be relative to the nature of the reclaimable building elements or to their condition. The 'nature' groups aspects such as the function, the composition, and the origin (e.g., manufacturer, date of production) of the building element/material. The 'condition' evokes parameters such as the general state of the element, the presence of pathologies of contaminants or the estimated capability of assuming the design function. Quantitative information reflects size and performance parameters. Studies rarely go about one unique material or element. Characterising a group of similar components is often useful (e.g., all the windows of the building with similar composition). Describing a set involves a series of new criteria, as shown in Figure 3.

How to reuse Determining the type, conditions and quantity of a certain element is only part of the assessment. Of course, other parameters enter in play when it comes to evaluating reusability. The accessibility of the element, the logistics involved for dismantling, or the risk of damage during the dismantling are examples of such parameters. Figure 3 summarises part of the critical information.

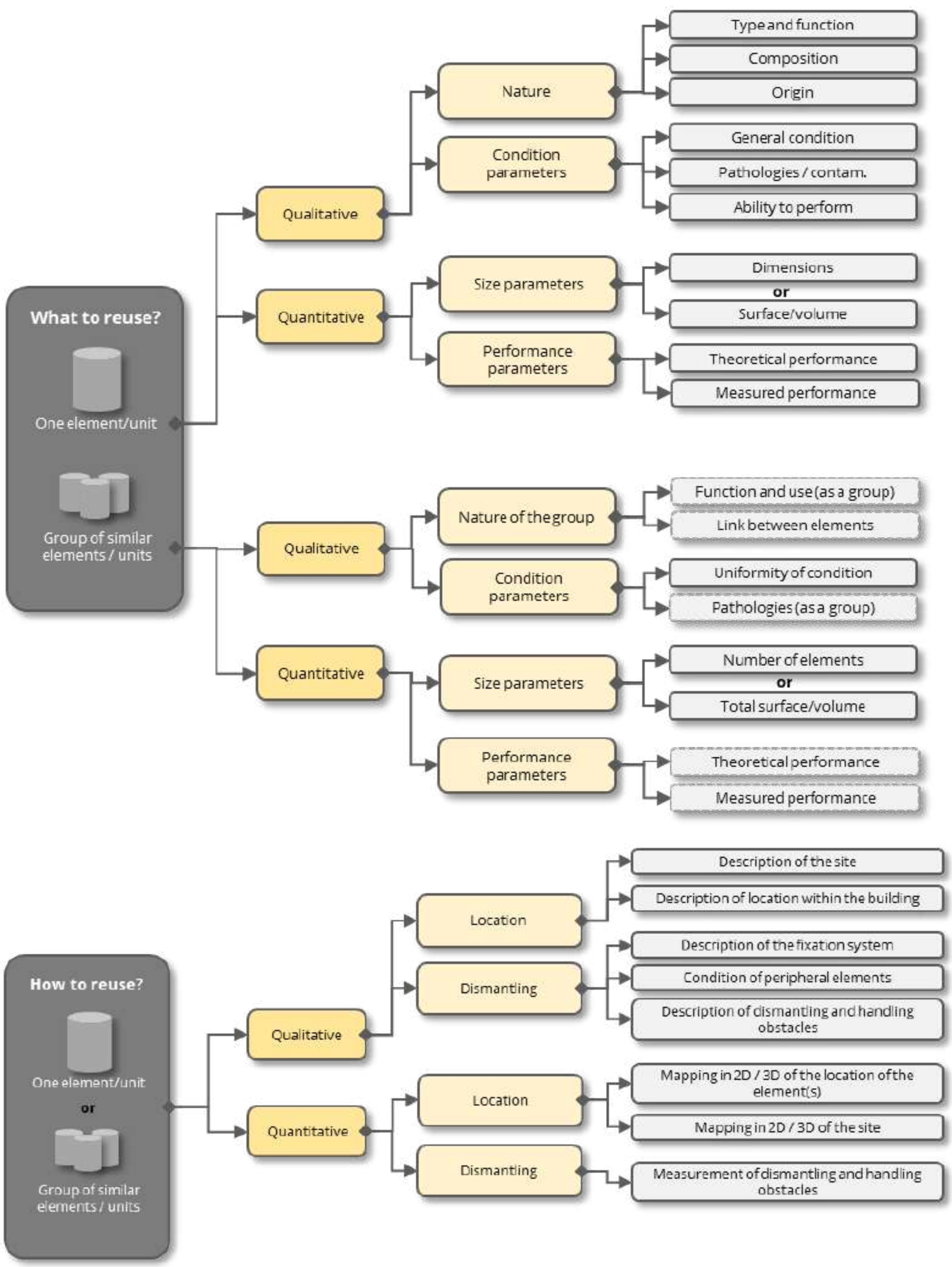


Figure 3. *The broad range of information that can be sought after and resolved with a reality capture study.*

More information on this topic can be found in the FCRBE guide for identifying the reuse potential of construction products[4].

4 https://www.nweurope.eu/projects/project-search/fcrbe-facilitating-the-circulation-of-reclaimed-building-elements-in-northwestern-europe/#tab-3

3.1.6. Working data

Obtaining useful information involves creating adequate deliverables where this information can be observed. There is no unique answer to each question, and with reality capture technologies, the possibilities in terms of data are tremendous. Before starting to describe the different surveying techniques, it is thus essential to **briefly recall the types of representation of reality that exist, in 2D or 3D.** We should mention that in any dimension, a distinction must be made between 'raw' or 'direct' representations (directly produced by the scanning equipment), and 'constructed' or 'indirect' representations (obtained by a transformation or modelling process from raw data).

2D data:

The main **2D data** types useful for reuse assessments can be summarised as followed:

Raster images

- Multiple channels
  - RGB images
  - Multispectral images
- Unique channel
  - Thermal images
  - Other

Vector graphics

- Vectorized images
- CAD drawings

Bi-dimensional data can exist in two forms: raster or vector. **Raster images** are very common, as their basic unit is well-known: the pixel. It means that the captured reality is represented in the form of a grid of finite size. Most imaging sensors are characterised by a 'resolution', which translates the fineness of this grid. On the resulting image, each pixel is attributed a value on a defined range, which can represent many physical variables.

The most basic raster representation of reality is well-known: the **colour picture**, or 'RGB' image (for the three main colour channels used to represent reality, Red, Green and Blue). On the field, pictures remain the easiest way of capturing and sharing information. The universality of this format makes it extremely useful. It can also complement any technical analysis in a clear and visual way. Additionally, various metadata can help the assessor to better contextualise the picture, with timestamping or geotagging for example. **Multispectral images** are produced by advanced cameras capable of extracting the

radiation of specific wavelength ranges. Those images may improve the detection of specific materials or categories of materials.
Sometimes each pixel is associated with one unique variable. The simplest example is a black and white image, where most of the time each pixel has an **'intensity'** ranging from 0 to 255. **Thermal images** are pictures produced with a sensor capable of isolating part of the infrared (IR) spectrum. Any object above 0°K will emit IR radiation and the thermal camera will produce an image where the intensity of each pixel depends, among other parameters, on the surface temperature of the captured object. On more expensive devices, a calibration process can allow us to estimate those temperatures. Thermal images are particularly precious because they allow to highlight hidden material configurations, as seen on Figure 4.

A segmented picture is another example where a unique scalar field exists: each pixel is categorised as belonging to a specific object or category. The segmentation process is a key step within many artificial intelligence processes for material or damage recognition (see Chapter **Error! Reference source not found.**).

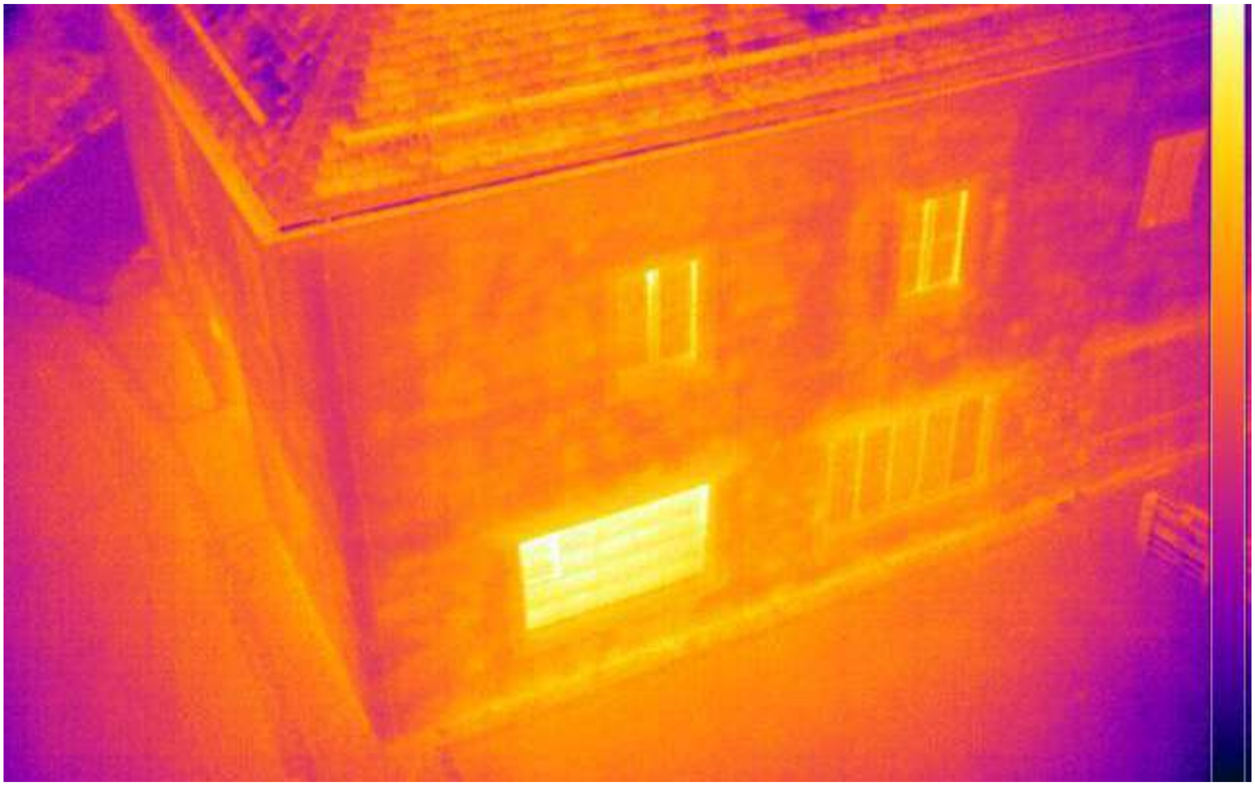


Figure 4. *A thermographic image. (Source: BBRI)*

Vector data is scalable but cannot be produced directly by imaging sensors. The object of interest is therefore represented with geometric shapes that are scale independent. Those shapes are defined mathematically and can be easily modified in an appropriate software.

CAD drawings are very common in the construction sector and consist mainly of polylines defining building-related objects. Any image can be converted into vector graphics with appropriate algorithms (Figure 5).

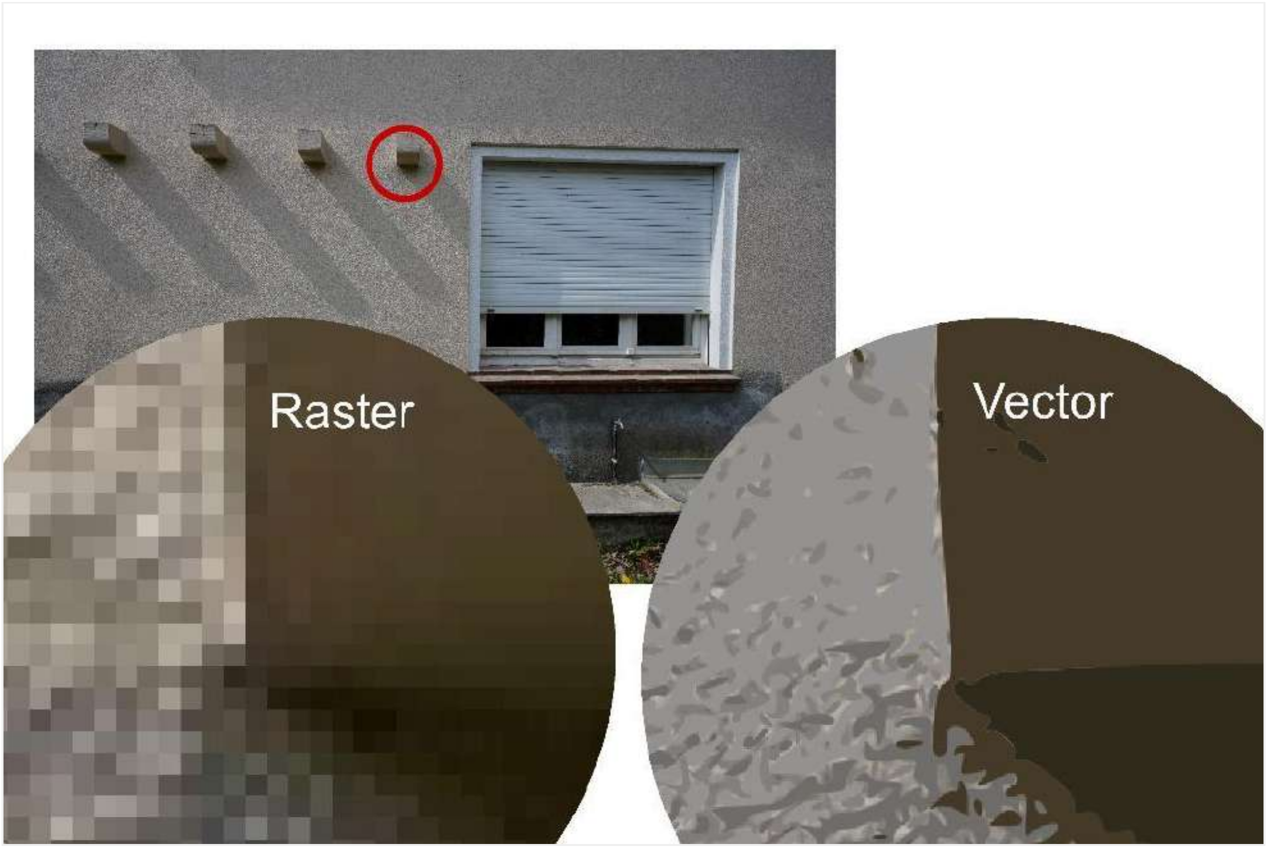


***Figure 5**. Raster and vector data. (Source: BBRI)*

3D data

Tri-dimensional information can exist in many forms (see Figure 6). Two main categories can be defined: non-modelled 3D files and modelled 3D files. The second category groups 3D files where some modelling operations were performed, i.e., manual or automated drawing using 2D primitives, such as lines or arcs, or 3D primitives, such as planes or cylinders. A distinction can also be made between semantic and non-semantic files or models depending on the association of useful information to the geometric data.

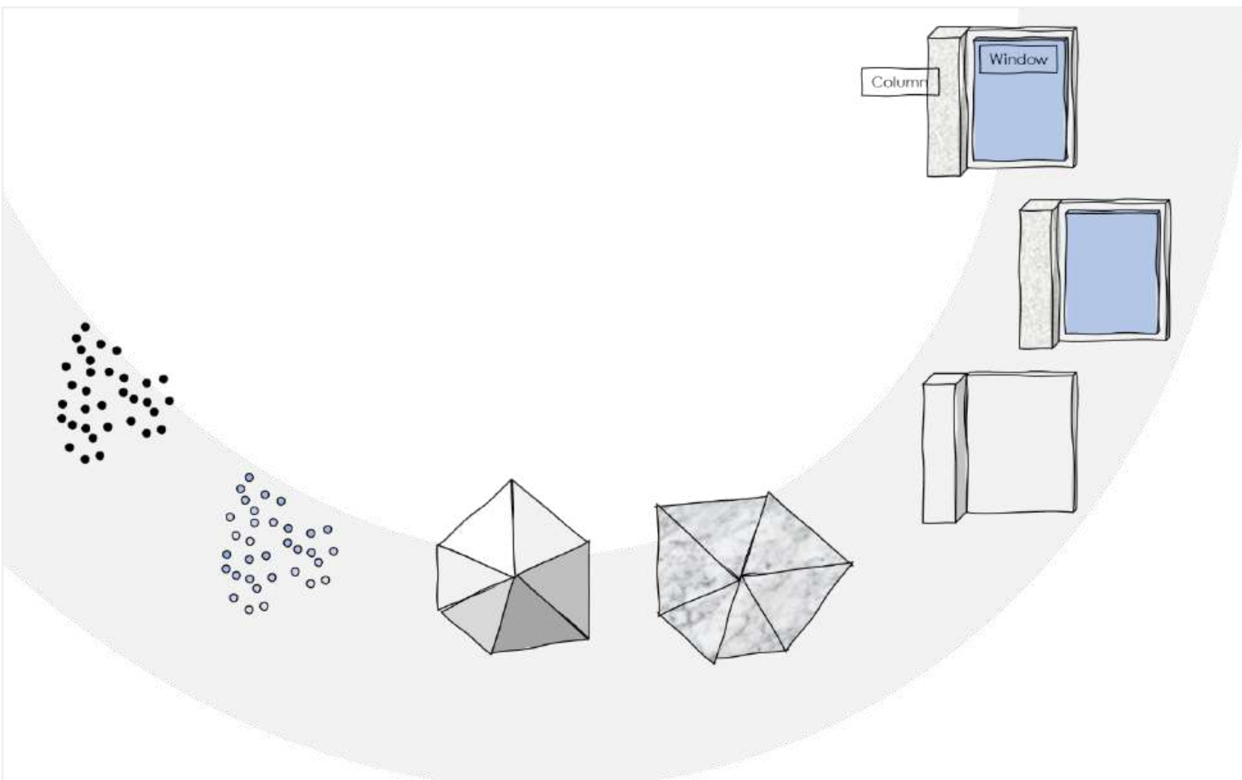


Figure 6. *The many types of 3D data, from point clouds up to modelled geometry with semantic value. (source: BBRI)*

The most common 3D file types and subtypes can be listed as followed:

Point clouds

- XYZ point clouds
- XYZRGB point clouds
- XYZA point clouds (or scalar field point clouds)
- XYZ… + ABCD… point clouds (or multiple variables point clouds)

3d polygonal meshes

- Untextured / Textured meshes
- Triangle / Quad meshes

- …

Geometric models
Semantic geometric models
BIM models

The point cloud is the most typical representation associated with 3D scanning technologies. In its simplest form, the point cloud is a text file that contains the geometric coordinates of all points (XYZ point cloud). Thanks to modern technologies, information about the colour of the scanned object can also be associated with each point (XYZRGB point cloud, see Figure 7). The geometrical and colorimetric data being the main interest for most of the studies related to buildings, the customers will generally not need additional information, even though other elements may be collected within the file. In fact, any kind of variable can be associated with each point. This allows the creation of specific point clouds that can highlight key information for reclamation audits. For example, different classes of objects can be defined, and each point can be associated with one of those classes. This so-called 'segmentation' process is particularly crucial to gain access to the useful information. More and more, point clouds appear as the standard format to record existing buildings in high resolution. They already offer a large panel of uses thanks to a certain universality of how the information is stored (i.e., a long list of points located in 3D space).

Figure 7. *The XYZRGB point cloud, becoming one of the standard formats for high resolution 3D capture. (source: BBRI)*

A second type of 3D model is the **polygonal mesh**, i.e., a polyhedral assembly described by vertices and edges forming triangles (also called 'triangulated mesh') or quadrangle ('quad mesh'). It is therefore a continuous representation of the object, as compared to the discrete representation of point clouds (see Figure 8). The areas bounded by the individual edges can be represented (surface model) or not (wired model). Such models are often obtained by transformation from a cloud of points, usually by means of an algorithm called 'polygonization' or 'facetization'.

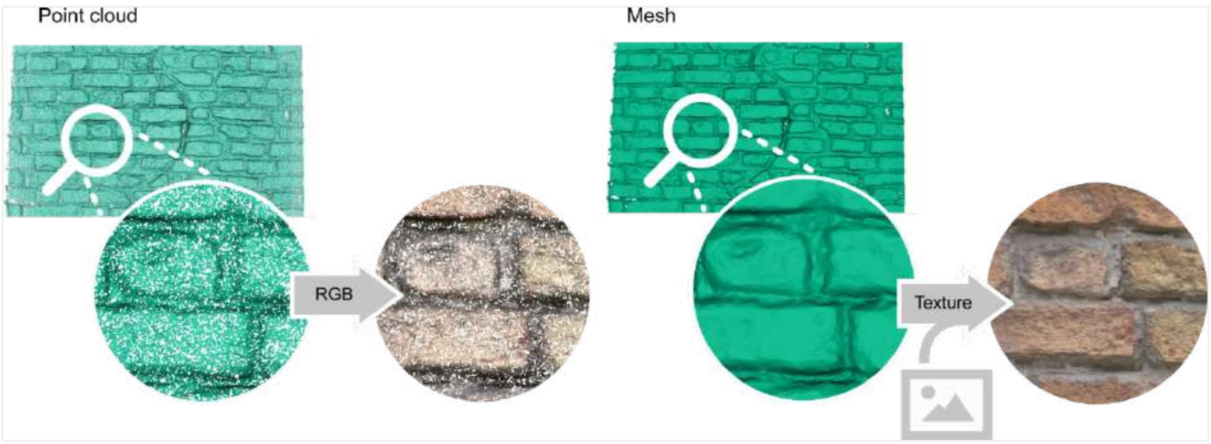


Figure 8. *The fundamental difference between point clouds and meshes. (source: BBRI)*

The **geometric models** are the result of a modelling process using geometric primitives, using a point cloud or polygonal mesh as a 'guide'. Primitives can also be made up only of closed volumes, for example, generated by extrusion. In this case, we speak of a solid model. Such an approach results in models that are aesthetically more sober and lighter in weight, but with the loss of much of the surface detail. In its most advanced form, the modelling approach aims to create 'parametric objects' to which properties can be associated. This is the basis for the creation of a **Building Information (BIM) Model** (see Chapter 5).

Beyond the type of 3D representation, the format used is crucial. First, there are the so-called 'proprietary' formats, which are specific to certain commercial software. The use of such formats is not recommended when the 3D model must be used by several people because of a risk of incompatibility/inconsistency (e.g., employees do not have the same version of the software) or access-barrier (e.g., one of the employees does not have a licence for the software). The conversion of data as open-format files (e.g., *.las for a point cloud,*.e57 for a laser scan,*.stl for a mesh, or *.obj for a textured mesh) is then desirable to guarantee an optimal workflow. It should be noted that such conversion can generally only be done within the commercial software associated with the proprietary format. It is therefore up to the actor benefiting from the commercial licence to oversee the operation.

Open formats are supported by most software and limit the risk of seeing issues. Those last remarks already show the importance of implementing clear data communication patterns between the people involved around the reclamation audit.

3.1.7. Imaging technologies

Many devices allow you to capture real-life scenes and generate pictures. As an illustrative purpose, Figure 9 shows how the different kinds of imaging devices are linked to various outputs. Drones act more like a transport vector on which different types of equipment can be attached. There is a wide variety of devices within the same category, and smartphones, for example, vary greatly in their capabilities from one brand to another and from one model to another. Those aspects are discussed in the following sections.

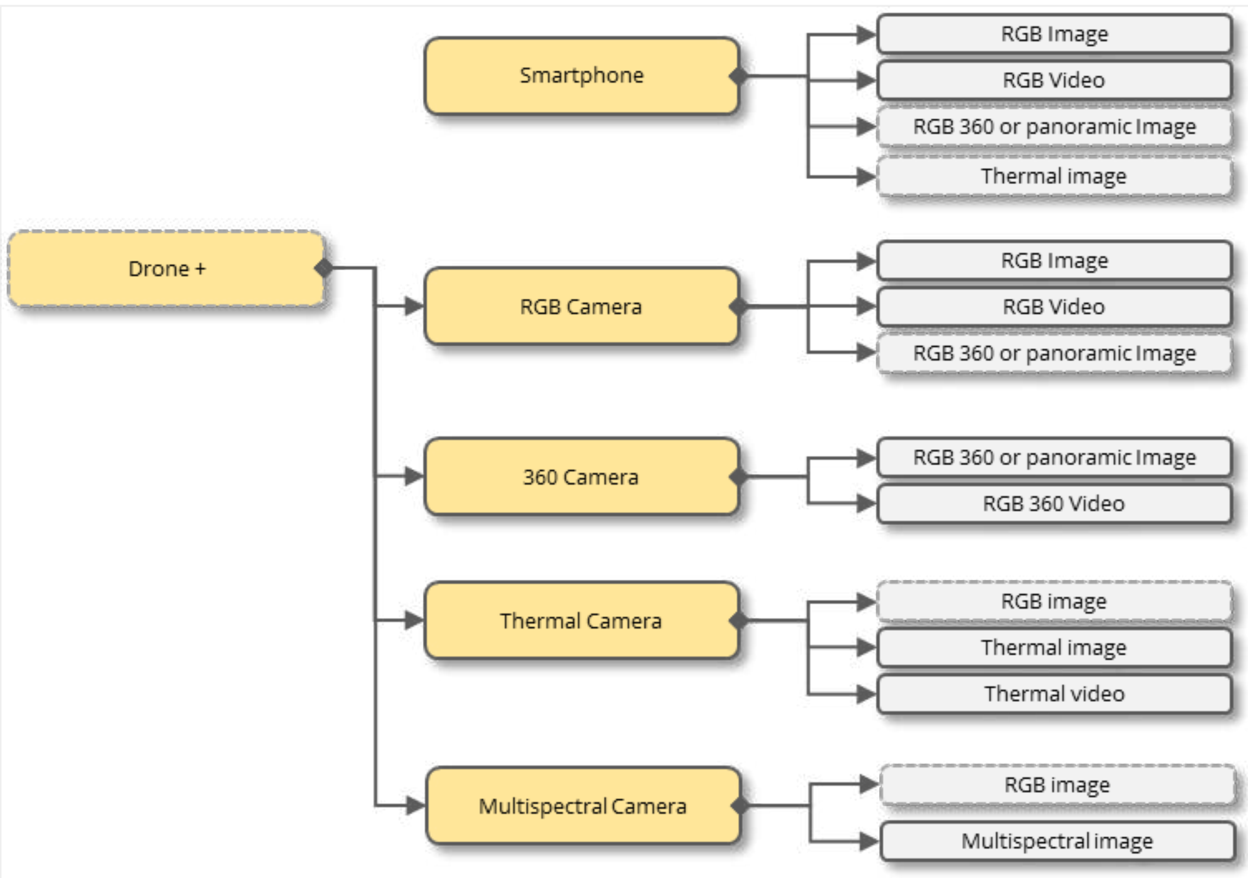


Figure 9. *All imaging technologies create raster data; This diagram shows the correspondence between the imaging technology and the generated data types. Dashed boxes indicate outputs that are less frequent for a particular device type (source: BBRI)*

Smartphones and tablets: The smartphone is the most versatile and affordable imaging equipment. Most of the time it allows you to capture decent footage. It is the 'go-around' tool for quick assessments. However, under some conditions, better equipment could be necessary (e.g., bad lightning conditions, far-away objects to capture).

Because they are also computers, modern smartphones and tablets bring a lot of new hardware innovation, like lidar or depth acquisition for quick 3D scanning (see 3.1.4.1). The integration of AI functionalities is also becoming more and more frequent. Many apps are flourishing for specific industry needs, which combine image capture and image processing (see 3.2.1.1) using the smartphone versatility. There seems to be room for many tools dedicated to reclamation audits.

RGB Cameras: The functional principle of RGB cameras will not be detailed in this report, as they constitute the standard equipment in many scientific and non-scientific disciplines. It should be recalled that many types of cameras can be found on the market. **Standard compact photo cameras** are the most basic devices. Often, smartphones will be preferred to them for their even greater compactness. Nevertheless, some compact cameras offer high levels of zoom, which will allow better capture of distant objects.

In terms of picture quality, **DSLR and mirrorless cameras** are a step above. Their greatest strength is the modularity they offer through lens interchangeability. Such devices can also incorporate up to 'Full-frame' or even 'Medium format' sensors, which are the champions of low light conditions. **Action cameras** were initially developed in the world of sports, to be embarked on a helmet, a strap or even a vehicle. Therefore, those cameras show qualities relevant to recording videos on large areas: robustness first, through the resistance to shock and weather, and minimalism, through a design that aims to reduce the weight and size to a maximum. With cameras barely larger than a matchbox, it is already possible to make videos in 4K resolution. Photos are possible but often limited in resolution and quality.

360 cameras: 360 cameras are devices capable of producing ultra-wide-angle pictures (see Figure 10). True panoramic devices will generate a complete spherical representation of the environment, all around the user. Naturally, the completeness of those pictures is extremely useful for reclamation audits. It should be kept in mind that the resolution of panoramic pictures is however crucial when small details need to be analysed on the scene.

Figure 10. *A '360' image, a powerful support for quick inventories. (source: BBRI)*

Thermal and multispectral cameras: Visible light is only a fraction of the electromagnetic spectrum. Although conventional cameras are adequate for many missions, more advanced inspection tasks may require the use of specific equipment. **Thermal cameras** are, for example, very useful for the diagnosis of buildings and installations. They can be used to detect temperature differences on the surface of captured objects, but also variations of reflectance. **The multispectral camera** is another state-of-the-art piece of equipment that allows, as its name suggests, to record several images simultaneously on specific bands of the light spectrum, in the visible, infrared, and ultraviolet. Increasingly common in the field of agricultural, forestry or geological research, its use for the study of buildings is expected to spread in the coming years. Indeed, materials tend to have a specific signature on the various analysed light spectra. Having more precise ways of detecting those subtle signatures would make the automated identification of materials easier.

Drones: The use of drones, or UAVs (Unmanned Aerial Vehicles), is a relatively recent development in geometric surveying. UAVs have enormous potential, but also raise some questions mainly related to security and privacy. They are more of a measurement vector than a measurement technique (Figure 11). Indeed, these light flying vehicles can be equipped with surveying equipment, which allows access to certain parts of the building that can be difficult to analyse by other means (e.g., high buildings, roofs, see Figure 12). In its simplest form, a drone can be equipped with a camera to collect many images or videos around the building. These images can then be processed using photogrammetric techniques (see 3.2.1.3)

Figure 11. *Professional drone, with two cameras (source: BBRI)*

Figure 12. *Typical drone camera footage (source: BBRI)*

There are several large families of cameras that can be transported on a UAV. First there are **miniature cameras** whose main quality is reduced weight. These small, minimalist devices are usually entirely dedicated to video capture. If the quality of the visual rendering sometimes leaves something to be desired, these cameras can be very useful to obtain video feedback from the UAV at a lower cost. A UAV can also **carry any type of standard camera** if it is capable of lifting it in the air. There is of course a wide range of camera models, as described briefly in 3.1.3.2. Although the image quality of compact digital cameras is satisfactory, this type of camera is not recommended for photogrammetric surveys or for making videos. DSLR cameras offer superior image quality; however, they have many elements that increase their weight and are not necessarily useful for the UAV operator. **Hybrid mirrorless cameras** are ideal in many cases, because their image quality tends more and more towards DSLR, with a lighter weight and a smaller footprint. This type of camera is extremely versatile and can be used for specifications of many missions. However, such devices are still too heavy to carry with low form-factor drones. In that matter, the new European drone regulations[5] is quite restrictive and drones with a weight below 900g will make it easier to comply soon. For the same reasons, professional movie cameras will rarely be used for surveying or inspection, where lighter equipment is often preferred. More and more small cameras are indeed able to film in 4K with a good image quality.

Beside standard RGB cameras, thermal and multispectral cameras can also be fitted on a drone. There, the advanced analyses offered by such tools can be extended: access to roofs or high areas, surveying of large zones or working in difficult environments (Figure 13).

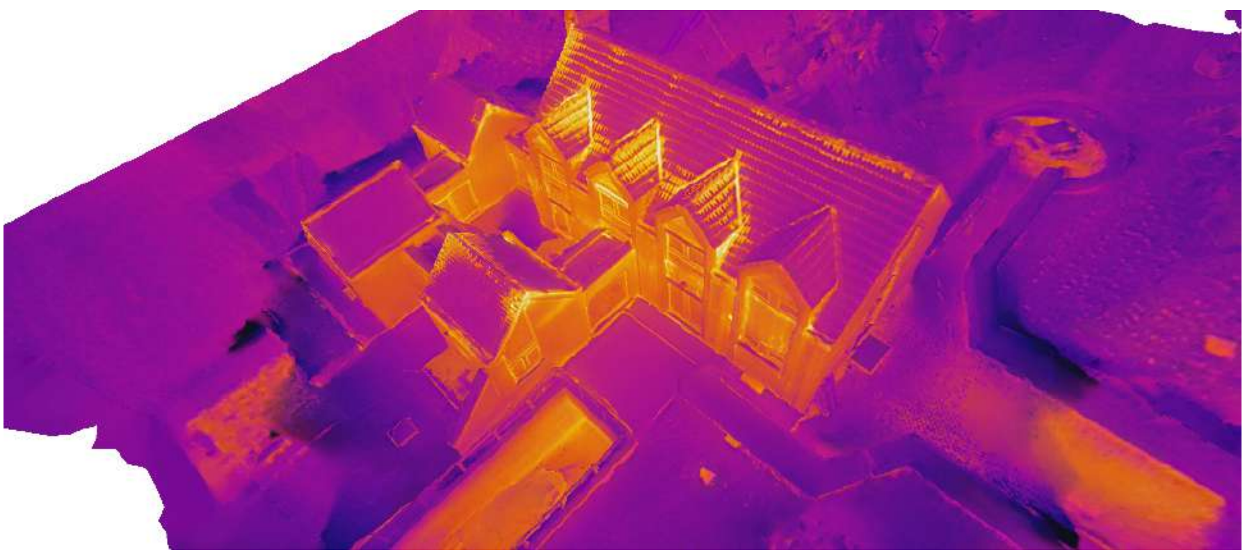


Figure 13. *Thermal imagery from the air with a drone. Thermal images are applied as texture on a 3D mesh (source: BBRI)*

[5] https://www.easa.europa.eu/domains/civil-drones-rpas

3.1.8. 3D scanning technologies

Smartphones and tablets: Smartphones constitute the entry point to 3D scanning technologies. While their reduced size is not compatible with the most accurate scanning methods, their versatility is a key strength. In the last few years, many apps were developed to take 3D measurements within the user environment with 'Augmented Reality' techniques. Whereas it often lacks precision, it can still be useful for quickly estimating room dimensions. Genuine 3D sensors are sometimes incorporated on high end recent smartphones and tablets. Those lidar or depth cameras will then produce real point clouds, with less accuracy compared to dedicated equipment (see Figure 14).

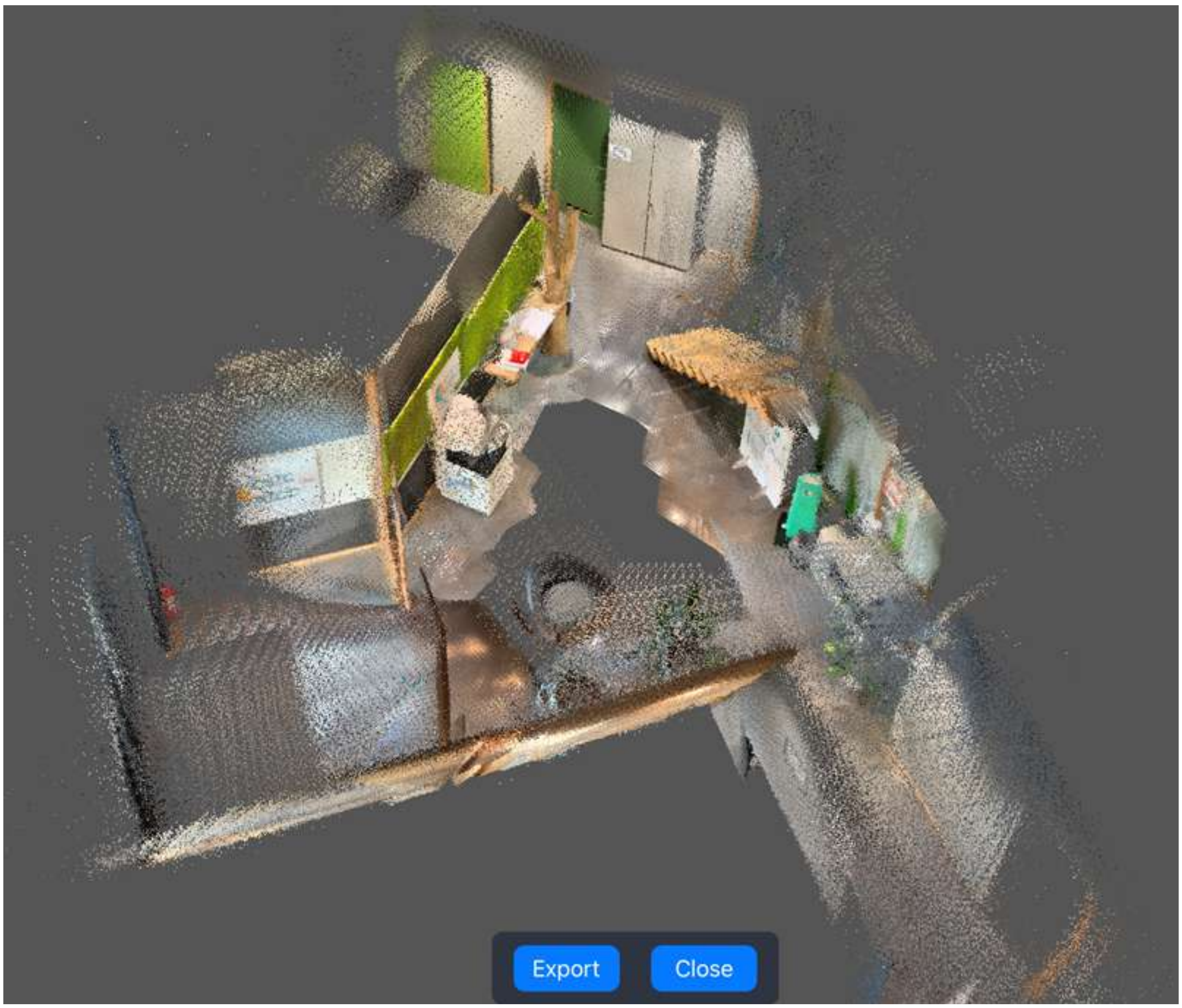


Figure 14. *LIDAR acquisition with a tablet (source: BBRI)*

Laser scanners: The term laser scanning uses various measurement principles but all are based on the analysis of the light reflected from a laser beam on the surface of an object. Terrestrial laser scanners (TLS) are active measuring instruments referred to as 'line of sight' devices – solid elements in the foreground therefore create 'shadow zones'. An object must, therefore, often be lifted from several positions, to limit this type of invisible zones as much as possible.

A laser scanner can record many points per second. Each of them is at least defined by:

- its spatial coordinates (X, Y, Z), see Figure 15
- an intensity value that represents the magnitude of the laser pulse returned by the surface of the object (Figure 16). The cloud of points is thus coloured according to the absorption of the signal by the materials. As an example, a white wall will absorb more of the laser beam than the foliage of a tree.

Figure 15. *XYZ point cloud (no colour information) (source: BBRI)*

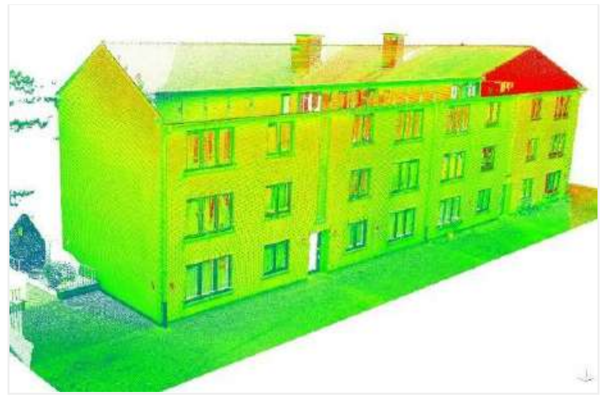


Figure 16. *Intensity value mapped on the point cloud (source: BBRI)*

A point cloud from a TLS can eventually reach a millimetric resolution. However, the principle of measurement, in the form of a 'grid' of points, requires geometric extrapolations to represent the 'edges' of an element. In addition, the farther the scanned area is from the laser emitter and oblique to its beam, the more distant the points measured on this surface will be (Figure 17). For a large object such as a building, a homogeneous resolution can only be guaranteed by using several successive scanning positions.

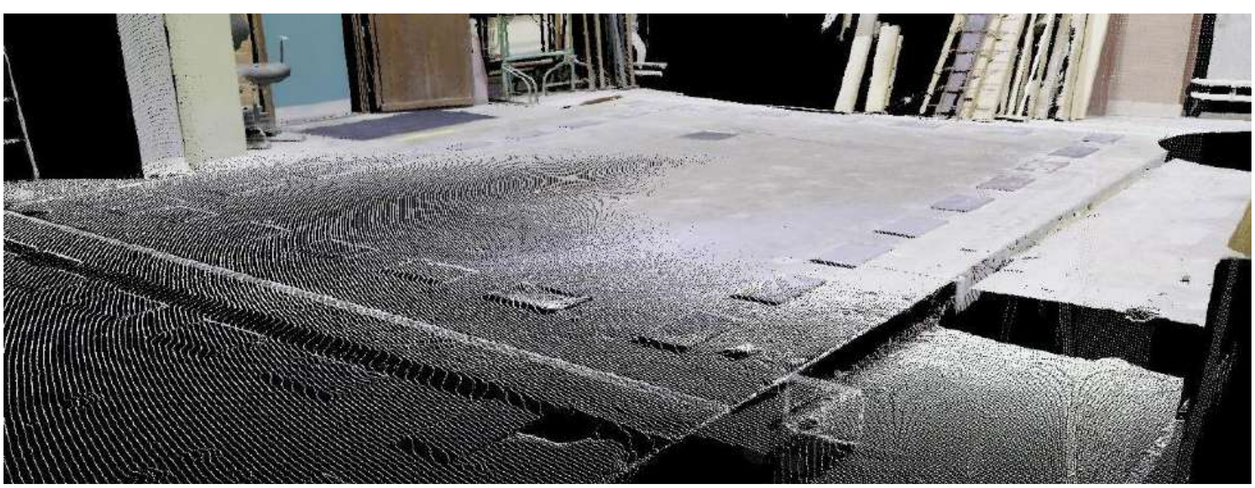


Figure 17. *Loss of point density for objects at further distance from the scanner (source: BBRI)*

Most modern TLS devices are also equipped with a standard camera to obtain colour information for each point (RGB values). Combined with a super high resolution of scanning, photo-realistic point clouds can be achieved, and serve as a basis for visual inspection or inventories. However, the manipulation of such point clouds is extremely demanding in terms of computational power. Further processing is thus often needed.

Terrestrial SLAM devices: In specific cases, IMMS-type mobile scanners (indoor mobile mapping systems) can also be used. These are usually mounted on a wheeled platform that can be moved continuously by the user, thus allowing them to move around the interior of a building. There also exist backpack systems (Figure 18).

Large areas can be scanned quickly, up to 5000 floor-square-metres per hour. Each device is equipped with a system for correcting the measurement according to its displacement. At present, however, such systems are much less accurate than static solutions; an accuracy of the order of a centimetre can be expected.

Figure 18. *A mobile mapping system, carried on the back of the surveyor (source: BBRI)*

There are also more portable solutions that can be handheld by the user (see Figure 19), which have undeniable advantages, but whose effectiveness is not yet sufficiently documented. Mobile solutions embedded on cars are also possible for capturing very large zones.

Figure 19. Point cloud from handheld SLAM (source: Geoslam)

Aerial SLAM devices: The usefulness of laser scanners on building sites is clear. However, lifting such equipment into the air and generating accurate data is a real challenge. First, they are very heavy and expensive devices. It is therefore advisable to choose a drone capable of ensuring the safe transport of the scanner, to protect both people and on-board equipment. Even if the drone can lift the scanner in the air, it must still have a flight autonomy sufficient to carry out the mission. Another problem is directly related to the measurement process, as the terrestrial laser scanners are designed to remain fixed for the entire duration of the scan, i.e., for 2 to 30 minutes on average. However, it is impossible to maintain a drone perfectly stable in the air, which necessitates a correction due to the motion of the drone.

Depth cameras: Another category of scanning equipment is the time of flight (TOF) cameras, which has the great advantage of offering a three-dimensional real-time display. We sometimes also talk about '3D cameras'. Although less accurate than laser scanning technologies, this solution has the advantage of obtaining a quick on-site assessment, if intense light sources are avoided (not recommended for outdoor use). Some commercial systems exist where multiple depth and colour cameras are mounted on a unique device, making the creation of virtual building visits very efficient (Figure 20).

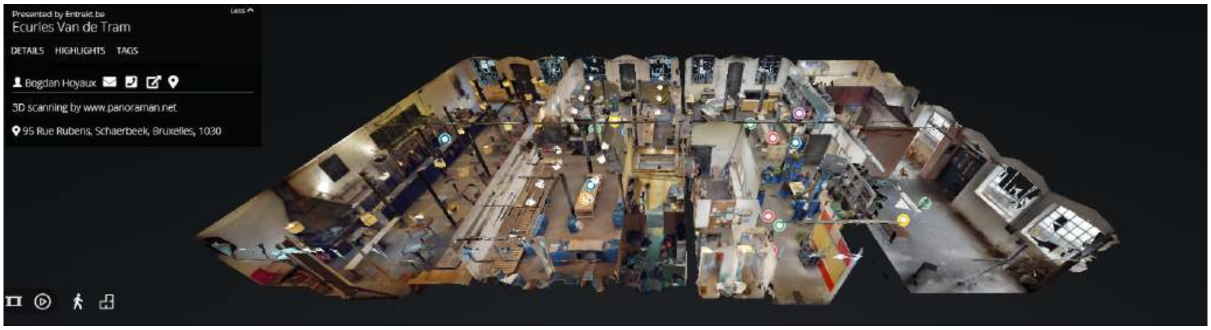


Figure 20. *Quick indoor reconstruction thanks to a commercial depth camera (source: BBRI)*

3.2. Processing the captured data

As shown above, there exists a wide variety of technologies that can be mobilised to generate 2D or 3D data. Sometimes, the raw outputs of those devices will be enough to provide useful information. A colour picture, for example, is often used without any processing. However, **performing digital transformations on captured data** allow to highlight some hidden information, or simply to generate secondary files, which may be more adapted to the end user.

3.2.1. 2D data processing

Digital image processing: Digital image processing (DIP) covers a series of digital approaches and algorithms related to the manipulation of pictorial information. It offers a large spectrum of opportunities for reuse assessments. In its simplest form, DIP allows to enhance the pictures collected on site or issued during lab experiments; with the most elaborated algorithms, it is possible to automatically recognize specific materials or pathologies and provide a detailed map of the observed categories. Such advanced tools may however require advanced expertise and/or computer resources.

The existing algorithms can be classified according to their use:

Simple uses (supporting the interpretation or preparing images for further processing)

- Image enhancement: Improve the sharpness of pictures, remove noise, adjust contrast and lightness (Figure 21), change colour space, remove optical deformations, etc.
- Image simplification: Highlight specific zones of the picture, remove unwanted objects, reduce image resolution, isolate colour channels, etc.
- Feature detection: Highlight all the edges of objects present on the pictures, highlight only specific edges, etc.
- Traditional Image segmentation: 'Binarize' the picture according to a global threshold, region-based segmentation based on local thresholds, etc.

- ...

Advanced uses

- Identification and verification: identify objects or materials, label and classify images, etc.
- Measurements: measure lengths or area, classify detected objects according to shape or size parameters (Figure 22), etc.
- Advanced image segmentation: semantic or instance segmentation, 'clustering' segmentation, etc.
- 3D reconstruction: Feature matching, 'bundle adjustment', dense reconstruction, etc. (see 3.2.1.3)
- ...

Figure 21. *A simple DIP workflow to enhance the lightness of a picture (source: BBRI)*

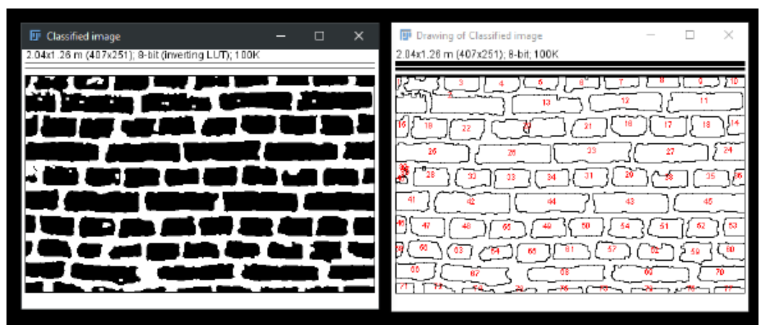


Figure 22. *An advanced DIP workflow to inventory the bricks of a masonry wall (source: BBRI)*

All those algorithms rely on the use of the information present on the picture, i.e., pixel colour intensities values. However, the way this pixel information is valorised varies from tool to tool. In consequence, algorithms can also be categorised according to their functioning principle. Point operators, for example, impact each pixel independently. On the other hand, 'more neighbourhood' operators modify the value of each pixel considering the values of neighbour pixels. A well-known application of such principle is the 'convolution' filter, where a square matrix characterises the transformation mathematically. Another approach is to use all pixel values of the image to perform a global optimization.
As a modern paradigm, 'intelligent' approaches are gaining popularity. Machine learning techniques are now widely applied in the DIP field. With such approaches, semantic information can be extracted from images.

Vectorization: A series of computer algorithms are dedicated to the transformation of images into vector graphics. As CAD drawings are widely used in the construction sector, transforming images into vectorized lines is a common need. Generally, it would require a pre-processed image where the shapes to be vectorized are well highlighted (Figure 23).

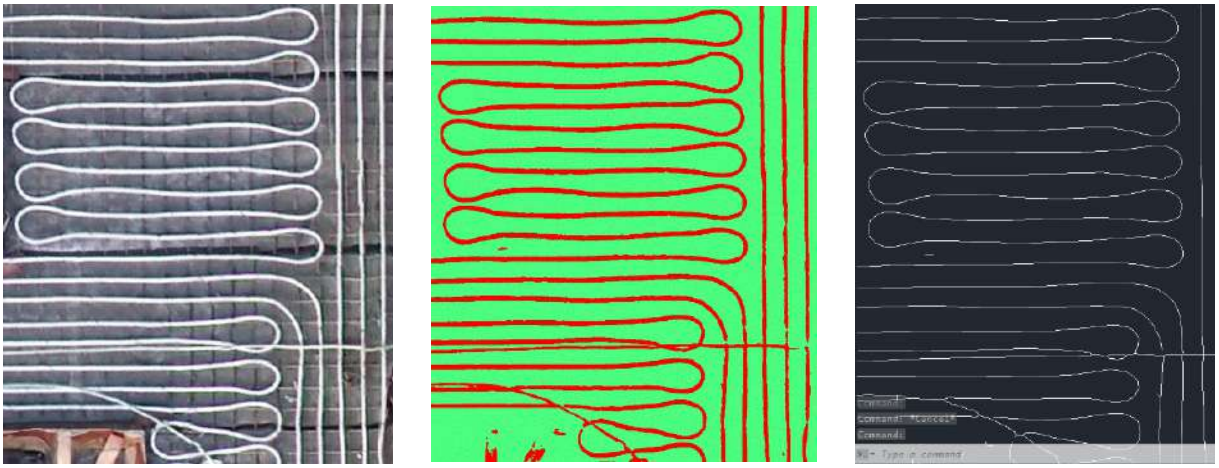


Figure 23. A digital workflow to vectorize the information from a picture (source: BBRI)

Multi-view 3D reconstruction ('photogrammetry'): The Multi-View Photogrammetry (MVP) approach allows the production of high-resolution 3D reconstructions of sites, buildings or building parts only from pictures. It is thus not a true 3D scanning technology, as the 3D data is not directly created on-site. As its name suggests, the technique is based on the automatic processing of photographs in a software: the three-dimensional shape of an object is estimated from overlapping pictures with varying points of view (Figure 24). It is a multi-scale and multi-purpose approach, and many deliverables can be produced from the initial 3D reconstructions.

As stated above, the method relies on overlapping pictures. In consequence, the operator must capture the scene using a clear movement pattern with regular stops to trigger the camera. The adequate shooting protocol will vary depending on the properties of the interest zone/object(s), as well as on the available photographic material (camera, lens(es) & accessories). The expected resolution and accuracy of the 3D reconstruction will also influence the relevant equipment and camera positions.

Figure 24. *The principle of multi-view 3D reconstruction, or more simply called 'Photogrammetry' (source: BBRI)*

The operations linked to the spatial referencing of pictures is another crucial aspect. Indeed, no information regarding the actual size of the objects can be inferred from photographs. By default, the MVP allows the shape of objects to be reconstructed in 3D only with an arbitrary scale.

In a typical MVP software, the 3D reconstruction workflow consists of several steps. First, 'homologous points' (or tie points) are automatically matched on the different views of the object. Those are features of the object (e. g. a corner of a brick) that can be recognized from pixel colour information on several photographs. Based on the positions of the tie points matched on the different images, it is possible to estimate the camera parameters (optical parameters and poses). It is said that photographs are 'oriented' or 'aligned' in space.

This first optimization process is called SFM (Structure From Motion). It also produces a 3D 'sparse cloud' that roughly delimits the photographed object through the estimated location of tie points in space. From the aligned cameras, a second optimization process allows to refine the point cloud and produce a much finer reconstruction of the object (as a point cloud or a mesh), based on the camera calibration determined during the SFM phase. This second phase, which is referred to as 'dense reconstruction' or 'dense image matching', relies on the so-called 'Multi-View Stereo' (MVS) algorithm. Simply put, SFM and MVS are complementary and do not rely on the same assumptions; combined, they allow the object studied to be reconstructed in three dimensions and with great precision from simple photos.

With MVP, precise and very high-density 3D surveys can be created from various photosets (up to several thousand processed images). It has some great value for reuse assessments:

- The method is **non-destructive** (remote sensing) while providing **large possibilities in terms of analysis.**
- The method is **multi-scale**. Depending on the type of photographic lens used and the typical capture distance, objects ranging from the microscopic up to the terrain scale can be digitised. Moreover, the method is **UAV-compatible**, which allows capturing large, inaccessible, or dangerous areas.
- The method **works well with old buildings**, which is often characterised by rich textural information. It can translate this textural information into detailed 3D models (Figure 25).
- Modern software provides a **high degree of automation to assist the user**. Some freeware solutions also exist.

However, the technique has some noticeable pitfalls:

- Many factors can affect the quality of the 3D reconstruction. The protocol followed to capture the interest object has a major impact on the results. If the computational principles and the inherent limits are not properly understood, there is a risk of creating erroneous or incomplete data.
- The method relies on the assumption of a static scene/object. In consequence, it is not adapted for dynamic scenes.
- Only a time-consuming quality control phase can guarantee the accuracy of data.
- Transparent, reflective, or uniform materials cannot be properly reconstructed. On the contrary, traditional masonry walls are an example of perfect objects to be captured with photogrammetry.
- The ambient conditions can impede the realisation of the scanning missing as well as impact the quality of results.
- High computing power is required to process 3D data from many photos.

In a scanning campaign, **the method is often complementary to other technologies** (e.g., LIDAR, SLAM). Indeed, it provides a high level of fidelity for colour restitution while a bit weaker on geometric aspects. Laser scanning is generally the exact opposite.

Figure 25. Photogrammetry is common in the Heritage sector, where highly textured buildings are found. It is legitimate to question the relevance of photogrammetry for more modern objects (source: BBRI)

3.2.2. 3D data processing

3D processing is a wide topic. Indeed, each type of 3D dataset can be transformed in specific and various ways. The two most common 3D datasets and useful schemes of data extraction will be discussed here.

Point cloud processing: Because of its discrete nature, a point cloud is highly transformable. The XYZ and RGB information of each point can be valorised in many ways. Downstream of the raw model acquisition phase, labour-intensive data processing is often required to obtain useful information in the form of 2D drawings or 3D models. This phase includes various subtasks.

Pre-processing: The **spatial referencing and alignment** of the different point clouds, often referred to as 'point cloud registration' is a first critical step. It is generally carried out using specialised software. The manufacturers of laser scanners generally provide complete software suites allowing many operations to be carried out, including the registration based on control points (sometimes called 'support points'). Note that the spatial referencing of a laser scan is sometimes directly ensured on site when the exact position of the scanner and its orientation can be defined at each successive measurement. Most of the time, the registration of clouds resulting from multi-image photogrammetry is carried out within the reconstruction software.

Then come some **basic operations** that are usually performed on a registered point clouds: denoising (removing outliers), filtering (removing elements that are not relevant to the study), sampling (reducing the total number of points by subsampling or resampling) or compression (reducing the file size with or without loss of information) of the raw point clouds. These basic operations can be performed in many software packages, some of which are open source (Meshlab, CloudCompare, ...).

Quality control: A quality control procedure can be particularly critical when very high accuracy is required. Unfortunately, such procedures are still difficult to implement and there are few recommendations for them. It can be advised to provide more control points than strictly necessary for the registration of the different point clouds. Those control points, surveyed with a total station, will allow an estimate of the scanning accuracy. High precision GNSS systems can also provide additional confidence in the mission results. For photogrammetric missions, having reference coordinates for each picture constitute precious data for error estimation (Figure 26).

Figure 26. *High-end drone equipped with a 'RTK' positioning system, providing highly accurate geotagging of pictures (source: BBRI)*

Segmenting: **Segmenting the point cloud** means subdividing it into coherent subsets, according to one or more criteria such as shape, orientation, type of material, etc. This phase is not always necessary and will depend on the final deliverables required. For reuse assessments, adequate segmentation workflow can help the assessor to organise the information more efficiently.The most basic segmentation method is the **manual approach**. There, the user will 'cut' the point cloud with various selection and sorting tools. **Automated processes** are however to be preferred when large datasets need to be analysed, or when more subtle classification methods are needed. Many algorithms can be used for segmenting the data. The most basic ones will use the value of one of the point properties and use this value to classify the points into categories. The colour of each point, for example, can be used for such categorisation (Figure 27). Of course, more complex properties can also be used, such as geometrical features computed for each point (e.g., the local density or planarity of the point cloud).

Figure 27. *Segmentation of a point cloud based on colour information. Here the process was aimed at detecting tiles (source: BBRI)*

The segmentation process can also rely on detected shapes across the point cloud. Detecting planes and cylinders is a frequent operation, as shown on Figure 28 and Figure 29.

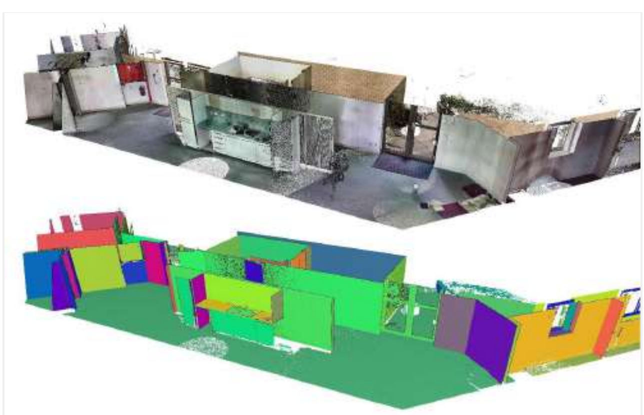


Figure 28: *Segmentation of the point cloud using plane objects detection (source: BBRI)*

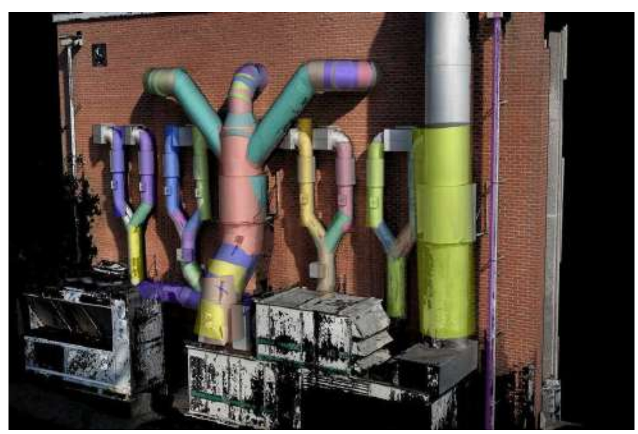


Figure 29*. Cylinder shape detection using the RANSAC algorithm (BBRI)*

Transforming and updating data: Many manipulations are possible from a pre-processed or segmented point cloud, to answer the needs of the reuse assessment:

- Computation of additional properties for each point (e.g., normal orientation, density of points in the neighbourhood)
- Combination and comparison of different datasets (e.g., estimation of the planarity of a wall, using a plane as reference)
- Transformation of the point cloud into a 3D model (e.g., point cloud transformed into a textured mesh)

Each type of processing will bring an answer to specific final use. Estimating the condition of materials is for example more demanding than estimating the general dimensions of the building. Therefore, we distinguish two categories of processing: simple processing, which falls within the general skills of surveyors, and advanced processing, which expresses specific needs for which experts at the frontier of several fields will often be required.

Simple processing: In the process of studying existing buildings, the most frequent need is the creation of models allowing us to take measurements. Many construction professionals will not specifically need the resolution offered by high resolution scans at any point of the building. They will be satisfied with **slices or cut section**s (Figure 30) created from point clouds. **Regularly spaced slices** are also very convenient to grasp the spatial organisation of a building and assess its general dimensions.

When it comes to the best visualisation of a 3D model and its textural information, it is sometimes desirable to transform **a point cloud into a polygonal mesh.** Indeed, 3D visualisation tools intended for multimedia applications are traditionally based on such models, which make it possible to generate photorealistic renderings. The transformation can be done automatically (using algorithms) or manually (using the point cloud as a support for polygonal modelling). Used alone or combined with laser scanning, the photogrammetric method offers in this case an undeniable advantage as textured meshes can be directly generated within the software.

Advanced processing: Many g**eometric or colorimetric features** can be computed for each point of a point cloud. Like image processing techniques, each point or a local group of points can be used for the computations. Such advanced operations will often serve advanced cleaning or segmenting operations. Parts of the point cloud with less point density can be filtered out, for example.

Many modelling or 3D file processing tools allow simultaneous importing of different types of models (point clouds, meshes, solid objects, ...). Among those, some also have dimensional analysis tools. It will then be possible to know the **deviation of a 3D scan** f**rom a reference object.** These geometric references can include simple primitives such as planes (e.g., for planarity analysis of a façade) or another point cloud (e.g., for analysis of the movements of a structure over time). Figure 30c shows an example of a comparison between a point cloud and a plane (so-called 'Cloud-to-mesh' analysis), for condition assessment purposes. Software such as CloudCompare allows to colour each point of a cloud according to its distance from the according to its distance to the closest point of another cloud.

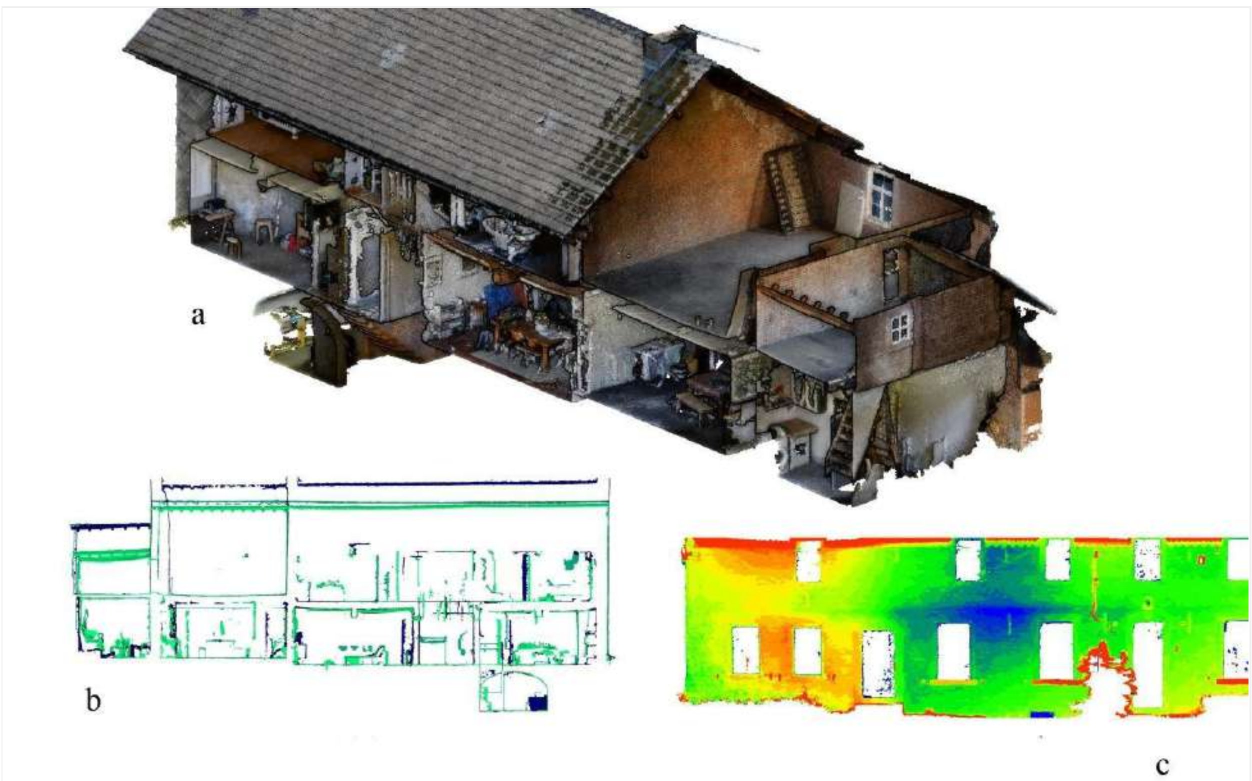


Figure 30. *Some possible transformations of the point cloud: a. Cut sections; b. Thin slices; c. Planarity analysis (cloud-to-mesh distance)*

Note on processing efforts: The ratio between the duration of the on-site survey and the processing can vary greatly depending on the method used and the requirements of the analysis. A common problem concerns the handling of data that can reach several tens of gigabytes in case of high resolution acquisition or a combination of several point clouds. Adequate hardware is crucial there.

Modelling and projecting: CAD files are frequent in the construction industry. They allow the objectification of construction objects into vectorized elements. The transformation of high-resolution 3D information into line drawings can generally be done within CAD software, provided that the latter allows the import of a point cloud. This is called **scan-to-CAD**. The main interest of 3D scanning lies in the availability of a complete model acquired once and for all, which can be used as a guide for a 'classic' 2D modelling. Some current practices in the two-dimensional representation of the existing could however come to disappear in the future when the working methods and the optimization of the software solutions will be adapted to the contributions of the modern technologies of 3D scanning. Today, there are already many applications in which 3D CAD modelling is an advantage. The designer will use the point cloud as an aid for 3D line drawing or for modelling in basic geometric shapes (spheres, cubes, ...). Many laser scanner manufacturers offer software suites or plug-ins for 2D or 3D CAD drawing that facilitate the scan-to-CAD process. The 3D CAD files can be integrated into a BIM model at a later stage.

For reuse assessments, it should be emphasised that CAD modelling can be labour intensive, and only relevant for large projects. In most cases, it may be more convenient to work from **orthoviews images** of the point cloud. The orthoview or orthographic projection is an orthogonal representation of a 3D model. In other words, it is a specific point of view on the 3D model without perspective effects. Unlike orthophotography, which is obtained from the assembly of photos and therefore has a very high potential spatial resolution, the visual quality of orthoviews depends strongly on the resolution of the underlying model. When the resolution offered by a point cloud is very high, ortho views can serve as a very good drawing or analysis support (Figure 31).

Figure 31. *Orthoview of a façade, generated from a point cloud (source: BBRI)*

Bridge to the BIM World: Integrating precise geometric information on the existing in a BIM model is greatly facilitated by the development of 3D scanning technologies. Point clouds can be used in several ways within a BIM process. For retrofitting applications, 3D scanning opens the way to an accurate and extremely complete representation of the building. This data is a boon for designers, who will find information that is often much less ambiguous than in archived documentation in the form of 2D plans. From the cloud, one can completely remodel the building into parametric BIM objects. Despite the important effort that this represents, one will then find the benefits of BIM for a renovation/reuse project (with even possibilities of planning dismantling operations). The different actors involved in the building transformation efforts will have at their disposal a complete parametric model that is best suited to the reality.

Mesh processing: Textured meshes are mostly used when visual information is critical. They are defined by the number of constitutive polygons, referred to as 'faces', and the number (and type) of image textures possibly coupled to it. It should be mentioned that the mesh can be 'coloured', as an alternative to an image texture. If so, only the vertices of the mesh receive a colour, which limits the amount of visual information that can be associated with the 3D model (see Figure 32).

Like point cloud processing, there are a wide variety of techniques to clean, simplify and transform meshes. We will only summarise here the typical operations that may be needed for reuse assessments.

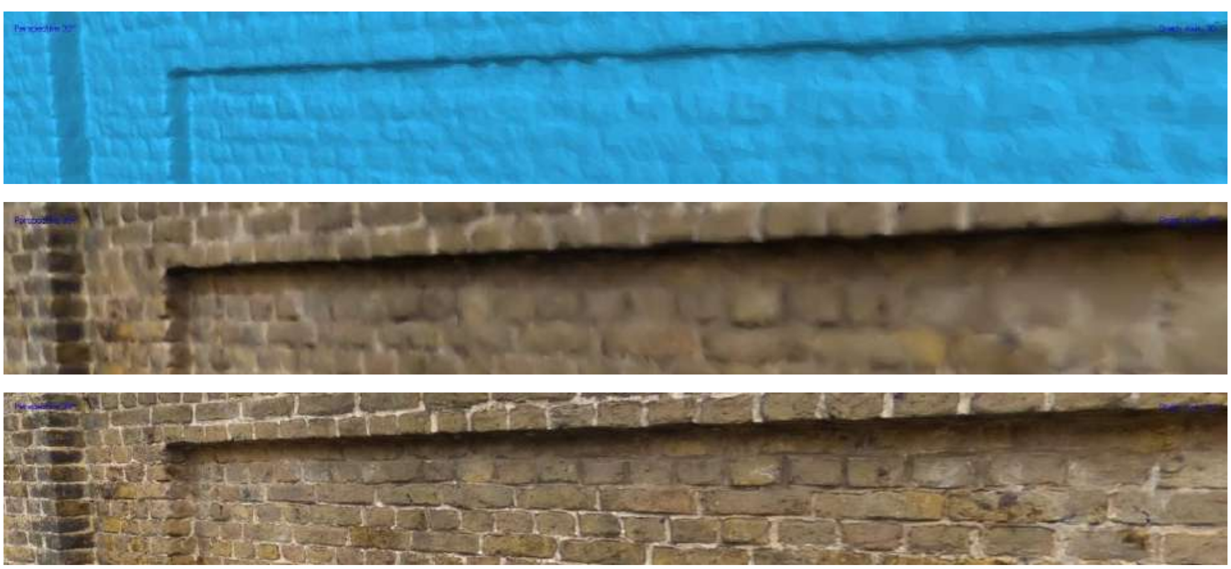


Figure 32. *The mesh and colour information: (top) mesh without colour information; (middle) mesh with coloured vertices; (bottom) mesh with image texture (source: BBRI)*

Because of its continuous nature, **cleaning a mesh** is more complex than cleaning point clouds. Automatic cleaning operations are not frequent, and the user will have to pass through time-consuming manual filtering of bad faces. **Decimating a mesh** is a very useful operation. It means reducing the number of faces, while attempting to preserve the general shape of the object. Still, if the reducing factor is too important (going from 200 million faces to 100 thousand faces, for example), there is a strong risk of losing a lot of precision of the main dimensions of the object. Small details, on their side, will be lost. **Smoothing operations** can make the edges of the mesh less sharp, making it more visually appealing but losing geometric accuracy. With photogrammetric software, it is always possible to **reproject a high-resolution texture on the decimated or smoothed mesh**, using the source pictures aligned in space.

Just as point clouds can be transformed into meshes, **meshes can be transformed into point clouds** if necessary. There are two common approaches to this: remove the face information and treat the vertices of the mesh as a point cloud; or sample a certain number of points on the surface of the mesh. The colour of the resulting points can be inferred from the texture of the mesh.

3.2.3. Communicating data

One of the major problems faced when using high-definition 3D surveys is the **sharing of data.** Indeed, point clouds created with modern scanning technologies or photogrammetric approaches are generally very large files, which are not only difficult to read and manipulate, but also to transfer between collaborative actors. In consequence, it is often required to find ways of communicating the data efficiently. For that, several solutions exist.

The first approach is to process and simplify the data, so that only the useful information is transferred to the final user. Orthoviews or CAD files are examples of documents that are easily transferable. For customers who do not have the necessary IT resources (software and/or hardware) to handle large files, but still want to access big chunks of datasets, it is also possible to host the point cloud on web servers. Laser scanner manufacturers usually offer cloud hosting solutions. It allows non-technical users to easily access the 3D information remotely and perform basic measurements or annotations (see Figure 33). Open-source web hosting solutions also exist, like the well-known 'Potree' (Figure 34).

Figure 33. A web-based point cloud hosting solution, developed by a mobile scanner manufacturer (source: BBRI)

Figure 34. An open-source web-based point cloud viewer (source: BBRI)

3.3. Tests and lessons learned

During the project, the research team had the opportunity to test various scanning technologies and to practically assess their performance for reuse audit. Specific developments were also undergone, focusing on the automation of data extraction. Two case studies are detailed in this report.

3.3.1. Scanning the 'alte Schaferlei' in BenediktBeuern

Case and data acquisition:

The specific building chosen as a case study here is shown on Figure 35. The 'Alte Schäfflerei' is part of the former craftsmen's district in the Benediktbeuern monastery. This listed building dates from the second half of the 18th century and was originally used as storage space for barrels from the adjacent monastery brewery. The Fraunhofer IBP is putting the building to a new use by establishing *the Fraunhofer Centre for Energy Efficient Building Renovation and Monument Preservation*. The reality capture initiative was here aimed towards a full energy diagnosis. Such study required an in-depth inventory of all building components and materials. This constitutes the highest level of inventory possible, with the mobilisation of high-end scanning solutions.

The whole building was captured from the inside and from the outside, producing several datasets. A *DJI M210 V2 RTK* drone was used for aerial photography (Figure 36), a *Leica RTC 360* laser scanner for terrestrial lidar acquisition and a *Sony a7r III* with various lenses for terrestrial photography. A *DJI X7 RGB* camera was mounted on the drone, with a 24mm lens and a mechanical shutter. The drone was also equipped with a high accuracy RTK positioning system. A mobile GNSS base was used to provide the differential position data. Hereafter is how the capture missions summarises:

- Aerial imagery. The drone flights allowed to capture 311 usable pictures.
    - 59 were taken with the camera in 'top-down' position, following a grid pattern **(dataset A1)**
    - 252 were taken with the camera forming an angle between 30° and 60° from a horizontal position, following a 'perimeter' scheme around the building **(dataset A2)**

- Terrestrial photography.
    - Outside, 320 pictures were taken from the ground, following a 'perimeter-mission' pattern around the building. A 20mm lens was used for those wide-angle shots (**dataset T1).**
    - Inside the building, 2088 pictures were required to cover the entirety of accessible spaces. The 20mm lens was used for most pictures. A 12mm lens was useful for confined spaces. **(Dataset T2).**

- Terrestrial laser scanning.
    - Outside, 13 coloured scans were made around the building to provide sufficient overlap **(dataset S1).**

- 82 scan positions were required on the inside **(dataset S2)**. Dedicated registration targets were used to improve accuracy.
- On all scanning positions, 360 panoramic pictures are generated to provide colour information to the point clouds **(dataset P1)**.

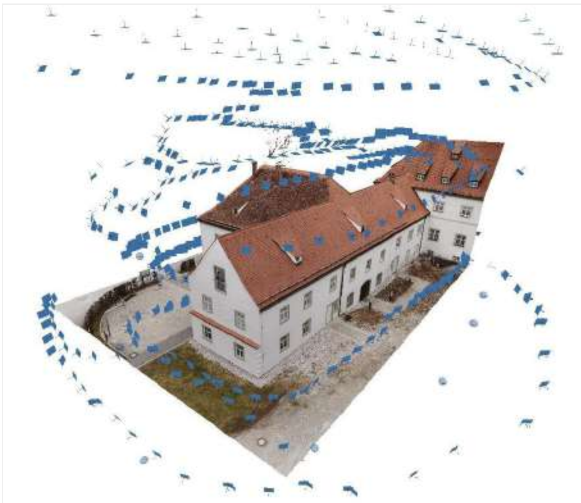


Figure 35. *Scanning the 'Alte Schäfflerei' of the Monastery of Benedikbeuern.*

Figure 36. *The drone used for aerial photography.*

Data processing:

Figure 37 illustrates the data processing scheme followed for this in-depth study and all the generated deliverables. It is a clear example on how captured data can be transformed according to many 'routes'. Each node of the diagram represents one specific type of data, which can be classified under a column that represents its nature (bidimensional, tridimensional …). A datatype node can have several inputs and several outputs, with some types being more 'transformable' than others. Naturally, this scheme constitutes only a part of what is possible – the diagram, despite its apparent complexity, is very simplified. Each data type could be further divided according to subtypes or according to the surveyed element (interior spaces, exterior …), for example. The actual processing stages from the 'Alte Schäfflerei' captured data are detailed in the following sections. Within this broad data transformation scheme, the focus is put on three main processing tools: the MVP software, the point cloud processing software and the image processing software.

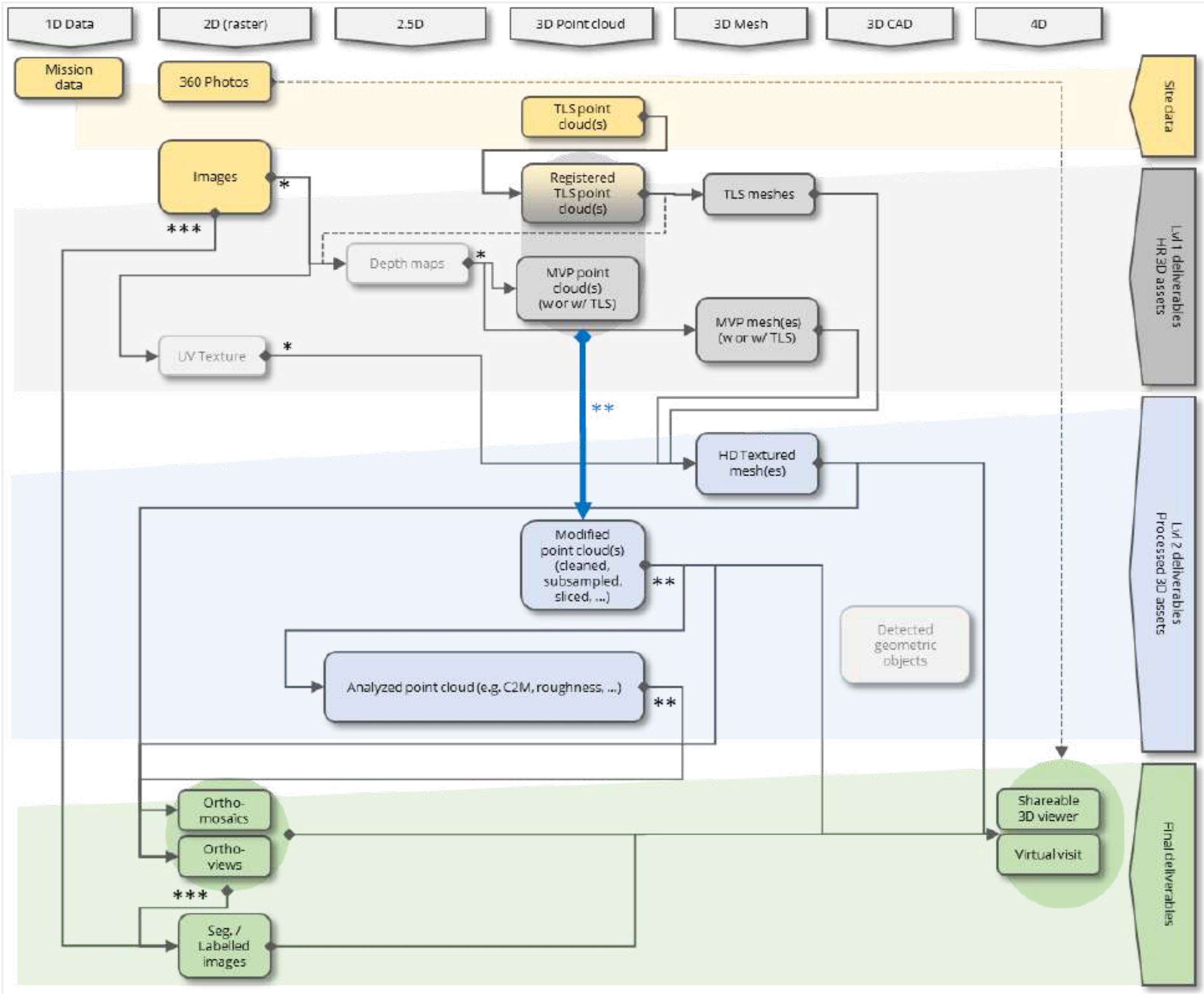


*Figure 37. Transformation of data types from one type to another: simplified view on how to valorise reality capture for energy diagnosis and simulation. The processes indicated with * are generally performed in the photogrammetry software. Processes marked with ** are linked to the point cloud processing software. Processes marked with *** involve the use of image processing software.*

3D reconstruction: From the raw collected data (i.e., images, laser scans and mission metadata) the first processing stage consisted in creating high resolution 3D assets in the form of point clouds or meshes. Those are referred to as 'Level 1' deliverables. Such files are generally particularly heavy, and their manipulation requires not only adequate hardware, but also specific technical knowledge.

Obtaining 3D assets is relatively straightforward when terrestrial laser scanning is used on site. The main task for the surveyor is to register the data. The 95 scans generated here were preregistered on-site using a SLAM technology embedded in the scanner. Later, the created links were optimised based on ground control points (solid targets). The possibilities in terms of 3D reconstruction with photogrammetric software were broader, especially given the variety and quantity of the collected data. Indeed, modern photogrammetry software solutions allow automatic registration of laser scans and photos. Here, photo datasets were processed both with and without lidar datasets to assess the impact on reconstruction quality. *Agisoft Metashape*[6] *and Reality Capture*[7] were used using the highest dense reconstruction quality settings. Both coloured point clouds and high resolution meshes were produced. When no laser dataset was used for photo alignment, ground control points were used to register the 3D reconstructions produced from images.

Processing 3D assets: making point clouds and meshes talk: Processed 3D assets are referred here to as 'Level 2' deliverables. Such files would already be useful for an inventory but are aimed towards people familiar with 3D technologies. For point clouds, the most basic processing steps consisted in cleaning, subsampling/resampling, or slicing the datasets. Those actions do not add any information to the existing datasets. They rather serve the purpose of making the 3D files easier to manipulate or focusing on zones of interest. More complex processing actions involved computing additional scalar fields. The simple and more advanced point cloud processing operations were all carried out in the open source software *CloudCompare.*

In their whole resolution state, the 3D meshes are particularly difficult to manage for most visualisation software. Decimation steps were required to make them more broadly exploitable. The number of polygons was reduced according to identified target software. For example, 3D PDFs required meshes with an extremely low number of polygons. A particularly useful aspect of using meshes is here the possibility of reprojecting the high-resolution colour information on low polygon density meshes, as shown on Figure 38. The files are kept reasonably light while retaining interesting visual information. We believe this approach is particularly relevant for reuse assessments. The decimation steps were performed in *Agisoft Metashape or Reality Capture.*

[6] Version 1.6.5
[7] Version 1.1

Figure 38. Reprojection of colour information on low poly meshes.

Formatting useful data from the prepared 3D files: In a later stage, so-called 'final deliverables' were produced from the optimised 3D assets. Emphasis was placed on producing files that are usable for a larger public, and easily transferable. To evaluate the scanning technologies, many files were produced here for describing the 'Alte Schäfflerei' extensively. Table 1 provides a selection of the most important ones, with their potential use for inventories. Above, we have shown how data types can be transformed to each other. Yet, we show here which dataset could be valued up to a specific use, in a common format.

Several remarks can be made. First, the useful information can be split into three main aspects: (1) the assessment of the geometry of the building, its environment, and its subparts, (2) the identification/mapping of materials, components, and systems and (3) the evaluation/mapping of the condition of the identified entities. Textural information is thus far from being neglectable, even crucial for aspects 2 and 3. Comparing 3D surveying technologies solely based on their geometrical accuracy would not cover the totality of relevant requirements. Secondly, images play a key role within the chosen end-user files. Indeed, thanks to the universality they retain, such deliverables ensure an effective communication between surveying teams and reuse specialists – for geometric as well as for textural information (e.g., materials and pathologies). Images also constitute a widespread medium for performing advanced analyses like segmentation and labelling, within an image processing software. Especially with orthoviews, which add powerful quantification possibilities.

Naturally, choosing only images as a communication medium will necessarily cause a loss of information. To avoid this, final image datasets were complemented by some 'immersive' deliverables, which allow anyone to manipulate 3D information. Firstly, Potree viewers were created to allow anyone to access the point cloud information, only using a web browser. Such WebGL solutions are simplifying the sharing of complex data. Later, a virtual visit application based on 360 photos navigation was implemented in 3DVista. This appeared as a very satisfying solution to centralise, organise, and contextualise all the generated deliverables.

Collected data		Level 1 deliverable		Level 2 deliverable		Final deliverable	Main use
*TLS, interior (**S2**)*	à	*TLS, Point cloud of indoor spaces*	à	Distance maps of selected wall/floor/ceiling elements compared to reference planes	à	Orthoviews of the distance maps	Evaluating the **condition** of the wall/floor/ceiling element
*TLS, exterior (**S1**)*	à	*TLS, Point cloud of the envelope*	à	Distance maps of each façade compared to reference planes	à	Orthoviews of the distance maps	Evaluating the **condition** of fabric
*Photos, exterior **(A1 + T1)*** *TLS, exterior (**S1**)*	à	*High poly mesh of the envelope*	à	High poly mesh of the envelope with RGB texture	à	Orthomosaïc photos of all façades and roof elements	Materials/pathologies **identification and mapping** (through image analysis and machine learning)
*Photos, exterior and interior **(A1 + A2 + T1 + T2)*** *TLS, exterior and interior (**S1 + S2**)*	à →	*MVP, Merged point cloud of the envelope and the interior spaces*	→	Horizontal sections of the point cloud at different levels	à	Plan of each storey	**Mapping** the internal organisation of the building rooms
			→	0.1m thick cross sections every 0.5m along the main building axes	à	Orthoviews of the sections	Encoding the building **geometry** and the thickness of envelope elements in whole-building energy models
*Photos, exterior **(A1 + T1)***	à	*High poly mesh of the envelope*	à	Low poly mesh with RGB and normal map texture	à	3D PDF of the mesh model	Materials/pathologies **identification** (direct observation)
Etc…							

Table 1. *Some of the chosen key final deliverables for inventories. Grey cells are further illustrated on Figure 39.*

Results:

As stated before, the quantity of generated data was extremely significant here. Only a general overview of produced files and performed analysis can be provided, along with some significant findings.

In Agisoft, A1, A2, T1 and T2 photos could be aligned without requiring any addition of manual tie points. The dense cloud reconstruction results show a high level of noise, which can be adequately filtered out using the ‘confidence’ level computation offered by the software. In Reality Capture, T1, T2, S1 and S2 datasets were aligned successfully. The sparse cloud created from aerial photo sets (A1 & A2) could be aligned to this first dataset with the use of some manual tie points. Ultimately, the dense reconstruction from all those datasets resulted in a point cloud of 1.2 billion points. From this particular point cloud, Figure 39 illustrates one of the specific and more relevant data workflows. It corresponds to the workflow which is greyed in Table 1. The final deliverables are here regularly spaced slices along all three axes and floor plans.

With the density of point clouds that can be achieved with modern MVP software, it is expected to reach a certain level of visual realism. Figure 40 shows how the different 3D datasets compared regarding this aspect. Incorporating images into the 3D reconstruction process not only greatly improved the visual rendition of envelope elements but also reduced the missing data areas. Combining photographic and lidar acquisitions has made it possible to get the best of both worlds, high accuracy for geometrical reconstruction and fidelity in colour rendition.

The richness of visual data offered by MVP could be useful for many following studies. However, the question of sharing of data stays critical, especially for huge point clouds. Working with meshes proved here to be satisfactory in that scope.

Abbreviations: C2M = Cloud to Mesh, HD = High Definition, MVP = Multi-View Photogrammetry, TLS = Terrestrial Laser Scanning

Figure 39. *An illustration of data processing: Merged point cloud of the envelope and the interior spaces processed into slices and then key orthoviews (images)*

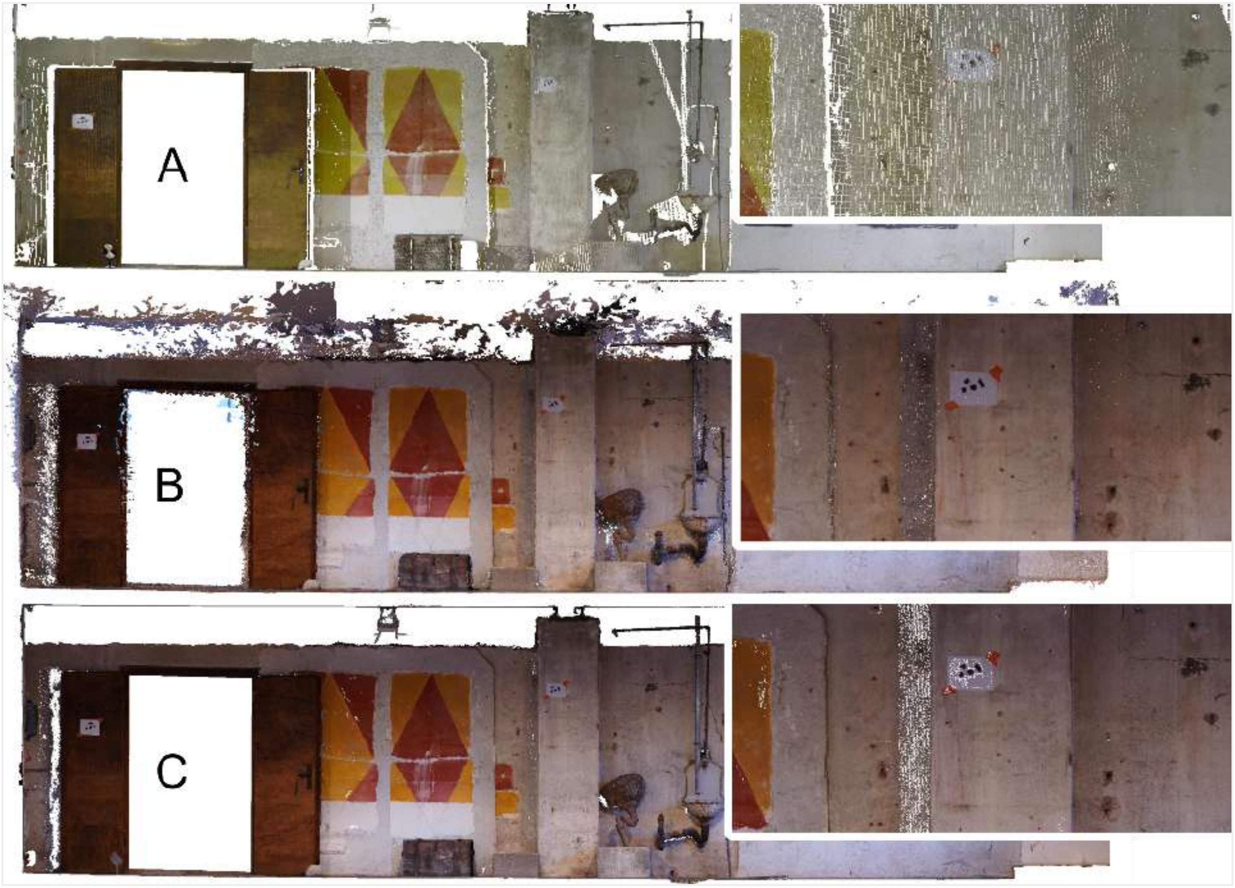


Figure 40. *3D reconstruction compared to a small interest zone. A: Laser scanning; B: Photogrammetry (only interior photos) from Agisoft; C: Photogrammetry (laser scans and interior photos registered together) from Reality Capture*

3.3.2. Scanning the 'Boza' in Brussels

Case and data acquisition: This second case study is again an in-depth exploration of modern 3D scanning technique. The BBRI team scanned part of the centre for fine arts in Brussels, also referred to as the 'Bozar' building (Figure 41). The scanning campaign was originally led for the purpose of humidity diagnosis. However, it appeared as a good opportunity to illustrate the potentialities of photogrammetry alone for material inventory studies, which involve diagnosis operations. Laser scans were still implemented to have a reference 3D dataset.

Figure 41. *The 'Bozar' building.*

The building was captured from the inside and partly from the outside, producing several datasets. A *Sony a7r IV* with a 12-24mm was used for terrestrial photogrammetry. To provide backup data in case of poor results of the photogrammetric reconstruction, laser scanning data was also generated. A *Leica RTC 360* laser scanner was used for this terrestrial lidar acquisition. Here is how the capture mission summarises:

Terrestrial photography:

- Inside the building, 1319 pictures were required to cover the entirety of accessible spaces. The lens was fixed on 12mm focal length all along the acquisition. Such a wide angle was chosen to cope with confined spaces **(Dataset T1)**. A typical picture is shown on Figure 42.
- Outside, 78 pictures were taken from the ground, to capture the street level in 'rue Royale' **(dataset T2)**. See Figure 43.

Terrestrial laser scanning:

- 38 scan positions were required on the inside **(dataset S1)**. Dedicated registration targets were used to improve accuracy.
- Outside, only 2 coloured scans were made at street level **(dataset S2)**.

- On all scanning positions, 360 panoramic pictures are generated to provide colour information to the point clouds. Those ultra high resolution pictures (20480*10240 pixels) were proven to be extremely useful for inspection purposes, as shown on Figure 44 and Figure 45 **(dataset P1)**.

  All scanning positions are shown on Figure 46.

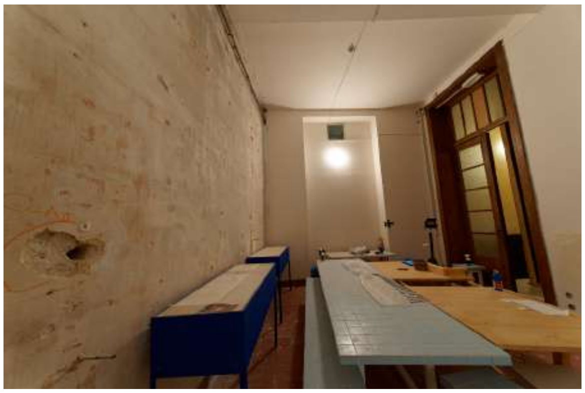


Figure 42. *Typical image taken inside the building .*

Figure 43. *An image taken outside the building, to capture the street level.*

Figure 44. *A high-definition panoramic image, generated at each laser scanning position .*

Figure 45. *Zoom on panoramic picture (Figure 44)*

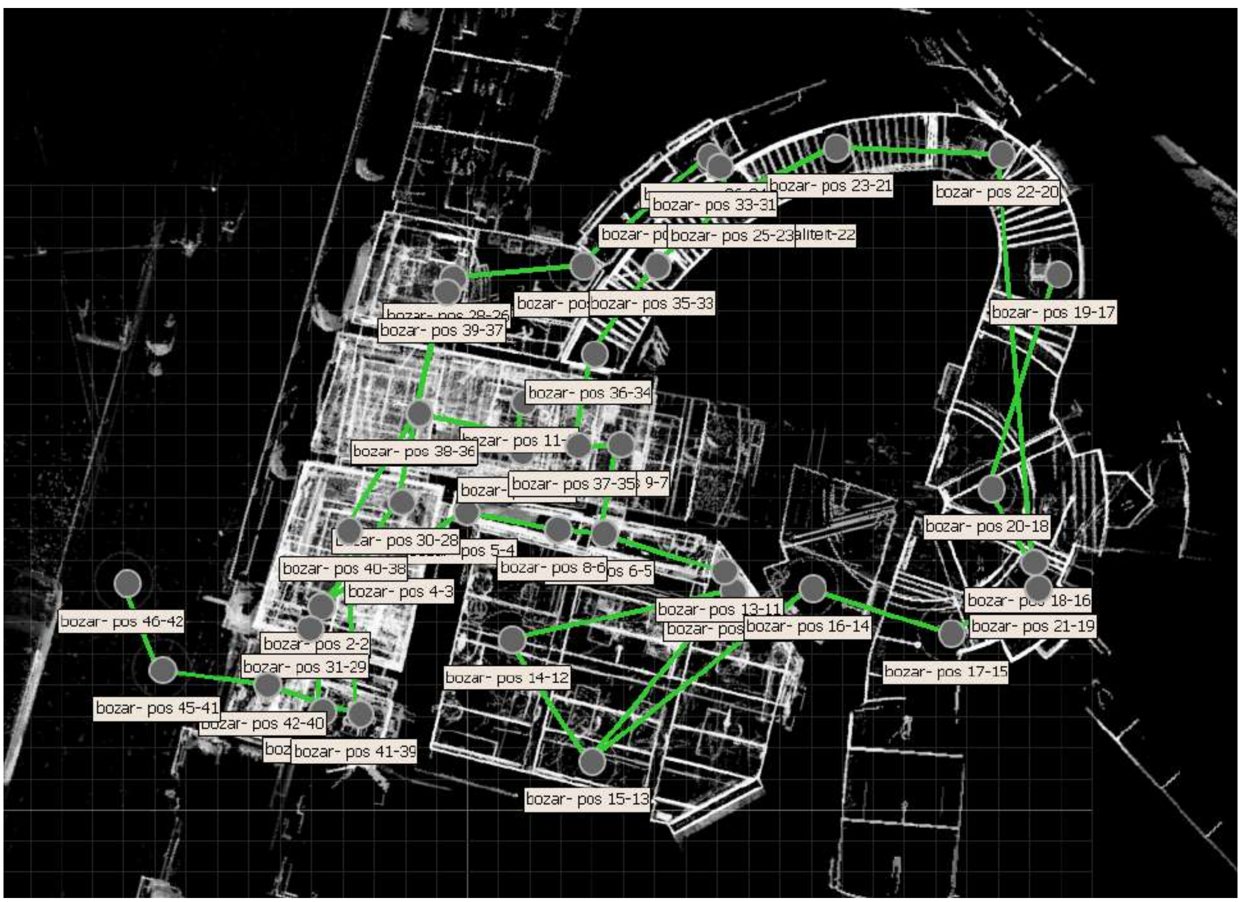


Figure 46*. Laser scanning positions (top view)*

Data processing: Similar to the previous case, Figure 47 illustrates the data processing scheme followed for this study and all the generated deliverables.

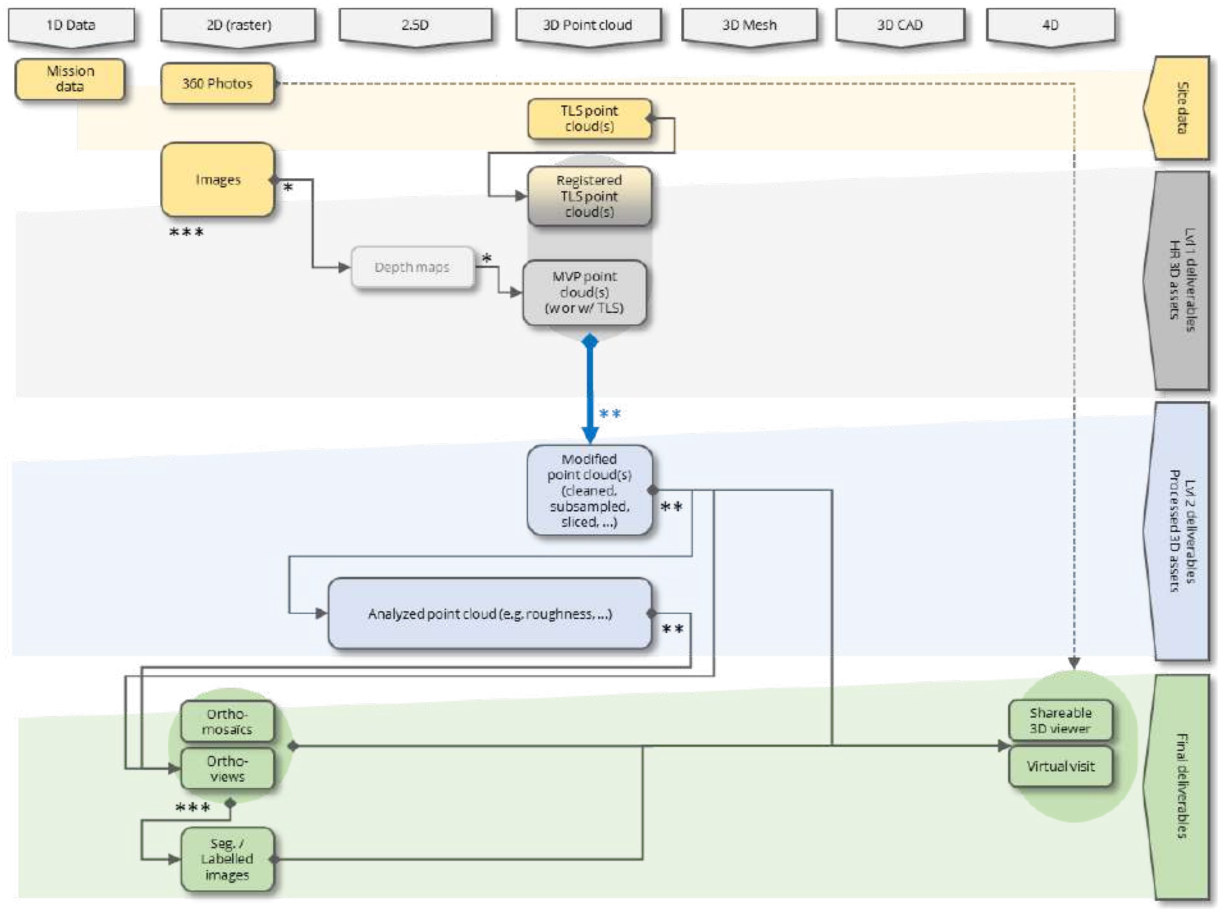


*Figure 47. Transformation of data types from one type to another. The processes indicated with a * are generally performed in the photogrammetry software. Processes marked with ** are linked to the point cloud processing software. Processes marked with *** involve the use of image processing software.*

3D reconstruction: from the raw collected data (i.e., images, laser scans and mission metadata) the first processing stage consisted in creating high resolution 3D assets in the form of point clouds. The 40 scans generated here were preregistered on-site using a SLAM technology embedded in the scanner. Later, the created links were optimised based on ground control points (solid targets). This dataset will act as a reference.

The possibilities in terms of 3D reconstruction with photogrammetric software were again very large. Here, photo datasets were processed without lidar datasets. *Agisoft Metashape* was used using 'medium' and 'high' dense reconstruction quality settings. Coloured point clouds were produced. Because no laser dataset was used for photo alignment, ground control points were used to register the 3D reconstructions produced from images.

Processing 3D assets: this diagnosis mission focused on a specific part of the building. In consequence, an interest zone was defined, as shown on Figure 48.

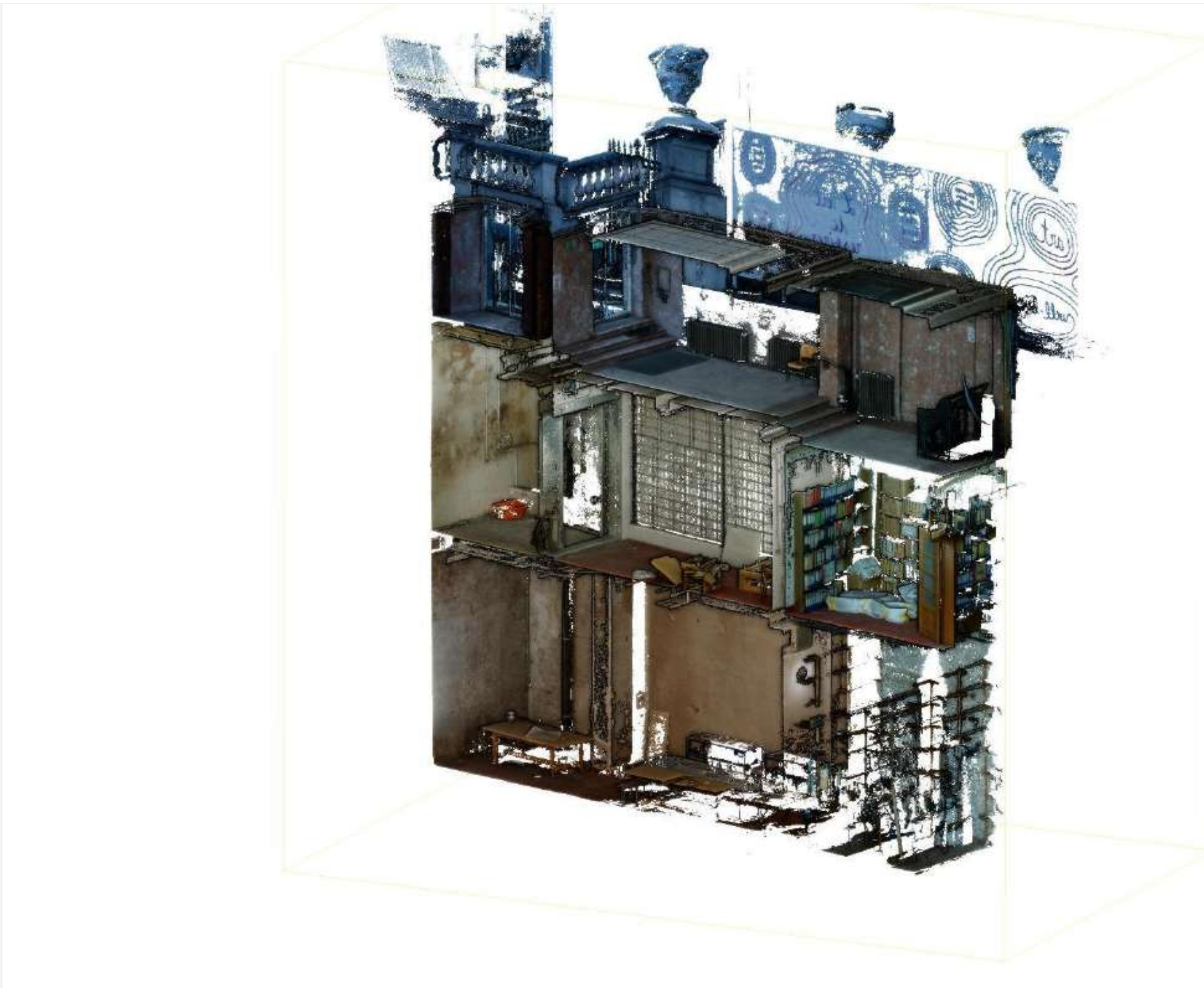


Figure 48. Definition of an Interest zone

From the definition of the interest zone and cleaning/subsampling operations, the list of the main optimised 3D files can be summarised as follows:

TLS

- 3D point cloud from for the whole scanned space, subsampled using 'octree method'
- 3D point cloud for the interest zone, no subsampling

Photogrammetry (pictures alone)

- 3D point cloud from for the whole scanned space, using 'medium' quality for dense reconstruction

- 3D point cloud for the interest zone, using ‘high’ quality for dense reconstruction

From these working files, more complex processing actions could be performed such as:

- Isolating more precise cut sections through the point clouds
- Computing local geometrical features on points (verticality, density, etc.)
- Computing the planarity of walls, floors, or ceilings
- Etc.

All of these operations can be done in the open-source software *CloudCompare*.

Formatting useful data from the prepared 3D files: In a later stage, so-called ‘final deliverables’ were produced from the optimised 3D assets. Emphasis was placed on producing files that are usable for a larger public, and easily transferable. Table 2 provides a selection of the most important ones, with their potential use for inventory missions that involve diagnosis.

Collected data	Level 1 deliverable	Level 2 deliverable	Final deliverable	Main use
*Photos, exterior and interior **(T1 + T2**)*	→ *MVP, Merged point cloud of the envelope and the interior spaces*	à Horizontal sections of the point cloud at different levels	à Plan of each storey	**Mapping** the internal organisation of the building rooms
		à 0.1m thick cross sections every 0.5m along the main building axes	à Orthoviews of the sections	**Understanding** the configuration of the building
		à Cut sections of key walls	à Orthoviews of those walls	**Evaluating the condition** of those walls **Contextualising** the humidity measurements

Table 2. *Some of the chosen key final deliverables or inventory missions that involve diagnosis.*

Results: As mentioned earlier, the amount of data generated here was extremely large. Only a general overview of the files produced, and the analyses performed can be provided, together with the most significant results. In Agisoft, the T1 and T2 photos could be aligned without the need to add manual attachment points. The advantage of this approach is of course the use of only a camera, and therefore a reduced cost of acquisition.

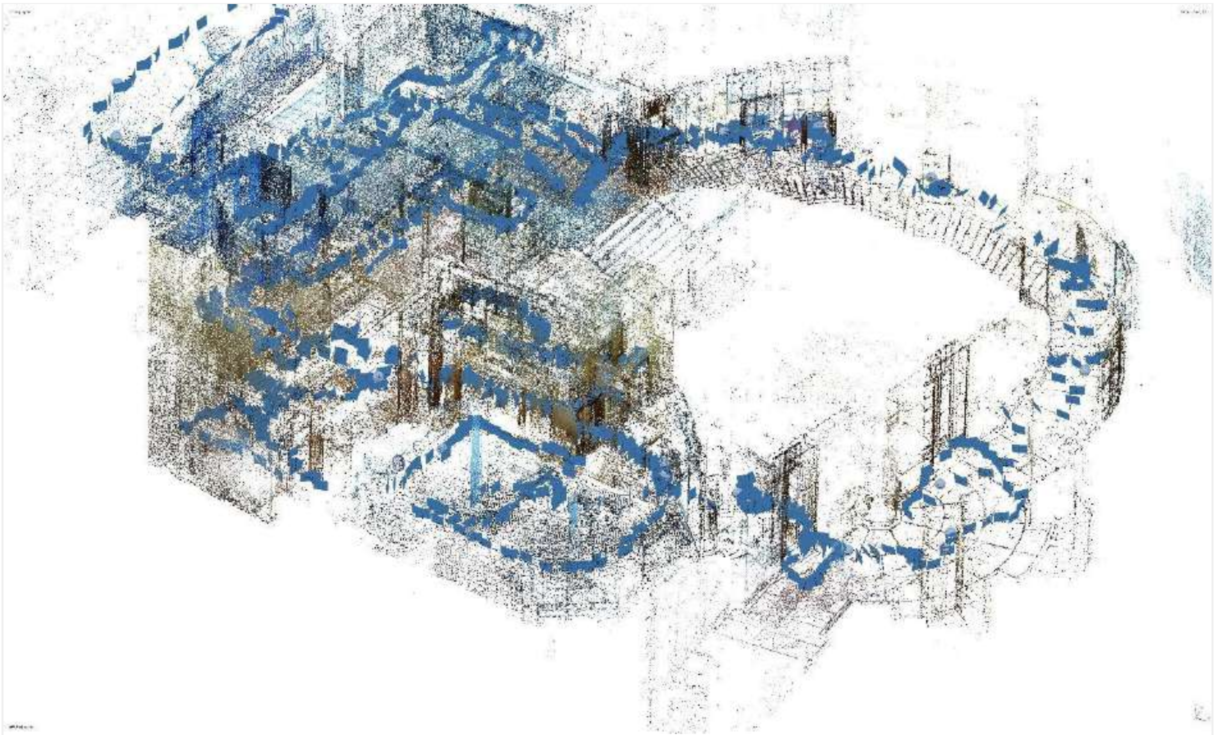


Figure 49. *Images alignment in Agisoft Metashape*

The results of the photogrammetric dense cloud reconstruction show a high level of noise, which can be properly filtered using the "confidence" level calculation offered by the software (Figure 50).

Figure 51 illustrates a specific data creation workflow from this particular point cloud. With the density of point clouds that can be achieved with modern MVP software, it is expected to achieve a certain level of visual realism.

Figure 52 shows how the different 3D datasets compare in this respect. It can be seen that the incorporation of images into the 3D reconstruction process significantly improves the visual rendering, but has also reduced the areas of missing data in places (e.g., at the water pipe). On the other hand, the laser survey is more reliable in terms of geometric measurement accuracy, and more robust for the reconstruction of solid-coloured surfaces.

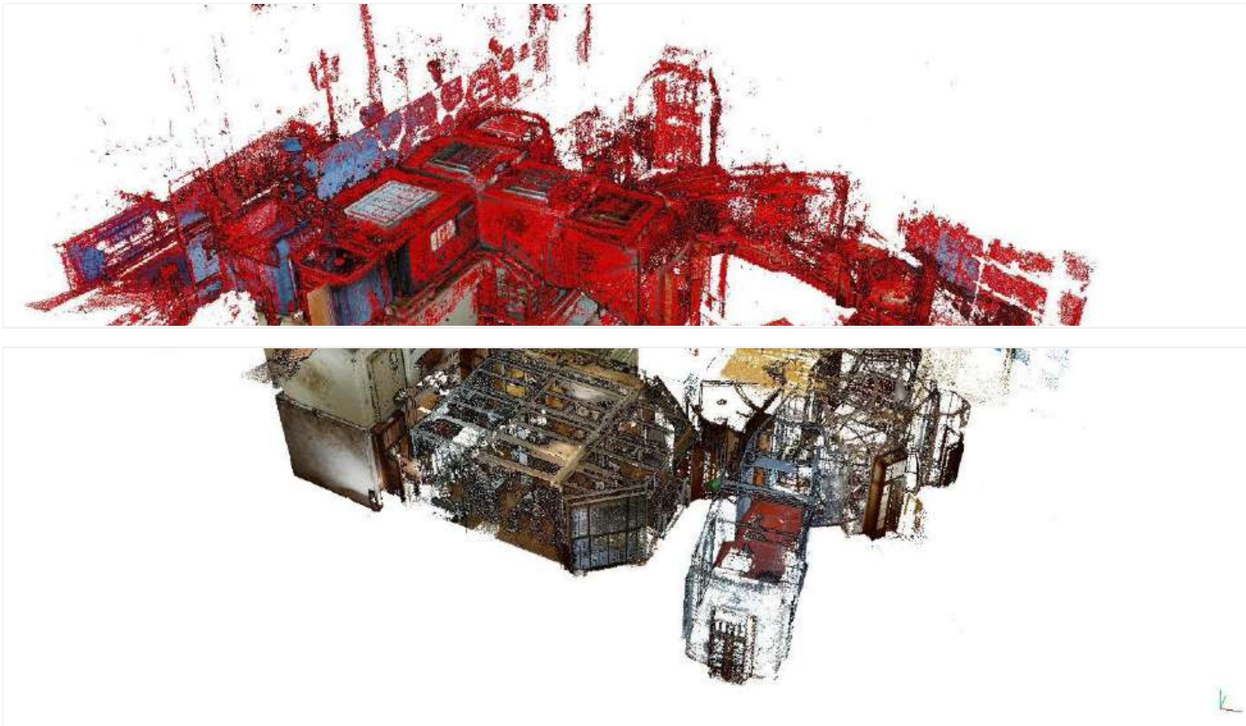


Figure 50. *Cleaning of the less 'reliable' points via the photogrammetry software: above: points to be filtered indicated in red; below: cleaned point cloud.*

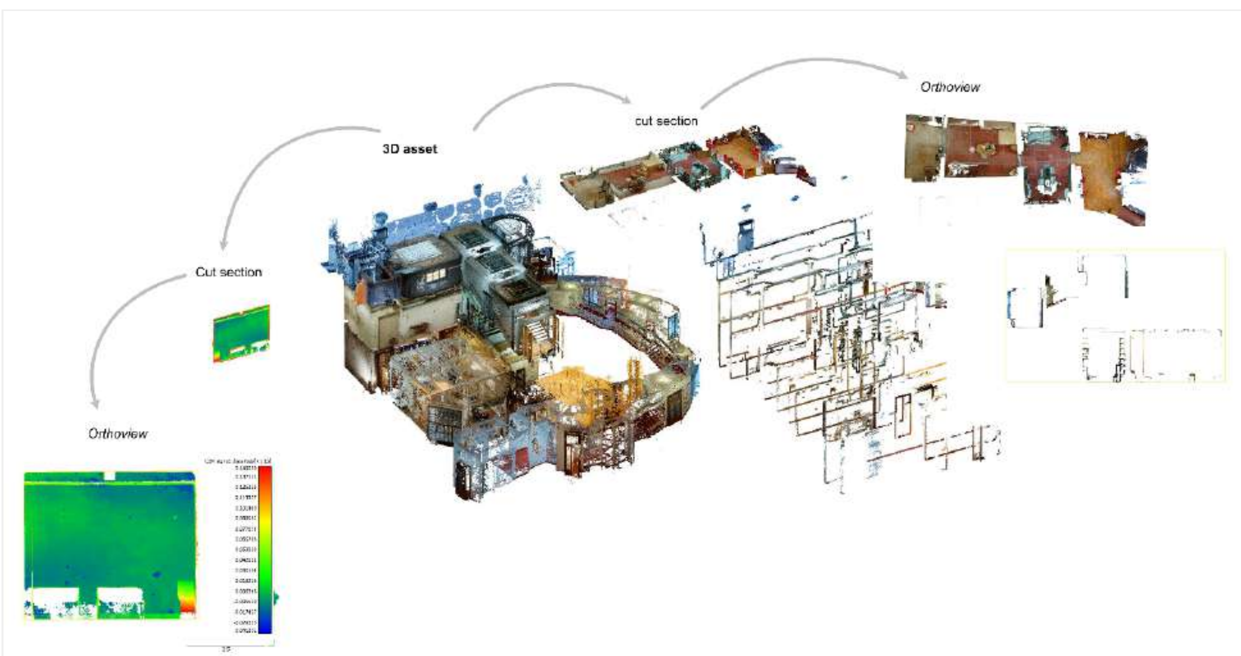
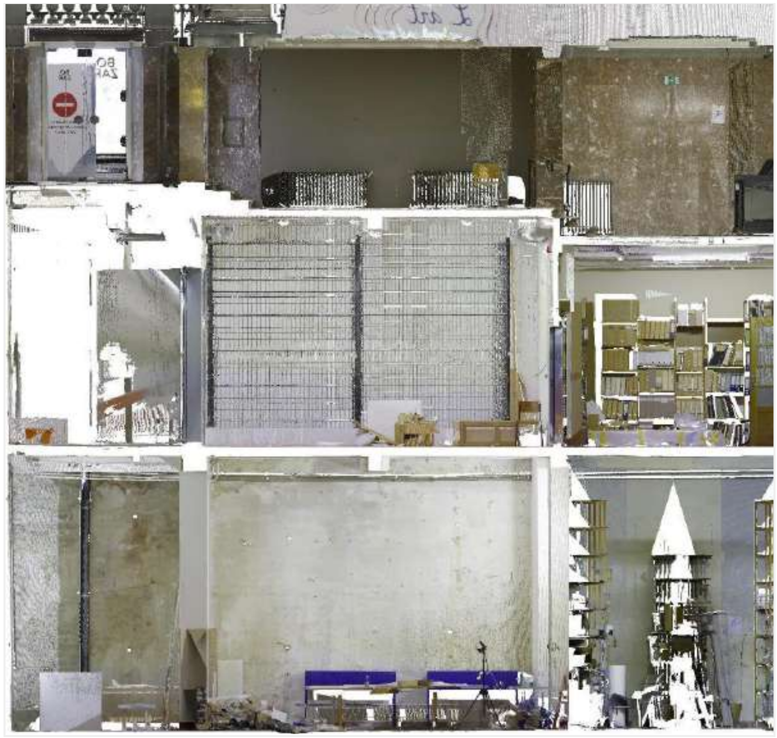


Figure 51. *An illustration of data processing: Merged point cloud of the envelope and interior spaces processed into slices and then into key orthoviews (images)*

(a)



(b)

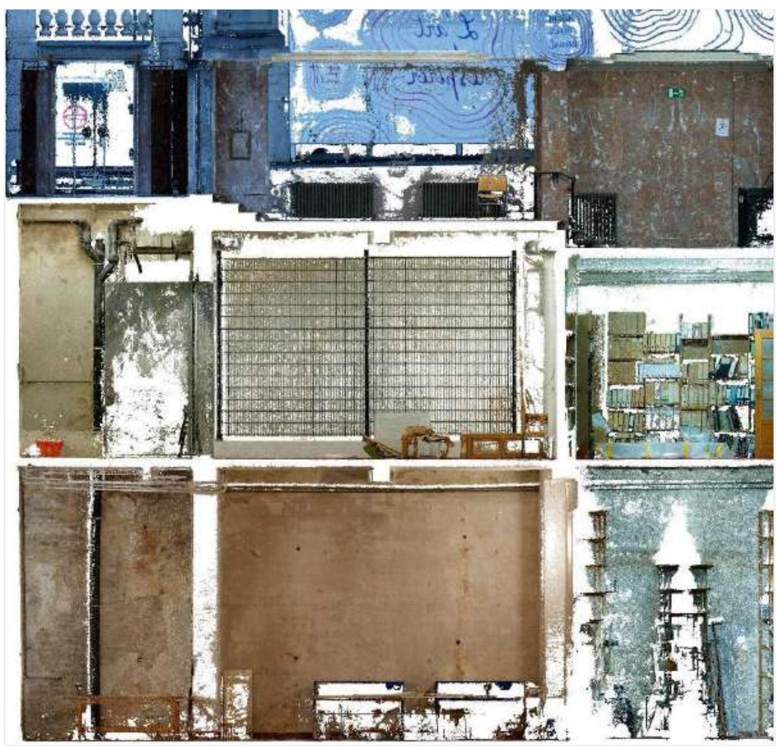


Figure 52. *Comparative 3D reconstitution over the area of interest (indoor pictures only)*
(a) Laser scanning
(b) Photogrammetry

3.4. Data processing workflows for reuse audits

3.4.1. How to define a reality capture workflow

As it was shown all along the document, many approaches, devices, and algorithms can be used to provide useful data for reuse assessments. One question comes naturally: How to choose the right scanning strategy? Once the needed data is identified, defining quality criteria is a first step. Then, depending on contextual parameters, the assessor can opt for the best resources. In-depth studies like the ones illustrated in the presented case studies are rarely justified. At the most, they show the potential of scanning technologies. In most real cases, a balance needs to be found between scanning exhaustivity and economic imperatives – especially for reuse audits.

3.4.2. Quality criteria for 3D assets

The quality of the initial 3D output can be assessed according to several criteria (non exhaustive):

- **The spatial restitution.** This criterion evaluates how a particular 3D asset allows us to understand the general geometry of the interest object. It is a quite subjective criterion: panoramic images, for example, can allow us to 'understand' the configuration of a room, without containing any actual 3D data.
- **The geometrical resolution.** This criterion evaluates how the 3D assets transcribes fine geometrical details of the scanned surface. Laser scanners generally offer a good consistency of point sampling for a given distance. In addition, the user can generally choose between predefined resolution levels (for example, 'medium', 'low' and 'fine' details). With photogrammetry, the density of the produced point clouds and meshes depends on many parameters, including the typical pixel size of the input pictures or the 3D reconstruction parameters.
- **The geometrical accuracy.** This evaluates how each measured point is accurate relatively to reality. It is often difficult to evaluate, as it requires some reference. Often, the manufacturer of the equipment will provide an evaluation of the accuracy in given conditions. Again, with photogrammetry, the final accuracy will depend on various factors.
- **The colour restitution.** If the digitising approach provides colour information, then this information can be evaluated qualitatively: how accurate are the colours, how is the exposure, are there chromatic aberrations, etc.
- **The data completeness.** This criterion evaluates how complete is the provided dataset: absence of holes or 'shadows', restitution of high objects, …

- **The data homogeneity.** This evaluates how robust are the measurements and how the quality varies within the dataset.
- **The proportion of exploitable data.** This evaluates the quantity of erroneous data, which cannot be used and need to be cleaned. Laser scanning, for example, has the tendency to generate inaccurate points close to windows, due to laser reflections and refraction. Moving objects on the scanned scene can also be problematic.
- ...

3.4.3. Elaborating a scanning strategy for reuse audits

In the end, reality capture strategies are defined by the type of data to be extracted, so-called 'deliverables', and their foreseen final use. Hence, two main aspects should be considered when studying 3D surveying techniques: the creation of 3D assets (and other side datasets) and the processing of these assets.

Facing the many possibilities in terms of both data acquisition and data processing can become challenging, especially for the ones less familiar with modern scanning equipment, the opportunities they offer but also their intrinsic limits. To cope with that risk, there exists a need to provide guidelines that would define adequate 'reality capture' strategies.

The actual final use, or uses, should always be the starting point when defining a 3D surveying mission. In turn, the needs will orient towards adequate deliverables. The latter should be defined with clear specifications in terms of quality, such as defined above. Depending on those specifications, a surveying technique, or a combination of techniques will be chosen. If only the building geometry matters and high measurement accuracy is sought after, then modern laser scanners might offer the ideal solution. If photorealism is a key aspect of the capture mission, then photogrammetry is an unavoidable step (Figure 53). Aerial surveying with drones, on their side, offer a unique perspective for digitising roofs or elevated surfaces (Figure 54). However, using such technology may prove to be expensive or more cumbersome from an administrative point of view. Because beyond the technical considerations, each inventory mission is also characterised by a specific socio-economic context. The budget, the building accessibility, the time frame, or the locally available expertise are some of the other aspects that will define the 3D survey specifications. A compromise might be necessary to define to cope with operational or budgetary limitations. If so, priority deliverables must be put forward.

To summarise, the term 'reality capture strategy' covers multiple aspects: the definition of on-site surveying equipment, the elaboration of the acquisition plan, the processing of deliverables and the sharing/updating of data. A balance must be found between the applicant expectations and the surveyor means. Table 3 provides an example of a diagram that would allow evaluating scanning approaches for a specific inventory mission. Providing such clear decision tools will be crucial in the future to encourage better retrofits thanks to better reuse assessment campaigns.

Figure 53. *Combining TLS and photos to maximise both geometrical accuracy and textural quality (illustration: mesh from combined photos and laser scans)*

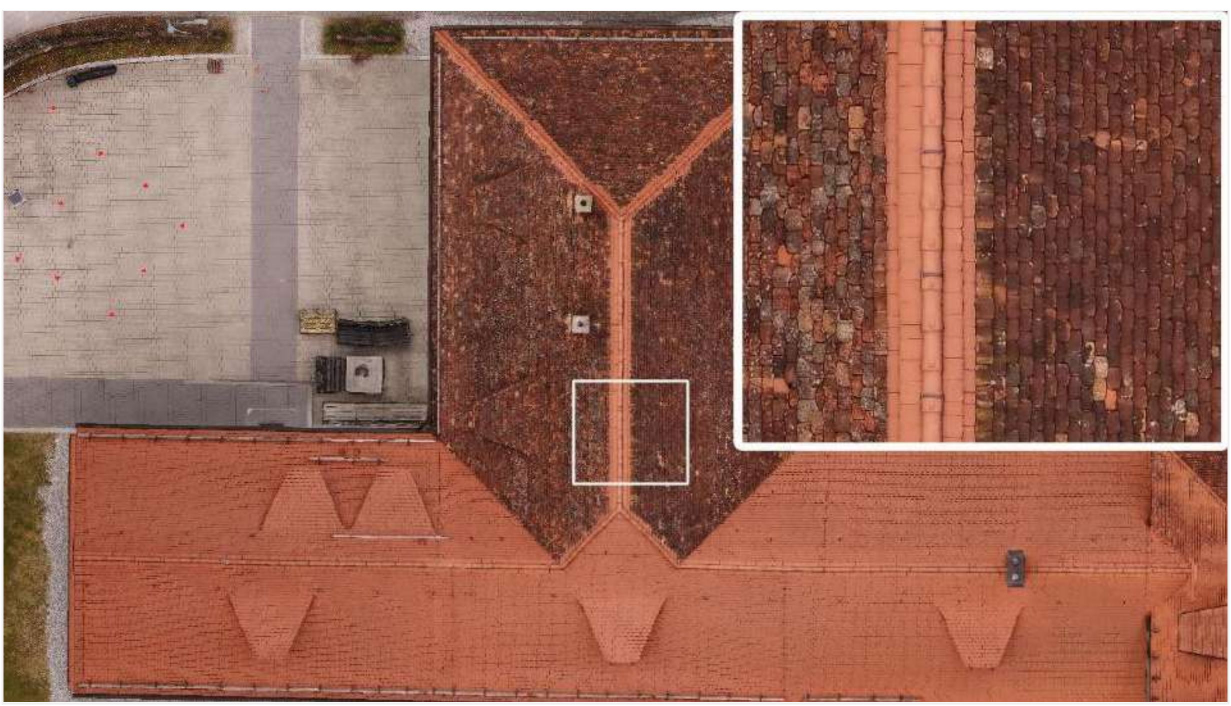


Figure 54. Drones allow detailed reproductions of roofs

Possibilities in terms of analyses and quality evaluation (completeness of data/relevance of data)

Reality capture approach ↓	***Site***		***Building***			***Envelope element***						
	Description	*Dimensions of obstacles/ topography*	*Exterior dimensions*	*Typology*	*General diagnosis*	*Description of openings*	*Thickness*	*Surface materials identification*	*Damages and pathologies*	**Efforts for sharing of data**	**On site efforts**	**Off site efforts**
Terrestrial images (low overlap), outdoor only	-/+	--/--	-/-	+ / ++	- /+	-/-		- /+	- /+	++	++	++
Terrestrial Panoramic images, indoor and outdoor	+/+	+/--	+/--	++ / ++	+/+	+/-		+/-	+/-	++	++	++
(...)												
TLS (no colour), indoor and outdoor	+/-	+/+	++/++	+/-	+/-	+/-	+/++	+/--	+/-	-	+	+
TLS (with colour), indoor and outdoor	+/+	+/+	++/++	+/++	+/+	+/+	++/++	+/+	+/+	--	-	+
(...)												
RGB TLS + indoor and outdoor photogrammetric photoset, including drone shots	++/++	++/++	++/++	++/++	++/++	++/++	++/++	++/++	++/++	--	--	--

Table 3. *Examples of reality capture strategies*

3.4.4. Proposed draft of scanning strategies for reuse audits

The type of assessment is central when defining a capture strategy. There are different levels of data collection completeness and quality, depending on the type of assessment, and the means that can be mobilised. A short draft of strategies is provided here, considering the case where an entire building needs to be surveyed to identify reusable materials and elements. It is only provided here as an illustration. For other types of mission (e.g., at district scale), the strategies should naturally be adapted.

Quick site visits and general analysis

True 3D scanning technologies are a bit over-mobilized to obtain a quick overview of a building. There, an intelligent mobilisation of imaging techniques would be preferred. Still, panoramic images offer a way of capturing more data more efficiently, to avoid missing crucial information. For technology enthusiasts, photogrammetry can be mobilised locally, to reconstruct interest zones in 3D.

	Equipment	Data capture	Recommended data processing
Strategy 1 **Cost:** $ **Expertise:** low **On-site efforts:** low **Off-site efforts:** low	1) Smartphone/DSLR/mirrorless camera and a wide-angle capable lens 2) Distometer (taking key measurements)	Terrestrial pictures: wide shots of rooms and façades of interest. Focus pictures on key interest elements	Minimum: organising pictures in a logical way (e.g., by storey) Recommended: Organising pictures on existing plans or schematic drawings
Strategy 2: **Cost:** $ **Expertise:** low **On-site efforts:** low **Off-site efforts:** low	Strategy 1 + panoramic camera	Strategy 1 + one panoramic shot in each room	Same as strategy 1
Strategy 2' **Cost:** $$ **Expertise:** low **On-site efforts:** low **Off-site efforts:** medium	Strategy 2 + small drone	Strategy 2 + aerial shots or videos of the building	Same as strategy 1
Strategy 3: **Cost:** $/$$ **Expertise:** medium **On-site efforts:** low **Off-site efforts:** medium/high	Same as strategy 2 (or 2')	Same as strategy 2 (or 2') + photogrammetric datasets for key elements or areas	Same as strategy 1 + creation of point clouds for captured areas or objects

General audit and inventory

When true audits are involved, it is crucial to get an accurate assessment of the building's spatial organisation and key dimensions. Relying solely on traditional imaging technologies runs the risk of missing information or misjudging quantities. It is therefore preferable to involve 3D scanning technologies, ideally at low cost. Here, the assessor can benefit from various approaches, depending on its expertise and the means that can be mobilised.

Strategy 1

Cost
$/$$

Expertise
medium

On-site efforts
medium

Off-site efforts
low

Completeness of data (geometry)
low

Completeness of data (colour)
high

Accuracy (geometry)
low

Accuracy (colour)
high

Equipment	**Data capture**
1) DSLR/mirrorless camera and a wide-angle capable lens	1) Terrestrial pictures: wide shots of rooms and façades of interest. Focus pictures on key interest elements
2) (Small drone)	2) (Aerial pictures: wide shots from the outside. Focus pictures on key interest elements)
3) Panoramic camera	3) Panoramic pictures: one panoramic shot in each room
4) Distometer (taking key measurements)	

Recommended data processing

Minimum: Organising pictures on existing plans or schematic drawings

Recommended: creation of a virtual visit of the building

Remarks

Whereas no 3D scanning technology is involved, organising panoramic pictures as a virtual visit can allow the assessor to understand how the building is organised and identify the element to be reused. The automatic evaluation of quantities based only on panoramic pictures is impossible, and there, manual measurements need to complete the information. Drone shots can be considered if there is no other means of capturing elevated elements.

Strengths	**Weaknesses**
Low cost Strong visual capture of the building	Very weak regarding geometric recording

Strategy 2

Cost
$$/$$$

Expertise
low

On-site efforts
low/medium

Off-site efforts
low

Completeness of data (geometry)
high

Completeness of data (colour)
high

Accuracy (geometry)
medium

Accuracy (colour)
high

Equipment

1) Panoramic depth camera or panoramic camera compatible with 3D reconstruction

Data capture

1) Panoramic capture: at least one panoramic shot in each room

Recommended data processing

Minimum: Creating the virtual visit with the web service

Recommended: Exporting the 3D model (see the associated costs)

Remarks

Some commercial solutions exist to generate 3D building reconstructions based on panoramic depth cameras or even standard panoramic cameras (e.g. Matterport solution). Whereas the geometrical accuracy is not the best, it can be judged sufficient for many audits.

The subscription fee for such service should still be considered in the final costs of the strategy. A strong limitation of this approach: it is not adapted for outdoor use, limiting the study of the building envelope.

Strengths

Easiness of data capture

Weaknesses

Geometrical accuracy
Hosting costs
Not adapted for outdoor use

Strategy 3:

Cost
$$$

Expertise
medium

On-site efforts
medium

Off-site efforts
medium/high

Completeness of data (geometry)
high

Completeness of data (colour)
high

Accuracy (geometry)
high

Accuracy (colour)
low/medium

Equipment

1) DSLR/mirrorless camera and a wide-angle capable lens
2) Low-end laser scanner and accessories (e.g., targets)

Data capture

1) Terrestrial pictures: wide shots of rooms and façades of interest. Focus pictures on key interest elements
2) Laser scans: sufficient scans to avoid large 'shadowed' zones. Ideally with colour capture.

Recommended data processing

Minimum: creating a point cloud of the building within the laser scanning registration software. Cleaning the point cloud and creating key cut sections.

Recommended: minimum + creating key orthoviews (e.g., façade elevations, slices, floorplans) + creating automatic panoramas (if possible with the laser scanning equipment) + hosting the point cloud on a web server

Remarks

The huge benefit of this strategy is to access a point cloud for the whole building, which can serve as a strong basis to identify materials and evaluate their quantities. Because laser scanners are expensive, such hardware can be rented. Alternatively, the mission can be subcontracted.

Strengths

Geometrical accuracy
Robustness of the method
Possibility of creating panoramas with some laser scanners

Weaknesses

Heavy processing
Large resulting files
Intense off-site efforts
Costs

Strategy 4

Cost
$$

Expertise
high

On-site efforts
medium/high

Off-site efforts
medium/high

Completeness of data (geometry)
medium

Completeness of data (colour)
high

Accuracy (geometry)
medium

Accuracy (colour)
high

Equipment

1) DSLR/mirrorless camera and a wide-angle capable lens
2) (Small drone)
3) Tripod
4) Distometer (taking key measurements)
5) Printed targets

Data capture

1) Terrestrial pictures: high overlap pictures on the whole building, from inside and outside
2) (Aerial pictures: high overlap pictures of the building envelope)

Recommended data processing

Minimum: creating a point cloud of the building within a photogrammetric software. Cleaning the point cloud and creating key cut sections.

Recommended: minimum + creating key orthoviews (e.g., façade elevations, slices, floorplans) + hosting the point cloud on a web server

Remarks

The huge benefit of this strategy is to access a point cloud for the whole building, which can serve as a strong basis to identify materials and evaluate their quantities. However, relying only on photogrammetry imposes that the building provides sufficient textural information. It is thus not adapted to modern buildings or buildings where uniform materials are dominant. Moreover, whereas the approach can be relatively low-cost, it requires high expertise from the operator, regarding the complexity of photogrammetry software.

Strengths

Colour restitution
Picture database created
Costs

Weaknesses

Heavy processing
Large resulting files
Robustness of the method
Intense off-site efforts
Expertise needed

Detailed audit and inventory

Detailed audits require higher confidence in the captured data, as well as complete datasets. The involved processing can be more demanding, to extract a large quantity of information. There, 3D scanning technologies seem unavoidable if we want to upgrade from the time consuming process of taking pictures and notes, and automation will be preferred when possible, for on-site operations as well as for data extraction. Laser scanning remains the leading technology, even if the efforts can be significant, especially for large buildings. In this case, mobile mapping solutions can be preferred. It should be noted that the strategies presented above can also be used for detailed audit but will bring less useful data.

Strategy 1:

Cost
$$$

Expertise
medium

On-site efforts
medium/high

Off-site efforts
medium/high

Completeness of data (geometry)
high

Completeness of data (colour)
high

Accuracy (geometry)
high

Accuracy (colour)
medium/high

Equipment
1) DSLR/mirrorless camera and a wide-angle capable lens
2) High-end laser scanner and accessories (e.g., targets)
3) (Drone with good imaging capabilities)

Data capture
1) Terrestrial pictures: wide shots of rooms and façades of interest. Focus pictures on key interest elements
2) (Aerial pictures: high overlap pictures of the building envelope)
3) Laser scans: sufficient scans to avoid large 'shadowed' zones. Ideally with colour capture.

Recommended data processing
Minimum: creating a point cloud of the building within the laser scanning registration software and a photogrammetry software to incorporate drone shots, if relevant. Cleaning the point cloud and creating key cut sections. Creating key orthoviews (e.g., façade elevations, slices, floorplans)

Recommended: minimum + creating automatic panoramas (if possible with the laser scanning equipment) + hosting the point cloud on a web server

Advanced: recommended + automated segmentation of the point cloud

Remarks
The huge benefit of this strategy is to access a point cloud for the whole building, which can serve as a strong basis to identify materials and evaluate their quantities. Because laser scanners are expensive, such hardware can be rented. Alternatively, the mission can be subcontracted. Drone can be used in a complementary way to capture the elevated zones. A standard photogrammetric approach will then be needed to process the aerial pictures

Strengths
Geometrical accuracy
Robustness of the method
Possibility of creating panoramas with some laser scanners

Weaknesses
Heavy processing
Large resulting files
Intense off-site efforts
Costs

Strategy 2:

Cost
$$$

Expertise
medium

On-site efforts
low/medium

Off-site efforts
medium

Completeness of data (geometry)
high

Completeness of data (colour)
high

Accuracy (geometry)
high

Accuracy (colour)
medium/high

Equipment

1) Mobile mapping system

Data capture

1) Laser scans: walking around the zones to capture

Recommended data processing

Minimum: creating a point cloud of the building within the mobile mapping software. Cleaning the point cloud and creating key cut sections. Creating key orthoviews (e.g., façade elevations, slices, floorplans)

Recommended: minimum + creating automatic panoramas (if possible with the laser scanning equipment) + hosting the point cloud on a web server

Advanced: recommended + automated segmentation of the point cloud

Remarks

The huge benefit of this strategy is to access a point cloud for the whole building, which can serve as a strong basis to identify materials and evaluate their quantities. Because such mobile laser scanners are expensive, such hardware can be rented. Alternatively, the mission can be subcontracted.

Strengths

Capturing large areas effectively
Geometrical accuracy
Robustness of the method
Possibility of creating panoramas

Weaknesses

Heavy processing
Large resulting files
Costs

Strategy 3:

Cost $$$$ **Expertise** high **On-site efforts** high **Off-site efforts** high **Completeness of data (geometry)** high **Completeness of data (colour)** **high** **Accuracy (geometry)** high **Accuracy (colour)** high	**Equipment** 1) DSLR/mirrorless camera and a wide-angle capable lens 2) Tripod 3) High-end laser scanner and accessories (e.g., targets) 4) (Drone with good imaging capabilities) **Data capture** 1) Terrestrial pictures: wide shots of rooms and façades. Focus pictures on key interest elements. High overlap pictures on the whole building, from inside and outside 2) (Aerial pictures: high overlap pictures of the building envelope) 3) Laser scans: sufficient scans to avoid large 'shadowed' zones. Ideally with colour capture. **Recommended data processing** Minimum: creating a point cloud within a photogrammetry software to combine pictures and laser scanning data. Cleaning the point cloud and creating key cut sections. Creating key orthoviews (e.g., façade elevations, slices, floorplans) Recommended: minimum + creating automatic panoramas (if possible with the laser scanning equipment) + hosting the point cloud on a web server Advanced: recommended + automated segmentation of the point cloud **Remarks** Again, this strategy provides access to a point cloud for the whole building, which can serve as a strong basis to identify materials and evaluate their quantities. It combines the strengths of laser scanning (high geometric accuracy) and of photogrammetry (colour restitution). Drone can be used in a complementary way to capture the elevated zones. An advanced standard photogrammetric approach is required to align the pictures and the laser scanning data. Such a process can be justified for very large projects, or for high-value missions. **Strengths** Geometrical accuracy Colour restitution Possibilities in terms of data processing Picture database created Possibility of creating panoramas with some laser scanners **Weaknesses** Heavy processing Large resulting files Intense off-site efforts Extremely high expertise needed Costs involved

Of course, once the building model is ready, the actual auditing process still needs to be done. The goal of a reuse or reclamation audit is not to have a complete (3D) model of the building, but to have a clear listing of materials and components in the building with a potential for reuse.

3.5. Development of automated solutions to answer 3D processing challenges

Valorising 3D data from reality capture is a time-consuming task. Although undoubtedly relevant, the many deliverables presented here are extremely demanding in terms of manual processing. It is thus logical to seek for automation solutions. In this research, the importance of textural data was put forward. Indeed, MVP allows the production of detailed visual maps of many building components. Creating a large and organised set of orthoimages, which would provide a comprehensive visual dictionary of the building, appears as a goal. However, that seems hardly achievable using manual approaches.

Whereas state-of-the-art scan-to-CAD or scan-to-BIM are certainly promised to a bright future, the automatic transformation of complex building elements into geometric (or even semantic) objects is still in its premises. At their stage of development, using them results in too much uncertainty. There is also a risk of oversimplifying or over-complexifying data for the energy modeller. Using simplified and robust algorithms wisely, on the other hand, could lead to significant improvements for the fast creation of orthoviews datasets.

In this exploratory research, the automatic detection of shapes was limited to using the RANSAC algorithm to detect geometric planes in the point clouds. These planes are relevant both as support for various analyses and for the segmentation of the building. CAD objects were used only to process the 3D information but, in the end, images remain the main output of our automation efforts. A prototype app was created to perform five main operations (Figure 55).

1) Performing a global RANSAC analysis and extracting the main constructive planes of the building as well as the points supporting those planes.
2) Analysing and labelling planes and their support points according to geometric (e.g., orientation, size, density) and textural information (e.g. average colour of the support points, variation of colours).
3) Using the characteristics of the detected planes to provide semantic information to the point cloud, while segmenting it in large classes (points belonging to a specific storey or a specific façade, for example).

4) Generating key orthoviews (as listed in Table 1) automatically, using semantic information as support.
5) Proposing modern image segmentation/labelling approaches to extract information from the orthoviews.

The application was developed in Python and relies intensively on *CloudCompare* command line interface and the *Open3D library.* The results are encouraging and show ways other than BIM to valorise surveying data. In the future, it is planned to have each generated orthoview (step four) projected on its reference planar mesh object, which would be registered in space and exportable as a CAD file. While particularly interesting, step five is still under development.

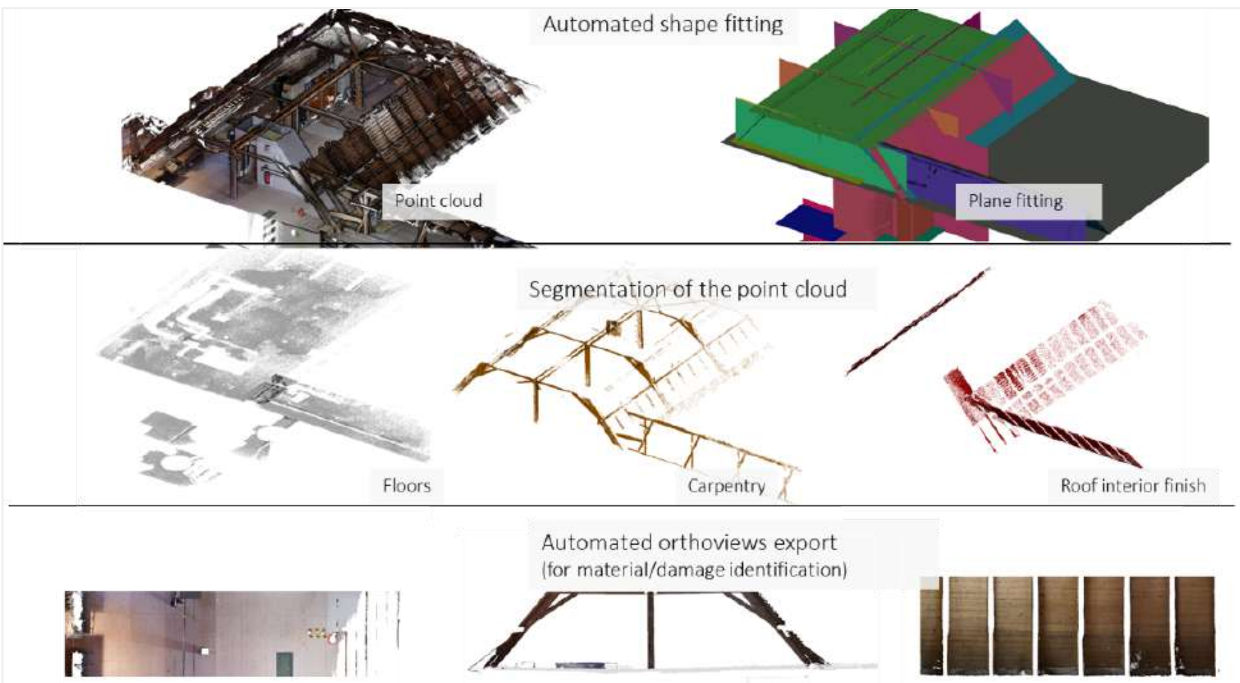


Figure 55. *Various automation processes implemented using CloudCompare CLI and Open3D library.*

3.6. Final remarks

Working with images is still the best 'all-around' solution for conducting most reclamation audits. In many cases, pictures can be used 'out of the camera', without any processing, and answer the needs of most simple inventories. However, simple image reports can also appear unsatisfactory for the main following reasons:

- The information is difficult to contextualise (e.g., 'Where was that photo taken?')
- Geometric measurements are, at the best, very approximative
- There is a strong risk of missing some important element, making it necessary to visit the site again

For all those reasons, 3D reality captures approaches need to be understood by field actors. Numerous approaches exist, and each one of them can answer a specific need. While it is true that some digitising techniques are expensive and difficult to implement, we believe that others can be rapidly deployed. Photogrammetry seems particularly interesting for technology enthusiasts, as demonstrated in the two case studies. Other relevant solutions were highlighted, such as the use of panoramic images, or the mobilisation of mobile scanning methods. In any case, 3D data processing is still a time-consuming task which will need to be facilitated in the future. For that purpose, the prototype point cloud processing app appeared particularly interesting and promised bright future developments. In parallel, the BBRI will keep its efforts to clarify and standardise the data transformation workflows.

4. Artificial intelligence in support of material reclamation

"Slowly but steadily the uptake of artificial intelligence (AI) is increasing in the construction sector. At construction sites, AI is used for automated progress monitoring to detect delays, critical errors and more. Additionally, object detection techniques can be applied to recognize potentially dangerous situations such as missing guardrails or missing signage. The benefits of AI are multiple: faster progress monitoring, possibility to detect deviations in advance without costly delay, real time detection of errors or threats and thus efficient risk management strategies."

The above paragraph was generated automatically by AI on the basis of a single human written sentence (example created using shortlyai.com). This is but one example of the potential of AI to support human tasks, here demonstrated for text writing.

AI can be defined as the capability of a machine to imitate intelligent human behaviour (definition retrieved from Merriam-Webster's Unabridged Dictionary). A characteristic benefit of AI is that its functionality does not need to be coded by hand. Instead, an AI network can learn to perform a task by itself using a dataset of problems and answers. The benefit of the self-learning aspect of AI is especially evident in cases where it would normally take an expert many months to code a complex task by hand, and even more so in cases where the task is simply too complex for a human due to the high dimensionality of the subject matter. In recent years, advancements in self-learning AI have passed a critical point where the use of AI may incur actual, tangible benefits across a range of industries. In light of this development more and more industries are increasing the uptake of AI related technologies in order to boost their competitiveness and increase profit margins. The construction sector too is coming to the realisation that AI holds potential to reduce costs by providing new ways to optimise productivity and is seeking opportunities to harness this potential. The present report examines the use of AI for a field where its use has potential yet where the technology is yet to fully prove itself: that of AI-assisted reclamation auditing of building materials.

While the construction sector has taken an interest in AI, its current possibilities and limitations at present are insufficiently clear. Moreover, knowledge is lacking regarding when and how to apply AI effectively, as well as the time and effort required to obtain actionable results. This is especially the case for the topic of AI-assisted building material reclamation, which is presently under research. This report serves to address this issue and is split into four parts. First, to create a basic understanding of the present possibilities and limitations of AI, and more specifically in the AI subfield of neural network based computer vision, a brief overview is provided of relevant computer vision concepts and technologies. Building on this foundation, next a guideline consisting of a series of steps is presented to give insight into the time, effort and decision process required in creating a proof-of-concept AI network that can automatically perform an object or material recognition task. Then, the results of several test cases are presented to illustrate how the steps of the guideline may be applied in practice. In the last part of the report an overview of lessons learned is provided, as well as a discussion of the opportunities and obstacles in using AI for building inventories. Finally, concluding remarks are presented along with an overview of possibilities for further research.

4.1. Core concepts

At its core, the self-learning capability of AI is made possible by what is called a “neural network” which is partially inspired by human neural architecture. A neural network can be broken down into three basic parts: a set of inputs (problems to solve), a network which changes those inputs to provide an answer, and a mechanism which verifies if the answer is correct and adjusts the network accordingly to optimise the likelihood of correct answers. By performing these actions repeatedly the network improves over time, a process referred to as training. After training is successful, the AI can solve problems it has not seen before at a certain level of accuracy.

One of the dominant uses of AI is its application for computer vision tasks, where AI networks learn to understand and quantify the visual world. Let us use the previous example of an AI network and see how its workings may assist the manual labour involved in making building reclamation assessments. Ceramic tiles are an example of a building material of comparatively high value and high reuse potential. Counting how many tiles and what type of tiles are present on a floor or wall can be an arduous task to perform by hand. As manual counting is often not feasible, total surface area may be estimated instead. This is one example where AI can assist by increasing accuracy and reducing required time to complete the task. Taking our previous AI network example, to have AI perform this task semi-automatically, in this case the set of inputs or problems to solve would consist of images of house interiors containing ceramic tiles, together with information about where the tiles are contained on the image. After feeding the network with this information and finishing the training process, the network can recognize the exact number of tiles in the image. The main benefit is the speed at which the network can do this, which presently can be performed at the rate of 30 images per second or higher depending on the hardware used. As parallel processing power and neural network architectures evolve, this speed is expected to increase further. This specific example of automated ceramic tile counting is an example of a test case which was performed as part of this report and is detailed in section 6.3.2. The main takeaway message here is that as long as a high-quality set of labelled images is available and the neural network is appropriately structured and trained, there is a potential path towards automatically quantifying a broad range of building reclamation object types and materials using AI.

For computer vision, the tasks AI is able to perform is dependent on the type of neural network architecture used. From a functionality standpoint, a distinction can be made between four object recognition techniques of progressively increasing complexity: classification, object detection, semantic segmentation and instance segmentation. Taking the example of an image of a lamp and chairs presented in Figure 1, we can see that classification would suffice if we just need to know if a chair is present in the image or not. Yet, from the figure it also becomes clear that we would need object detection to know where the lamp and chairs are approximately located in the image and how many there are. Additionally, it also transpires that we would need semantic segmentation if we want to know the exact location of the table and chairs in the image at pixel level accuracy. As segmentation "segments" the image at the level of individual pixels, this has the benefit of allowing the total surface area of objects or materials of interest to be computed. Lastly, if we additionally want to tell apart the individual chairs at pixel level accuracy, we would need instance segmentation.

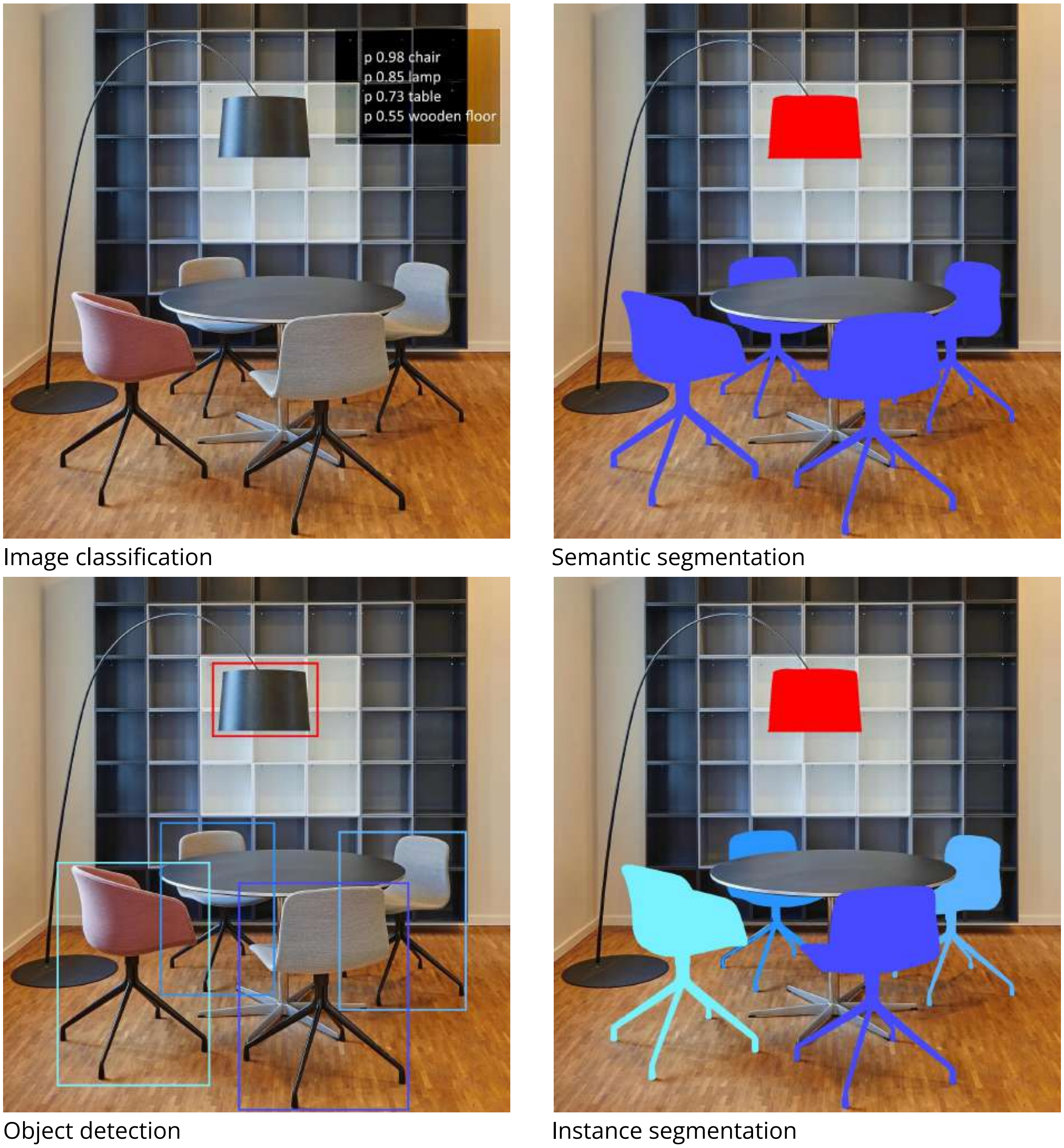


Figure 1. *Object recognition techniques (original image source: ATBO).*
Inspired by images of Facebook Research.

4.2. AI technologies overview

At risk of oversimplification, here we will provide a brief overview of the landscape of available AI technologies for computer vision tasks. Broadly speaking, AI technologies can be divided into two parts: commercial solutions and research-oriented free resources. Each has their own associated strengths and weaknesses. We will first discuss commercial solutions, which can be further divided into AI services and cloud-based DIY AI platforms.

4.2.1. Commercial solutions

AI services and software solutions: AI services target specific use cases relevant to a large number of industries. Examples of these use cases in the construction sector include (semi-) automated scan to CAD/BIM, building element detection, construction site progress monitoring, hazard detection, and inspection of structures such as bridges and other hard to reach areas. AI services typically require little client-side effort as they utilise premade AI pipelines to extract valuable insights from data in a restricted number of focus areas. Tailor-made AI services provide more flexibility, at the expense of higher cost. Generally, due to IP related issues, how the AI exactly generates the employed functionality in question is abstracted away from the end user and therefore remains a black box.

Cloud-based DIY AI platforms: AI platforms can mostly be likened to a self-help service. The platform provides a set of tools needed to perform the AI task, which are to be utilised by the user to generate results. By its nature this self-help process requires more client-side effort, yet allows for fine tuning of the AI task to the needs of the end user, and may be less expensive compared to tailor-made solutions. Oftentimes AI tasks can be performed using a variety of neural networks. For the most part, these can be divided into the four image recognition techniques discussed in section 2, yet in a range of variants, each with their own merits. For example, some neural networks may be more accurate yet require additional computational power and are therefore not suitable for use on regular desktop computers or mobile devices such as drones, while other networks may be more lightweight to run on cost-effective yet less powerful mobile hardware at the cost of reduced speed and/or accuracy. As such, there is a trade-off between methods and means, such that the network most suited for the AI task is both dependent on the nature of the task as well as the hardware used to perform the task.

A key strength of DIY AI platforms is that they allow the user to easily experiment with several neural networks. This allows quick comparisons of performance and speed, beneficial for finding the best network for the given task and hardware. It is also of note that this comparison often can be performed in the cloud without the need to install any software on local computers, which is a time saving feature. The experimentation with different networks is enabled using a so-called “model zoo”. Put simply, this is a collection of neural networks that each can be applied to perform a specific AI detection task. Another strength of AI platforms is the labelling tools offered which are used to generate problem sets and answers for the neural network to learn from. For computer vision this process is conventionally performed by manually labelling images, and is one of if not the most time-intensive part required to train neural networks. As the process is time-intensive, it is often performed by teams of labellers, and DIY AI platforms mostly provide tools to facilitate team-based work and track labelling performance. For companies lacking the time to perform the image labelling task themselves, the platforms often offer the option of paid labelling services where the labelling burden is taken care of by professionally trained labellers.

Lastly, for an additional fee, some platforms also offer what is called pseudo labelling, in which an AI network pre-trained on many object types learns from a few examples of manually created labels, and is then able to automate this labelling process to a certain extent. The task remaining for the user is then to verify the automatically generated labels, and to only correct the inaccurate ones. Especially when the number of images to label is high, such as in the case of the labelling of the numerous frames of a video, this semi-automated labelling may lead to significant time savings.

4.2.2. Free ressources

Advancements in the state-of-the art in neural network architectures for AI-based object and material recognition are largely brought forth by the research community and are conventionally free to use. The aforementioned DIY AI platforms mostly provide their own implementation of these architectures as part of their platform and add a range of features on top to increase the ease of use. Where high usability is not essential or monetary resources are limited, these research-based architectures and freely available additional resources may constitute an alternative to commercial methods. As mentioned, a clear difference with commercial tools is the lower ease of use of free resources. Software and dependencies need to be installed, code may need to be altered, and the obtained results may not be as intuitive to interpret. At the very least, the use of free resources means that several tools in the toolbelt of commercial solutions need to be collected and installed individually, and have to be configured correctly for them to work together.

The quality of free resources may also be inconsistent, and the implementation as a whole may not be optimised for deployment in real-world environments. Besides being free of charge, research-based free resources do have an important advantage, as this is the place where most of the newest state-of-the-art neural networks and techniques appear first, which may take time to be fully incorporated into commercial solutions.

Ultimately, both commercial and research-based free methods each have their merits, and it is up to the end user to determine which solution is optimal given the nature of the intended task and the resources available.

4.3. AI-compatible devices

AI-compatible devices can be fit into different categories, depending on the stage of their use: during AI training, and during deployment. Training a neural network to perform an AI computer vision task is a highly computationally intensive process. Cloud-based services sit at the very high end of the computation power spectrum and are therefore well-positioned for the AI training stage as their use means the training will be completed faster. Cloud-based services have several additional benefits: they can often be utilised on a pay-per-use basis, without the need for maintaining physical computers locally, installing software, performing regular updates and more such issues. Additionally, for a slightly higher fee the level of computational power can be up- or down-scaled by demand. In short, the use of cloud-based computing is mostly hassle free and allows for a high degree of flexibility. Given these characteristics, the use of cloud-based computation is advantageous during the computationally intensive training stage of an AI network and its benefits are most apparent in cases where there is a need to deliver results fast which can be realised by upscaling the computation power accordingly.

Local workstations with powerful graphics cards sit a bit lower on the computation power spectrum yet can be a viable alternative to cloud-based solutions. Where there is no direct need for very high computational power and fast AI training is not essential, the benefits of local workstations become more apparent. While being less performant, local workstations may already be sufficient for the AI task at hand, and have the benefit that their use is not time-limited, which is a clear benefit for times when initially a lot of experimentation is required to verify which network with which configuration and which training dataset delivers the best results. Using local workstations, this stage can be completed on a local PC without the pressure of the time-based payment model of most cloud-based services. Local workstations can also be usable for on-site deployment, for instance for highly time sensitive AI tasks where cloud-based services may be less self-evident, when data streams simply cannot be uploaded to the cloud for processing due to their sensitive nature or when internet connectivity itself is lacking. Then, for less computationally intensive tasks, at the lower end of the spectrum are the more lightweight and cost-effective edge devices.

These devices contain graphical processors which are less powerful and therefore not optimal for AI training yet can still be sufficient to perform AI detections in the deployment stage. Depending on the AI task at hand, it may be needed to employ a reduced version of a full neural network in order to make it operate smoothly on mobile devices, which comes at the cost of a somewhat lower level of AI accuracy. Whether or not this is acceptable will depend on the nature of the task. These mobile devices are well-positioned to be used on drones due to their small form factor and weight, and, due to their affordability, can be readily deployed on the construction site at multiple locations to obtain more convergent data from a variety of viewpoints to increase AI accuracy. Depending on the device in question, these mobile solutions are presently priced in the range of 50-150 EUR, with prices expected to drop further in the near future. Finally, at the very bottom of the spectrum are conventional consumer-oriented devices such as smartphones, tablets, and conventional laptops with even less computational power. These may still be usable when there are no high demands regarding time to obtain results and accuracy.

In practice, the borders between the use of these different devices across the two stages may be more dynamic. For instance, combined use of both cloud-based and local workstation solutions may be preferred in some cases, and recent advancements in mobile hardware provides new opportunities to deploy increasingly high-quality AI detections on consumer-oriented devices. The last category of devices to be discussed here is a bit of an odd one, and is that of free cloud-based computation resources. For research projects, some services exist which allow free cloud-based computation including AI network training. An example of this is presented in section 6.3.1. The limitations here are that the level of computational power may fluctuate, that the number of consecutive usage hours is limited, and that it is intended for interactive use, meaning that the user needs to "babysit" the process in order to keep the cloud-based computation process up and running.

Nonetheless, especially for those who simply want to try their hand at experimenting with different AI networks, this may be an interesting option for students and other education-based projects. For instance, when the code base of a new research-based neural network architecture is made available on such code repository sites as Github, a demonstration of the network is often provided using free cloud processing such that interested parties can experiment and learn from it with ease.

4.4. Steps to apply AI for neural network based computer vision

Is it possible to perform this task using AI? How much time and effort do I need to put in order to obtain a proof-of-concept? What are the general steps from start to finish? Building on the information of the previous sections, here we provide information to assist in answering these questions. Please note that the information provided is limited given the scope of the present report and thus may gloss over a number of details, especially given the broad range and complex variety of computer vision object and material recognition tasks.

The essential raw material needed to train an AI to automatically perform a neural network based computer vision task is the required set of inputs and answers. As we have seen in section 2, in the case of object and material recognition tasks these inputs and answers respectively consist of images and labels which indicate where which object/material is contained in each image. As the AI cannot learn to perform a task without these labelled images, one of the steps to take is to consider whether enough images can be obtained of the object or material type to be recognized. This either by taking these images in-house or by using premade datasets. At present, high-quality datasets exist for everyday household items and other common objects, yet far fewer to little to none exist for items which are less mainstream. Thus, it may be hard to find high-quality datasets for less common items such as construction materials. Additionally, even when premade datasets exist, their use may be limited to non-commercial usage.

At the risk of oversimplification, as a rough measure of thumb a minimum number of 100 source images is needed to train an AI to detect a certain object or material type for the purpose of a proof-of-concept. If the object or material type in question has many different representations, has few characteristic features or is present in a varied number of settings, the required number of images increases. For the images, it is not sufficient to simply take multiple pictures of the same object or material from different viewpoints. The set of images needs to accurately reflect all the different representations of the object/material in conditions which reflect the variety of settings in which one wants the AI to do its work after it is trained. In other words, if there is a large discrepancy between the images the AI learns from and the images it is tested on, high detection accuracy is not to be expected. In short, you get what you put in. In the case of computer vision based networks this can be well understood as these networks essentially compress the training image dataset within the network. Therefore, if the AI has not seen the object or material enough, it is not compressed into the network enough, and subsequently cannot properly recognize it. We stress this because it cannot be overstated that a high-quality image dataset quality is paramount and is the key factor to improve when AI detection accuracy is lacking. Oftentimes a network is trained to detect multiple objects/materials at the same time. For the purpose of high detection accuracy, the number of images in the dataset for each object/material type should be as equal as possible.

After determining whether the required images can be obtained, a second step is to determine whether one is willing to invest the time and effort needed to label each of the images, or is able to outsource this work. Again, with labelling we mean that one indicates by hand where the object or material type is contained in the image. Here we will provide two examples of important factors in determining how long it takes to label an image. The first is the type of labelling needed, and the second is the number of objects/materials present in the image which needs to be labelled. The type of labelling to use depends on the AI detection type one needs. Looking back to Figure 1, if one wants to know how many objects of a certain type there are within an image and if it suffices to have information about their approximate location, object detection labelling can be used. This requires that, say each window of a building façade is labelled by drawing a rectangular box around it, and assigning the name of the object type to the box. This is a fast process which takes just a few seconds per object. Yet, if many to be recognized objects are contained within the image, labelling everything in the image correspondingly takes that much more time.

In the case where one needs to have a more accurate indication of the position of an object/material shown in an image, semantic segmentation may be more suited, which provides pixel level accuracy. This also means that labelling the object/material on the image for semantic segmentation takes much more time, as this has to be done at pixel level as well. Labelling for semantic segmentation entails that one essentially paints over the pixels containing the object/material. In practice this is often done using a tool which allows one to draw a polygon shape on top of the outline of the object/material in the image, and to cut holes in the polygon where it contains objects/materials of a different type. As the labelling needs to happen with pixel level accuracy instead of simply defining a rectangular box, labelling for segmentation can take up to 20-30 minutes per image if the number of pixels to label is high and/or if the material in the image has an irregular shape, which requires many more mouse clicks to create the aforementioned polygon shape. Correctly determining whether one really needs the accuracy gained from semantic segmentation is therefore important given the impact on the required labelling time.

After labelling is completed, the next step is to artificially increase the number of images using image augmentation techniques. For instance, one may create different copies of one of the same image by applying rotations, warping, hue and image brightness variations and others. Doing so may increase the robustness of the detections. For instance, by applying brightness variations, the AI network will not rely on brightness as a critical factor to determine whether an object concerns a certain element of interest. In effect this means that the object is more likely to be detected accurately in different lighting conditions. Important to note is that when artificially increasing the number of images, this is done for the labels of those initial images as well, meaning that there is no need to label those newly created images.

The next step after image and label generation is to select the appropriate AI network architecture to use. Taking the example of DIY AI platforms, this step is supported by the aforementioned model zoo often available on such platforms. For the choice of which architecture to use, not only is it important to determine whether it supports the appropriate detection type, but also whether it needs to be able to run on systems with a powerful graphical processing unit or on more computationally limited mobile hardware. The next step is to decide whether to use cloud-based computation, or to train the network on a local workstation. Some DIY AI platforms provide a way to install and configure the required software on a local computer more easily, thus saving time.

After choosing between cloud and local computation, the next step is to train the network. For this, some platforms predetermine a number of parameters, while others require the user to tweak these parameters themselves which gives the user more control over the quality of the output yet requires more expert knowledge. The time required to train the network depends on several factors including computational processing power, the number and size of the images, and the training parameters used such as the learning rate, which go beyond the scope of this report. These factors combined determine whether the training is completed in several hours or takes longer. At set intervals during the training, statistics can be generated to indicate how well the network is performing at that stage. This enables one to determine whether the training should continue or should be stopped because performance has already maxed out for the purpose of the intended AI task. Both ending a training run prematurely and continuing it for too long can cause performance issues. One example of this is overfitting, in which the AI performs very well on the training dataset but is less performant in the case of real-world images. Several methods exist for speeding up the time required to train and obtain a performant network. One often used method is to use a network which has been pre trained to a certain extent on an image domain similar to the images in one's own dataset. Another is to determine more quickly whether a given network and the training parameters used are optimal or need to be tweaked in order to attain high detection quality. This can for instance be done by performing an initial training run using downsized images, which require less time to process. Once it has been determined that the network is performant for small images, the training can be redone using images of larger size.

After training, the user can perform a visual check regarding whether the network can recognize the objects/materials accurately in new images previously unseen by the network. Detection errors often provide hints as to which type of images are still lacking in the image dataset for the network to learn from, and/or indicate issues with the labels applied to the images. After training the network and obtaining sufficient detection accuracy on images, an often overlooked step is to assess the robustness of the network when used in real-world settings which often contain more variation than was contained in the images of the training dataset. This step is essential, as only a test in real environments will provide insight into the actual added value of an AI network.

4.5. Test cases

To gain insight into the practical value of AI and more specifically computer vision for building material reclamation assistance as part of this report a series of tests were performed. While the general learnings of these tests have been incorporated into steps to apply AI for neural network based computer vision contained in section 5, here we present the aim and results of each of the individual tests.

4.5.1. Building material detection

The purpose of this test was to assess whether building materials can be detected automatically, what differential value may be extracted using object detection and semantic segmentation, as well as the time involved in preparing an image dataset to apply these two detection types.

Image collection and labelling: After determining that AI detection using deep learning was the most suitable technique for the task, it was assessed whether readymade building material image datasets existed which could be used for the purpose of AI training. For this, a series of searches were conducted on Google Scholar (https://scholar.google.com/) and Github (https://github.com/). The result of these searches showed that online building material databases are very limited in number, and that the few databases located were mostly not readily available. An example is the Construction Material Library (https://raamac.cee.illinois.edu/visualization/appearance/data), a database of 22 typical construction materials with 150+ images per category, yet which at present is not available for download.

Lacking ready-made resources, Google images were scrapped for suitable close-up images of bricks, wooden elements, and stone. Additionally, for testing of building material recognition in real-life scenes, a commodity DSLR camera was used to capture images of building façades. Subsequently, the AI platform Supervisely (https://supervise.ly/) was selected to: 1. apply labels to the collected images, 2. train the neural network, 3. make predictions about the three building material types present in the images and assess the prediction accuracy.

Given the purpose of this test, the collected images were labelled both for object detection and semantic segmentation. For object detection, bricks, stones, and wooden elements were individually labelled using bounding boxes. For semantic segmentation, the selected building materials were labelled on a pixel level by applying polygon shapes around the edges of individual building materials. As this process requires more precision and more mouse clicks, the task of labelling for segmentation required 4-5 times the amount of time required to apply bounding boxes.

AI training and object detection results: After image labelling was completed, AI training was performed on Linux distribution Ubuntu 18.04.4 LTS running on an Amazon AWS p2.xlarge instance (NVIDIA K80 GPU, 4 vCPUs, 61 GiB memory). The cloud compute instance was accessed using PuTTY, an open source SSH and telnet client. For the task of object detection, neural network You Only Look Once (YOLO) v3 was selected from the Supervisely model zoo. An example of the result of AI detection is shown in Figure 2 and indicates the feasibility of using AI to automatically recognize and quantify bricks in façade images. Simultaneously, the result also demonstrates the need for proper images for the neural network to learn from. Here specifically, it can be seen that whereas horizontal bricks are detected, this is not the case for vertical bricks, which were not contained in the image training dataset. As stated in section 5, this demonstrates the importance of a dataset which reflects all different appearances of the object/material to be detected.

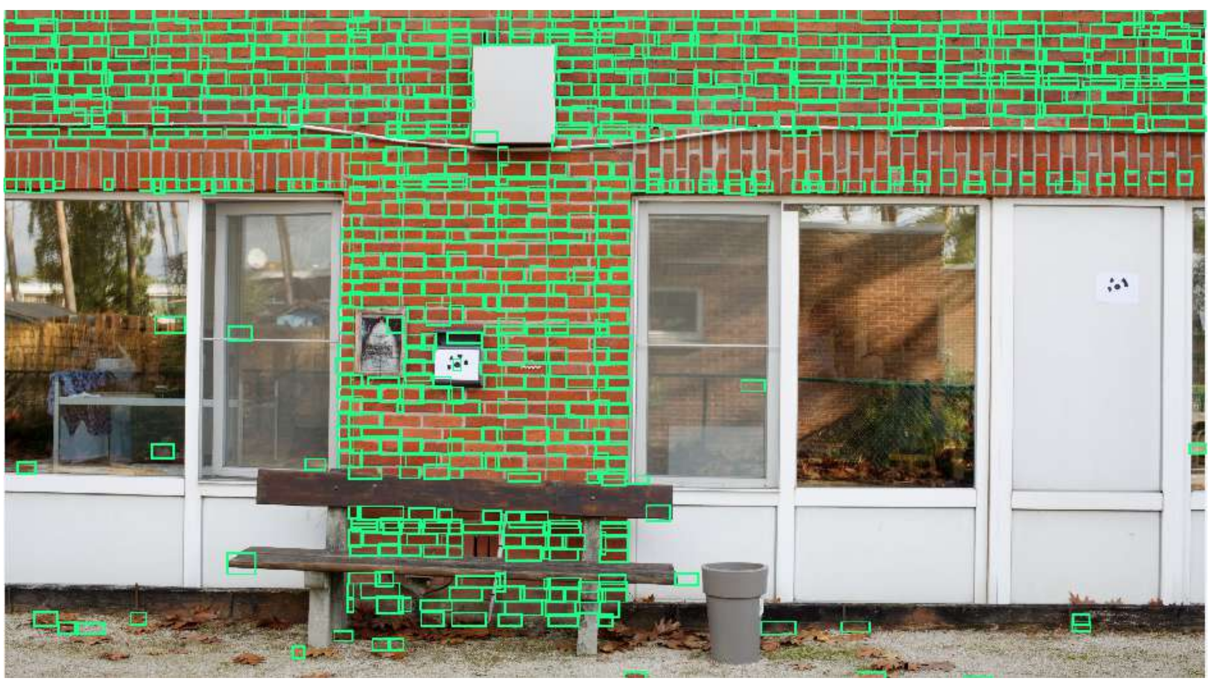


Figure 2. *Result after initial training, showing detection of horizontal bricks while vertical bricks are left undetected (source BBRI).*

Another issue is that bricks may not be recognized when they are only partially visible due to hard shadows or by being located at the periphery of the image. The undetected bricks in Figure 3 are a clear example of this. One way to resolve this issue is to perform AI detections on images of whole building facades. A second possibility is to use a neural network for semantic segmentation, which will be discussed in the next section.

Figure 3. Red ellipses indicate areas where brick detection failed due to partial brick visibility.

Semantic segmentation results: In addition to counting building materials such as bricks individually, there may also be value in extracting the total surface area of materials. Different from the detection using bounding boxes as shown above, surface area is more easily obtained from semantic segmentation, the detection of materials at the level of individual pixels, as introduced in section 2. To test this, after data collection and training identical to that described in section 5, Deeplab v3 plus, a neural network for semantic segmentation, was applied to detect wood, stone, and brick elements in images of façades. As detection is performed at the level of individual pixels, different colours show which pixel was automatically associated to which material type.

Examples of the results are presented in Figure 4 and show that pixel level detection was most accurate for bricks, and that the neural network correctly differentiated between brick and mortar, consistent with the labels in the images the network was trained on. This is the same for the segmentations of stones. For wood detections, Figure 4 shows that some noise was present. A possible cause for the latter is that wooden elements have more varied representations in building facades, which must be contained in the training dataset to be detected correctly. An important difference is that where for bounding box based object detection bricks at the periphery of the image were not always detected correctly, this is not the case for the bricks detected using segmentation and is indicative of the fine pixel level of accuracy of this method. With these results, surface area can be calculated by having an object of known size in the scene such as the height of a wood panel, and measuring the number of pixels of the height of a wood panel in the image. The total number of pixels of a certain material type can thereby be converted to the total surface area.

Figure 4. Detected building materials are indicated using different colours, usable for surface area calculation.

Conclusion: The findings of this first test can be summarised as follows:

- Detection of building materials was shown to be feasible.
- To accurately detect materials which vary in visual appearance, labelled images of these different appearances need to be presented to the neural network at the training stage. In short: you get what you label. This makes bricks easier to detect because of their characteristic shape, and wood harder to detect because of a larger variability of both shape and colour.
- Images can be labelled quickly for object detection, while labelling for semantic segmentation can take 4-5 times as much time depending on the material type.
- For obtaining the total surface area, semantic segmentation may provide better results by performing material detections at the level of individual pixels.
- Online AI platforms save time in two ways: 1. Quick setup with little need to install software, 2. Easy verification of which neural network provides the best results through the availability of a neural network model zoo. A downside is that the model zoo effectively determines which model can be used unless time and effort is invested to add one´s own model.

Future work: Several possibilities exist to further increase the usability of AI to support building material reclamations:

- Detection of additional building materials with a strong reuse potential.
- Increase ease of use by applying AI detection to images of whole building façades at once. This will be discussed in the next section.
- Combining object detection and segmentation pipelines to count individual elements (i.e., windows, doors) as well as calculate the total surface area of large building material surfaces (i.e., bricks) in one go.

Steps for increasing ease of use: To make detection of building materials on large building façades practical, capturing the required images and obtaining value from them needs to be as easy as possible. A quick method would be to make a single panorama of a building façade using a photo app commonly pre-installed on smartphones and to measure the distance of one large element on the façade. Having this single large image containing the whole façade prevents the same building material from being double counted in separate overlapping images.

The panorama can then be divided into smaller images of equal size using a script, and fed to a semantic segmentation network to detect the building materials. The detected number of pixels for each building material can then be converted to surface area using the distance measure taken of the façade. For this method to work properly the neural network should preferably be trained on images of near equal size as the test images to ensure high detection accuracy. The building materials to be recognized should also be clearly visible from a frontal view of the building façade. This also means that this method is not optimal for buildings with complex geometry, impossible to capture in a simple frontal view.

4.5.2. AI building interior inventory

Rotor asbl-vzw is a cooperative design practice which performs reclamation audits to assess salvageable materials in buildings. As part of the audit, Rotor presently takes multiple images of the building interior and manually indicates which image contains which object or material in order to inventory reusable elements. The purpose of this test was to verify whether objects of potential interest to Rotor can be detected automatically to assist the inventory creation process. Additionally, different from the previous test, here free computation resources were utilised to assess the time and effort involved in generating results as compared to when using commercial solutions.

Try-out: For an initial try-out, three object types were selected: light switches, power sockets and studio couches. These object types were selected not because they were of high interest to Rotor, but because pre labelled image collections of these objects were readily available from the online Google Open Images Dataset V6 (https://storage.googleapis.com/openimages/web/index.html). This allowed us to skip the time-consuming step of labelling the images. In this case, Google Colab, a free cloud computation service was utilised to train on the aforementioned three object types. While the service is free, it is not without restrictions. Firstly users cannot choose which type of graphical processing unit (GPU) is assigned to them, which matters as faster GPUs reduce the time needed to train a neural network. Secondly, usage of Google Colab may be restricted to a maximum number of consecutive hours, after which the system cannot be used for a set period of time. As neural network training can take many hours, it therefore becomes important to save training check points so the training progress is not lost when the maximum number of consecutive use hours is reached. For the present task of object detection, neural network architecture YOLO version 4 was selected.

Unlike an AI platform, the neural network needed to be installed manually in the cloud and training parameters needed to be configured correctly. This process took several hours and also involved reading documentation and editing training parameters in multiple scripts. Per object class, 100+ initial images were used. YOLO version 4 automatically augments these images at runtime using a range of different techniques, such that the actual number of images the AI trains on is a multiple of the initial image set. The employed augmentation techniques make the detections more robust, for instance by randomly hiding parts of an image during training such that the neural network can detect an object even when parts of it are occluded.

The resulting object detections of the three object classes were determined to be accurate enough to be usable for making automated object inventories.

AI inventory of six object classes: Given the result of the initial try-out, as a next step six new object types of potential specific interest to Rotor were selected, namely windows, radiators, lighting fixtures, parquet floors, fireplace mantles and ceramic tiles.
As no image data was available from Rotor directly and no readymade image databases were found online, images of the six object classes were collected by scraping them from Google images and filtering them for usability. Lighting fixtures in particular can have many different representations. The lighting images were therefore selected to be as comprehensive as possible by including various lighting types, ranging from tiny spotlights to large chandeliers. Lacking the built-in image labelling tools of the AI platform utilised in the previous test case, the freely available labelling solution CVAT (https://github.com/openvinotoolkit/cvat) was utilised as it directly supports the YOLO annotation format.

During labelling, several issues came up which needed to be addressed. The first was how to label lighting consistently. Larger lighting elements can be composed of multiple lightbulbs. The decision was made to label each lightbulb individually, as it was deemed to be difficult for the neural network to determine when a cluster of lights belong to one and the same group. Additionally, reflections of objects in mirrors and other reflective surfaces were expressly not labelled, as this might result in the same object being detected twice by the neural network. These examples indicate the importance of following a labelling manual and updating it when needed in order to obtain consistent and high-quality labelling results, especially when labelling is performed by a group of people.

Results: Results indicated that windows, radiators, lighting fixtures and fireplace mantles were overall detected with reasonable accuracy. Of these object types, lighting was sometimes not detected adequately when the light shown on the image was very small. Ceramic tiles prominently displayed in images were detected, yet this was not consistently the case for tiles of which the visual appearance deviated by being small, warped, or shown only partially. Parquet was detected only partially. This result is likely due to the fact that large parts of parquet are often occluded by furniture. Given this result, and the fact that parquet often concerns large surface areas and that parquet tiles do not need to be counted individually, detecting this class using semantic segmentation is likely more suitable.

Figures 5a-5c show detection examples. The number displayed atop each detection indicates the confidence level associated with the detection, with 1.00 being the maximum. Figure 5b is illustrative, as it shows that lighting is detected, and not its reflection in the mirror. Additionally, the figure shows that the lamp on the far left is correctly detected even though it is only partially visible, albeit at a lower confidence level. Figure 5c shows that tiles in the foreground are mostly detected correctly, yet for instance not those only partially visible on the left-hand side.

Figure 5a (top). *Windows and radiators are detected with maximum confidence (source: Getty Images).* ***Figure 5b (bottom left).*** *Lighting on the ceiling is detected, and not its reflection in the mirror (photo credit: Lauren Miller. Source: lauren-miller.com).* ***Figure 5c (bottom right).*** *Tiles in the foreground are detected correctly, while tiles in the background and those only shown partially at the edges are left undetected (photo credit: Hannah King. Source: dougcleghorn.co.uk).*

Conclusions:

- Most of the object types could be detected accurately. Objects depicted very small, warped (tiles) or partially occluded are detected less well.
- Parquet and other surface areas composed of elements which do not need to be counted individually are more suited to be detected using semantic segmentation.
- The importance of consistent labelling of exceptions was shown, for example by not labelling reflections of objects in mirrors.
- Using free resources to perform image labelling, neural network training and testing is feasible and has the added benefit of being able to choose the latest and most performant neural network architectures.
- Compared to commercial AI platforms, the use of free resources may require substantially more time and knowledge of neural network training parameters.

Future work: As can be seen in Figure 5c, tiles can be harder to detect using object detection in this particular case. One approach to improve the detection is to capture tiles from close range at a straight angle to the surface. This ensures that all tiles are shown prominently in the image, and that their appearance is not warped due to the straight angle at which the image was taken. An alternative approach is to verify whether detecting tile surfaces using semantic segmentation yields improved results. This alternative is especially viable if there is no need to count tiles individually. Counting objects individually using instance segmentation is possible, yet further increases the time required to label the training images as each instance of the object to be segmented would have to be labelled with a different colour.

4.5.3. Automated AI analysis

From the perspective of the end user, the AI detection itself forms only part of the solution. If the solution is not easy to use in a real-world environment it is unlikely to see much actual use. The present test case as well as the next case specifically address this point. This is expressly a low-tech test case which uses 2D images, a conventional laptop and software which allows to obtain results for the purpose of making building reclamation inventories at the push of a button. For the present test case, we again took the example of the cooperative design practice Rotor introduced in section 6.3.

AI pipeline outline: To facilitate Rotor work, a pipeline was constructed which requires minimal effort to detect objects of interest in hundreds of images at a time. A visual presentation of the pipeline is shown in Figure 6.

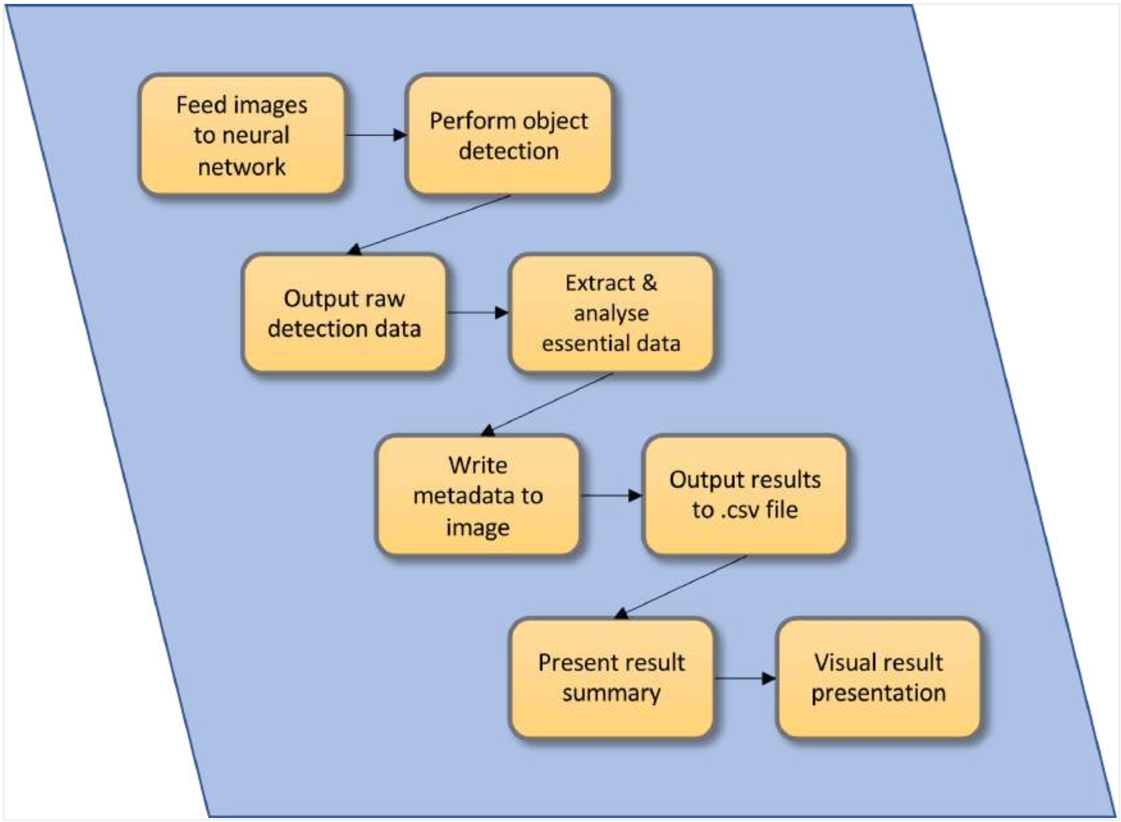


Figure 6. *Pipeline for using images to create an automated AI inventory of building materials*

The first part of the pipeline is a script which feeds camera images to the neural network. The object detection task is then performed on the images using YOLO version 4 (together with a set of added convenience functions, https://github.com/vincentgong7/VG_AlexeyAB_darknet). Next, the raw object detection output is saved to a file. A script then extracts essential data from the raw detection output and analyses it. The next part of the pipeline then writes easily interpretable results of the analysis to each image file by adding metadata to it. Then, the results of the analysis are written to a copy of the images and to a .csv file, followed by the on-screen presentation of a text summary of the results. Lastly, a visual presentation of the results is generated by loading the generated .csv file into MS Excel.

AI pipeline usage example: Figure 7 shows how the pipeline functions in practice from the perspective of the end user, as demonstrated to Rotor vzw. Figure 8 shows a close-up of the visual representation of the results.

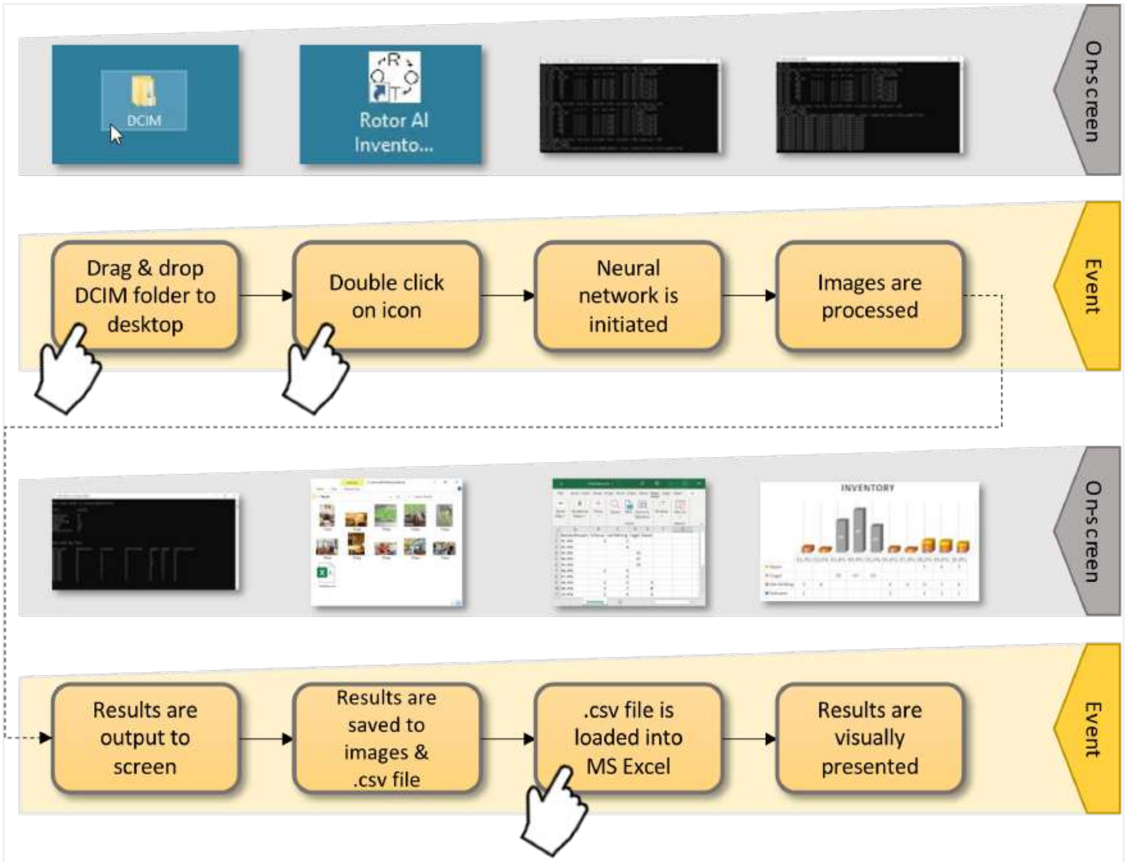
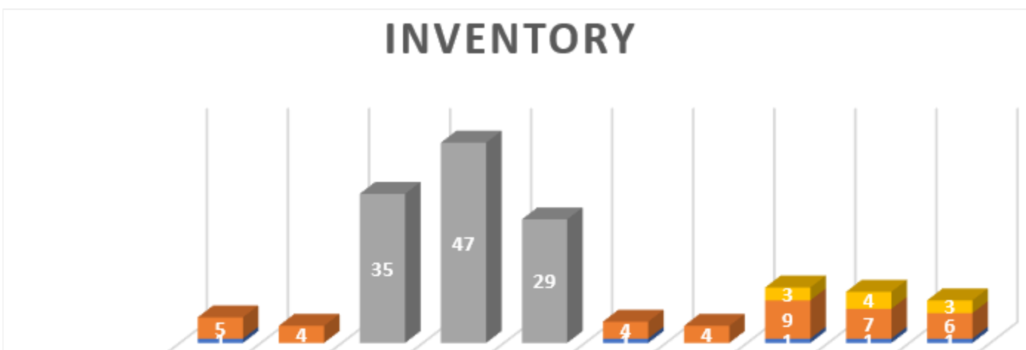


Figure 7. AI inventory as experienced by the end user. Yellow boxes indicate inventory events, and snapshots above the yellow boxes indicate the accompanying on-screen visual for each event. Hand icons indicate actions required from the end user in order to obtain results.



	01.JPG	02.JPG	03.JPG	04.JPG	05.JPG	06.JPG	07.JPG	08.JPG	09.JPG	10.JPG
Raam								3	4	3
Tegel			35	47	29					
Verlichting	5	4				4	4	9	7	6
Schouw	1					1		1	1	1

Figure 8. Visual results of the AI inventory. Colours and numbers indicate the detected object type and quantity per image. "01.JPG" and "05.JPG" respectively correspond to the detected objects in the images of Figure 5b and 5c

The metadata written to each image file as part of the pipeline contains information about the type and quantity of objects shown in the image. This metadata travels along with the images. Figuratively speaking, it is as if the information is written on the back of a postcard. Figure 9 demonstrates how the added metadata allows the end user to go to MS Windows Explorer, open a folder containing images, input the name of a sought for object, and automatically find only those images containing said object. This functionality can be a timesaver, especially when the number of images is high.

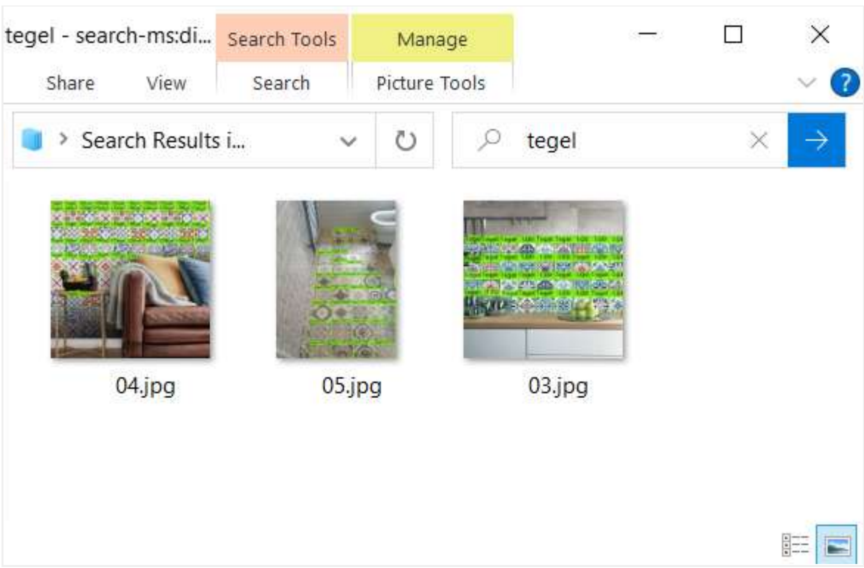


Figure 9. *Metadata usage example. A search for "tegel" (English: tile) on the 10 images referenced in Figure 8 is shown to accurately retrieve only the images containing tiles.*

Conclusion: This test case demonstrates that the ease of use of an AI-based object detection system can be significantly increased with a limited number of scripts. The scripts together act as a wrapper, such that Rotor did not have to resort to inputting command line instructions and multiple other actions. Using the scripts, this process was simplified to the point of dragging and dropping an image folder and double clicking on an icon.

Limitations and possible solutions: This AI solution was configured such that it could run on a standard laptop without a fast graphics card such that Rotor vzw would not have to invest in additional hardware to obtain results. The limitation of using a standard laptop is that it takes multiple seconds to recognize objects and materials per image. With a dedicated graphics card, the detection rate is vastly improved and can reach 30 images per second or more. One way to solve this limitation is the use of a cloud service such as Google Colab, Amazon AWS or Microsoft Azure.

4.5.4. Rotor exterior capture and AI detection

Documenting whole building sites using regular camera images can be a time-intensive and tedious task. Additionally, the accurate estimation of building reclamation material quantities may be difficult when the surface area is large, especially when the surface is shaped irregularly. This test case assessed whether 1. the exterior of a whole building site can be documented quickly and cost-effectively and 2. whether the visual data thus gathered can be leveraged to quantify large building material quantities using AI object detection, thus assisting the conventional building audit process.

360-degree imagery: For the purpose of documentation, a 360-degree camera was utilized. 360-degree images capture the whole scene visible from the perspective of the camera from top to bottom, left to right. 360-degree cameras are typically affordable, with prices typically ranging from 400 to 1000 EUR for a medium to high-end camera. These cameras are easy to operate by requiring only a single press of a button to capture the whole scene from a fixed point of view.

Image capture and processing: For the purpose of this case, the exterior of a site to be audited by Rotor vzw called Recyclart was utilised. Recyclart is a multi-disciplinary arts centre and is located in Molenbeek-Saint-Jean. To capture the site, 82 360-degree pictures were taken at 7K resolution using a Ricoh Theta Z1 camera placed on a tripod. The use of a free “timeshift” plugin (Ricoh Company, Ltd.) allowed the photographer to move out of view of the camera while it captured the scene. The capture process took 30 minutes. Figure 10a-b shows the Recyclart exterior, Figure 10c shows a top-down view of the location. The locations where the 360-degree images were taken are indicated with blue circles.

***Figure 10a-b (top)**. Recyclart exterior. **Figure 10c (bottom).** Top-down view of the captured area, with capture locations indicated with blue circles.*

The 360-degree images were processed using photogrammetry software Agisoft Metashape Professional version 1.6. As the images were taken using a tripod and the tripod feet showed on the images, these were masked out. After masking, the software was successively used to align the images, to create a sparse and dense point cloud, to convert it to a mesh, and lastly to create a texture and ortho (perspective corrected) photo. Figure 11a shows an animation of the resulting 3D model of the Recyclart site. As can be seen in Figure 11b, the ground surface of the 3D model is especially detailed and accurately represented, while elements further away from the camera such as window edges have less accurate geometry. The 3D model thus created can be used to virtually explore the site from any angle and position. Additionally, orthophotos can be created on any desired surface.

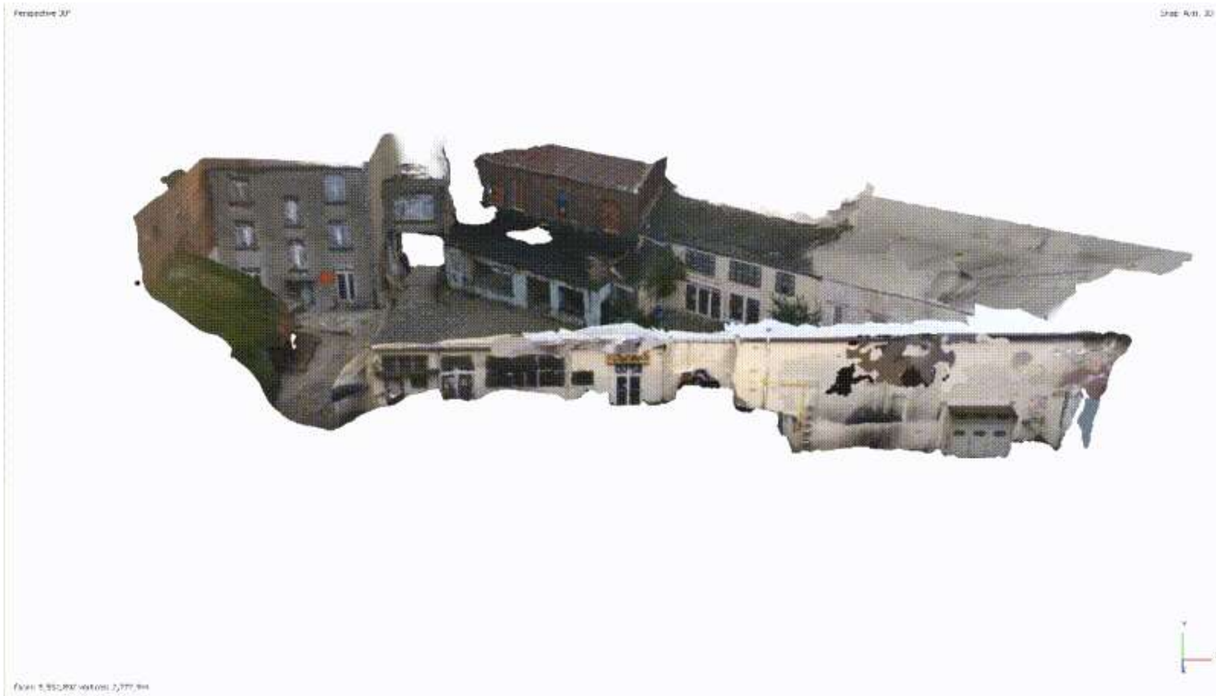


__Figure 11a (top).__ Animation of the resulting 3D model of the Recyclart site, starting with a birds-eye view and finishing with a close-up of the ground surface. __Figure 11b (bottom).__ Ortho photo of the ground surface. Red rectangles indicate examples of areas for which cobblestone detection was performed.

Object detection results: After generating the ortho photo of the ground surface, the next step was to use object detection to quantify cobblestones. For this purpose, a neural network was trained using the method detailed in section 6.3.1. After training, an initial detection trial performed on images from the Recyclart cobblestone surface showed the network failed to detect most stones. Overall, the images were rather dark. Reasoning that this could be the cause of the failed detections, automatic colour correction was applied to the images. This greatly increased detection accuracy. Examples of the resulting cobblestone detections are presented in Figure 12. With the detections, the number of cobblestones present on the ground surface can be calculated, albeit with some limitations which will be discussed in section 6.5.5.

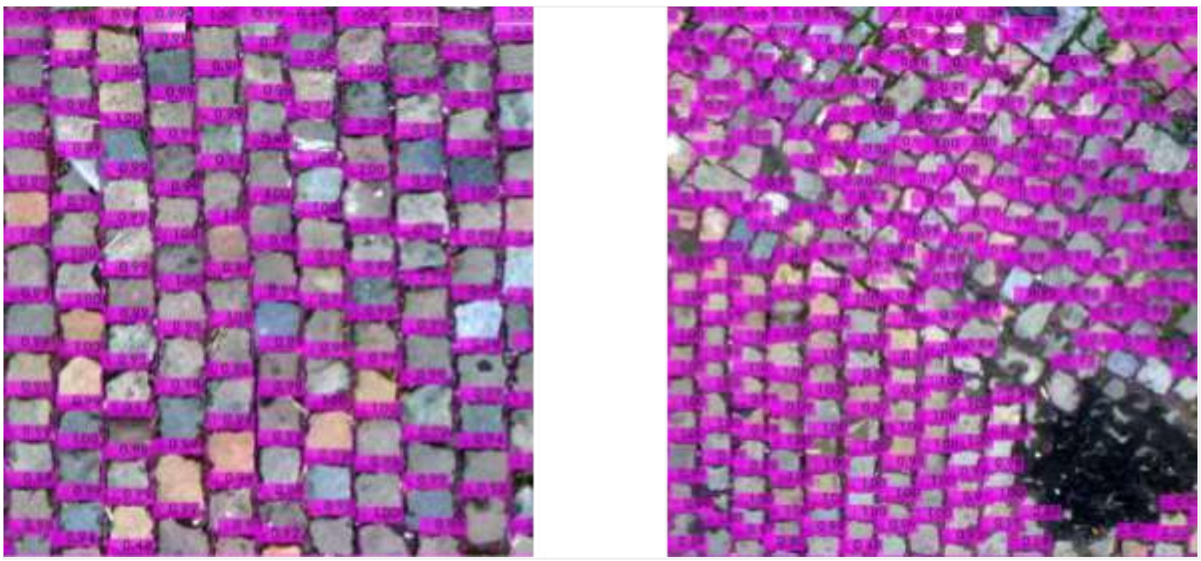


Figure 12. *Cobblestone detections of the areas indicated with red rectangles in the ortho photo of Figure 11b.*

Conclusions: The current case demonstrates the benefit of using digitization technology that meets and not unnecessarily exceeds the demands of the task. This was shown by using an affordable camera instead of more accurate but more expensive and less mobile laser scanning equipment to capture a site exterior. 360-degree images were found to be suitable for quick documentation of the whole site as well as for input to a neural network to perform automatic detection of cobblestone quantities. Colour correction was found to be an important step to obtain accurate object detections. As discussed in section 6, by training an AI network using images augmented for brightness, this issue may be alleviated as it increases robustness for this aspect.

Based on the obtained results, it is concluded that automated quantification may provide a tangible benefit to support reclamation audits. This especially for cases where the surface containing the cobblestones is large and irregular such as in the case of the Recyclart exterior, which makes it hard to make accurate manual estimations of cobblestone quantities. When site documentation is not required, the image capture process of large single surfaces may become faster by using regular RGB images as input instead of 360 images. Lastly, the importance of image colour correction was demonstrated for obtaining higher object detection accuracy.

Limitations and possible improvements: The cobblestone detections of the present test case could be refined in several ways. As can be seen in Figure 12 (right), a limitation of the detections is that no cobblestones are detected if they are obstructed from view by vegetation or debris. This could be alleviated by applying a script to the raw detection data which determines that small patches (e.g., vegetation) surrounded by cobblestone detections are in fact also cobblestones.

To increase accuracy of cobblestone quantities, double counting of the same stones showing on multiple images could be prevented. As discussed previously in section 6.2.2., if there is no need to count individual stones and total surface area would suffice, using a neural network to segment a tiled orthophoto of cobblestone images is one solution to the double counting problem.

4.5.5. AI assisted Rotor interior audit using 360 degree images

Rotor vzw conducts building interior audits to assess the reclamation potential of the materials contained within. This test case set out to potentially support this inventory process using automated AI analysis of building interiors. To increase usability, it was predetermined that the AI solution should not interfere with the regular work process of Rotor by being quick and easy to use and to require next to no effort to produce results. Given this goal, it was determined that using regular still images for the AI to perform detections on would not work, as it would require too much time and effort to capture the whole building in 100+ images. The solution chosen therefore was to use 360-degree images, which proved to be useful for building exterior documentation in the test case of section 6.5. For building interiors, a single 360-image is sufficient to capture a small-size room, and just a few images for larger size rooms. This effectively allows the interior of a whole building to be captured in just a few minutes. The key insight here was to use the AI-based object detection method presented in section 6.4 and apply it directly onto 360-degree images.

Trial : After learning that object detection applied directly to 360-degree images worked reasonably well on a set of test images, the method was trialled during an interior audit of Rotor vzw of a residential building located in Brussels. The building consisted of two floors and a cellar. The building was captured using a series of 360-degree images. For the detections, the previously discussed neural network trained on windows, lighting fixtures, fireplace mantles, radiators and tiles was used.

Results: The automated AI analysis pipeline of section 6.4 was utilised to analyse the images and to produce results. Examples of the results are presented in Figures 13-14.

Figure 13a (top). *Ceiling lighting and windows are detected.*
Figure 13b (bottom). *One window marked with a red rectangle is detected as lighting.*

Figure 14a (top). *A reflection on the floor marked in red is detected as lighting.*
Figure 14b (bottom). *Example of an error due to the spherical projection of the 360-degree image, as a window marked in red to the left and right is detected twice*

The two figures show detected building elements in real-world 360-degree images. At the same time, several detection failure types indicate that the neural network could be trained further to produce more consistent results. Figure 13b is an example of a detection failure, showing a window which is mistaken for lighting. The associated confidence level of the failed detection is low (47%). A remedy for such cases is to filter out detections with low confidence values. Figure 14a shows that while lighting is detected, its reflection on the floor is detected as well. These failure cases illustrate that for object detection to work correctly, the neural network has to be trained on a sufficient number of examples of these exceptions.

An additional failure type occurred due to the way the scene is projected in 360-degree images. This can be divided into two parts. Objects would not be detected due to being distorted in the 360-degree image. This would happen at the top and bottom of the equirectangular image, where distortion is most severe. Additionally, objects at the border of an equirectangular image can be detected twice by being split into a left and right half. Figure 14b is an example of this, where the same window is detected twice. Both failure types are due to the fact that the spherical projection of 360-degree images is not taken into consideration in the architecture of the utilised neural network YOLO v4.

Conclusions: Automated AI inventory of building elements was shown to be feasible in a real-world setting and required little time and effort by using 360-degree images as input. While detections were obtained with ease, several detection failure types were observed. It is therefore concluded that the neural network could be trained more extensively to increase the accuracy of the detections and thereby improve its robustness and usability.

The present case also stresses the importance of training a neural network on images similar to the real-world images the network will be making the actual object detections on. For the present test case, the training and testing images were rather dissimilar. That is, images obtained from the internet were used as it was hard to procure real images to use for training given the COVID-19 situation at that time.

Limitations and possible improvements: General detection failure cases were observed. A next step is to use these failure cases as feedback to pinpoint which images the neural network should additionally be trained on and how those images should be labelled.
Some detection failures were accompanied by a low confidence value. A straightforward way to prevent this type of issue from occurring is to filter out detections below a set confidence level threshold.

Failures were observed due to the spherical projection of 360-degree images. A next step is to experiment with neural network architectures which take the sphericity of 360-degree images into account for increasing detection accuracy.

A limitation is that for larger rooms, multiple 360-degree images may be taken, which brings with it the possibility of doubly counting one and the same building material. Experimentation is needed to verify whether the addition of a second pipeline of object tracking can reduce the occurrence of double counting.

4.6. Lessons learned and future possibilities

Several lessons were learned from the test cases of the present report. As most of these were touched upon in the discussion of the results of the individual test cases, here were focus on two of the most essential ones. One of the main lessons learned is the importance of a high-quality dataset of labelled images which closely resemble the images the AI is to be tested on, and which is essential for obtaining high-quality results. A limiting factor in creating a good dataset is the amount of time needed to label the images, which was significant in most of the test cases. Labelling speed may potentially be increased by semi-automated AI labelling, and the possibilities and present limitations of this are to be investigated as this may yield clear time savings. Even if such a semi-automated system is employed, it should however not be underestimated that the manual verification of the output generated by such a system will still take time. At present, still a high number of images is necessary for AI to learn from to properly recognize objects and materials. One reason for this is that present-day neural architectures lack the capacity for human-level understanding and reasoning. This may explain why detections for instance may be accurate for horizontal bricks but not for vertically oriented bricks, a difference which does not require conscious thinking for humans but caused a significant difference in AI brick detection quality in the test case of section 6.2. A future breakthrough therefore will be when AI networks gain part of this level of understanding, and to do so on the basis of a limited number of inputs. As discussed, at present few high-quality datasets exist with images of construction objects/materials. The availability of such datasets would facilitate their rapid AI-based quantification for the purpose of building material reclamations, and is an avenue for further research.

A second main lesson learned was the importance of the usability of the trained AI in the deployment stage, which was addressed by creating an interface to obtain fast results and with minimal effort. There is however still ample opportunity to increase the usability further. In the exterior site capture test case of section 6.5, AI detections were generated on the texture of a 3D model of a site to be audited by Rotor vzw. Generating the required 3D model using photogrammetry at present still requires a significant amount of time and is a limiting factor which reduces the immediate usability of the method on job sites where there is a need for quick results. One interesting possibility for improvement in this area is the use of Lidar. Instead of calculating a point cloud from images as is the case with photogrammetry, a Lidar sensor allows the points to be captured directly. This means that the computation time needed to acquire those points is drastically reduced from hours to minutes. At the same time, video frames can be captured and projected on the 3D model generated from the point cloud. This process can be performed locally on mobile devices (at present only on flagship phones and tablets) and may result in a 3D model and texture of medium to low quality, yet which may still be sufficient to perform AI object/material recognition. While there are definite quality differences compared to photogrammetry and limitations exist such as a limited scannable area per capture, this Lidar technique is an interesting one as it could potentially significantly speed up the process of obtaining the information required to create AI-based building reclamation inventories. This especially in cases where regular images would not suffice as input due to the complex geometry of the building structure.

Part of the process of improving the immediate usability of the automated AI pipeline created for Rotor vzw was its configuration to run on a regular inexpensive laptop without a dedicated graphics card. Here too future improvements may be made, as it is not outside the scope of possibility to do away with the need for a PC altogether and perform the AI task locally on regular smartphones and tablets, albeit at the cost of reduced speed and accuracy. This may be feasible using neural networks which are specifically attuned to work on these lower powered devices. Multiple solutions towards this end exist, yet at the time of writing remain largely untested in the construction sector. The possibility of this is exciting by enabling AI-powered applications on devices already in wide use and would enable companies of all sizes to better reap the benefits of AI-based applications.

4.7. Conclusions

The results of the test cases performed as part of this report indicate that building elements and materials can be recognized and quantified automatically using AI. Moreover, we demonstrated the feasibility of creating a proof-of-concept AI-based inventory system for building material reclamation. At the same time, it became apparent from the test cases that additional work is required to increase the robustness of the automatically generated inventories. Nonetheless, the findings of the present report are promising as they indicate that an AI system can be created from start to finish within a reasonable timeframe, and that its use may yield actionable results in real-world settings. Key learnings of the aforementioned test cases were incorporated into a guideline of steps to apply AI for neural network based computer vision tasks. Taken together these steps enable those who are new to the field to gain insight into the time and effort required to obtain AI-based results, as well as how to avoid common pitfalls. Several avenues exist for further research into how the use of AI-based systems may yield results faster using more affordable hardware. Two highlighted opportunities include the use of Lidar for fast generation of point clouds, and performing AI object and material detection locally on ubiquitous mobile devices.

5. Building Information Model (BIM) in support of reuse in the deconstruction industry

5.1. Context

In the construction sector, digitalisation is transforming design, cost and management aspects of buildings. For deconstruction and reuse, digital tools and methods also have a great potential, but their implementation is only at its start. Building Information Modelling (BIM) is a digital collaborative working approach which is already implemented and rapidly growing in the construction industry. Strengthened by its widespread, and rich of its use in project design, the BIM technology has much to offer to enable sustainable building end-of-life.

At the design stage, BIM can be used to design buildings in which element disassembly is optimised, facilitating reuse and limiting future demolition. At the end of life of the building, prior to transformation (renovation or demolition), BIM can generate detailed information about existing structures, which can be exported digitally, publicising the availability of well-described salvaged elements and favouring their incorporation in new projects. BIM could also be coupled to other tools to evaluate if elements can easily be disassembled within a building, evaluate the environmental impact of building elements' end-of life, and assist planning of a sequenced disassembly process.

With no commercial solutions existing for the uses of BIM in deconstruction, this report develops opportunities for further development, through literature review and case studies. The meaningfulness of the use of BIM is also discussed, without setting aside the barriers to its massive appropriation. The creation of a BIM model, which is the prerequisite for any BIM-based analysis, is also described, and the legitimacy of creating a BIM model for an old (pre-existing) building is also addressed.

The objective of this section of the report is to provide a state of the art on current developments, opportunities and limits of BIM and BIM-based tools which are proposed to address the current needs of the reuse sector.

5.2. BIM definition and interest

BIM is the acronym of Building Information Modelling. It is a collaborative working approach using digital technology (e.g. BIM models) to define, manage and exchange information in a structured manner during the whole lifecycle of a project (from the design towards operation and beyond).

ISO 29481-1:2016(en) definition of BIM:
use of a shared digital representation of a built object (including buildings, bridges, roads, process plants, etc.) to facilitate design, construction and operation processes to form a reliable basis for decisions
Note 1 to entry: The acronym BIM also stands for the shared digital representation of the physical and functional characteristics of any construction works.

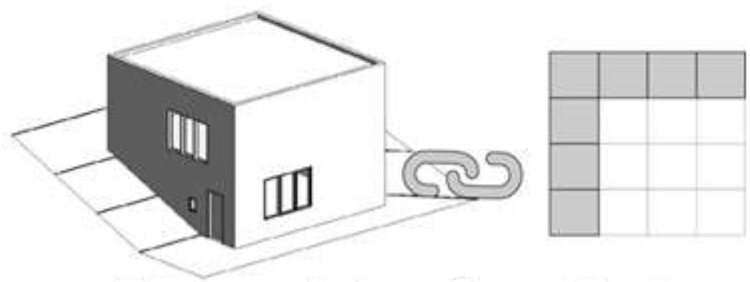


Figure 1: *A BIM model can be seen as an assembly of a 3D model and a database*

This is why BIM is more and more referred as Building Information Management rather than Building Information Modelling as the model itself is important, but the core of the BIM is the information and the capacity to share it.

In a BIM approach, one of the key elements is the BIM model which can be seen as a combination of a 3D model and a database which links every building element (object) with a set of specific and defined parameters. Indeed, BIM models are object-oriented models meaning that the computer "understands" the difference between a "wall" and a "door". Thus, these elements have different characteristics but also behaviour. A wall for instance, is a potential structural element which can be the host of windows and is in general connected to other walls horizontally and to slabs or roofs vertically. In other terms, on the technical side, a BIM model is much more than a set of geometrical elements, the object-oriented approach allows to provide a set of intelligent rules which are very useful for designing the building but also to support buildings' construction and operation.

Here is a non-exhaustive list of the potential added value of BIM processes and tools:

- The BIM process supports a more active collaboration and communication between the stakeholders. This should be done by adopting a common language and data structure but also by clearly defining the BIM requirements and objectives.
- A BIM model can be used to federate information which can be used by all the parties. This avoids every partner to develop their own, limits errors and facilitates coordination. It must be noted that today, it is not advised anymore to have one model for every partner but rather several coordinated models as it reduces the risk of altering someone else's work.

- By aggregating and connecting data and geometry, a BIM model facilitates the development of advanced simulations and analysis. Indeed, the geometry provided by the architect can serve as a basis for the structural designer. Similarly, the data generated by a specialist can be stored and be available at a later stage for another simulation. The more partners use, share, and refine the data, the more useful the BIM model is. Consequently, tasks such as definition of planning, establishing bill of quantities, estimating costs and material flow on-site benefit from a reduction of uncertainties.
- The collaborative approach and the sharing of models during design and construction facilitates the process of clash detection, which avoids mistakes or hazards on-site. It also facilitates the decision process by allowing better informed decisions with all the parties rather than attempting to solve the issue on-site with a limited time.
- A BIM model being an assembly of a 3D model and a set of data, it allows us to visualise the building digitally and access all its information without having to go on-site several times. Hence, it could be used to prepare an inventory, establish a preliminary audit, or get a basic understanding of a project. This is even more useful for areas with restricted access.

5.3. How is a BIM built?

5.3.1. BIM for new buildings

In general, it is considered that the sooner the BIM process is started the higher are its advantages. For new buildings, it is often advised to start the BIM process as soon as possible so as to include all the stakeholders (in as much as the contract allows it) in the discussion on the BIM uses and implementation. This makes it possible to adapt the BIM needs and requirements (e.g. in term of content, information, precision) to each partners' expertise, abilities and requirements (including facility management). It is important to consider the needs regarding the collaboration itself, the content of the model (geometry and information) but also the limit of the model (e.g. are we modelling rebars? What is the expected precision?)

Besides the key meeting which allows to set up the "rules and objectives of the collaboration", the start of the BIM model will also have to be addressed. Ideally, each partner should be able to:

- Model their discipline (geometry and data);
- Visualise the models of the others (geometry and data);
- Extract information from the models.

Consequently, a BIM process does not rely on plans, pdf and cad files anymore, it should rely on primary models with additional sets of documents completing it (e.g. details, technical notes). To avoid handling issues related to reliability of information, it is advised to have "generic" or incorrect value per default. Additionally, it is more and more considered that using a coordinated approach (each stakeholder has his own model which is linked or used as a basis for the other) is far more effective than having a unique shared model because it could create issues related to overwritten or deleted information. In that way, every stakeholder is responsible for the shared content.

The elaboration of the BIM model follows the various stages of the design process, to that extent the digital model is at first an evolving prototype of the future building. It is used for representation but also for analysis and studies. Once the actual construction starts, the BIM will be used as a digital twin. Indeed, every change or decision made on the site should be modified on the model, ensuring that "digital copy" of the actual building with all the key state-of-the-art information is provided as an As-built model. Then, this as-build model can either be used for facility management or be stored for a future use (renovation, reuse, demolition). The development of a BIM model by itself is considered as having a positive ROI by reducing the amount and cost of change on site (and thus, also delay), providing support for more advanced analysis and simulations (risk reduction and quality increase). This explains why even when a model is not made directly at the beginning, contractors often take the time to create one. However, this also means that if the use of that BIM model after construction is not well defined, the BIM model may be optimised for the construction process only which could be considered as a lost potential.

When it comes to foster the future reuse of the components of a new building, its BIM should be elaborated around the following key questions:

- Which information is relevant to encourage future reuse (manufacturer, specifications, technical data, chemical composition, etc.)?
- What is the best file format (open or proprietary) and how to store the information (within the model or in a database)?
- How to include major events related to the lifecycle of the building within the model?
- How to update the information and the model throughout the lifecycle of the building (digital twin)?

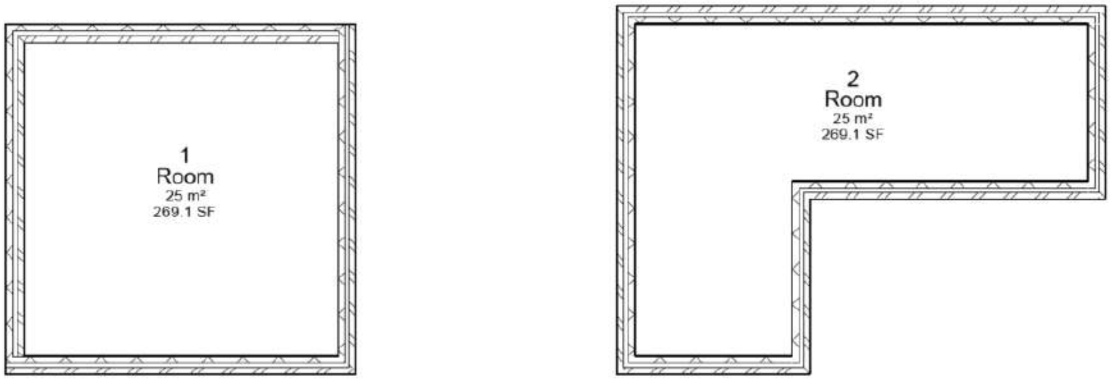
5.3.2. BIM for existing buildings

For existing buildings, the use of BIM and especially the cost of creating a new model from scratch offers a very different perspective. Indeed, if the project is a refurbishment of a big train station or a hospital, taking the time to remodel everything might make sense due to the importance of the project in terms of scale or heritage. Remodelling from scratch a 3-storey-gentry-house prior to its demolition might be seen as a lot of work for a low added value. BIM is a tool which can be adapted to the needs and not a unique way of working where one must blindly apply a predefined way of working for every project. Thus, for existing buildings the potential of BIM will depend on the BIM use. Potential uses of the BIM model for existing buildings could be to:

- Use the building model for new analysis (energy consumption, flux of people for the renovation of a train station, scenario planning, phasing of the renovation);
- Use of the building model as a support for inventory (and expected accuracy). Should the model be with a 1 mm precision or could it be used to estimate roughly (but still better than by hand)?

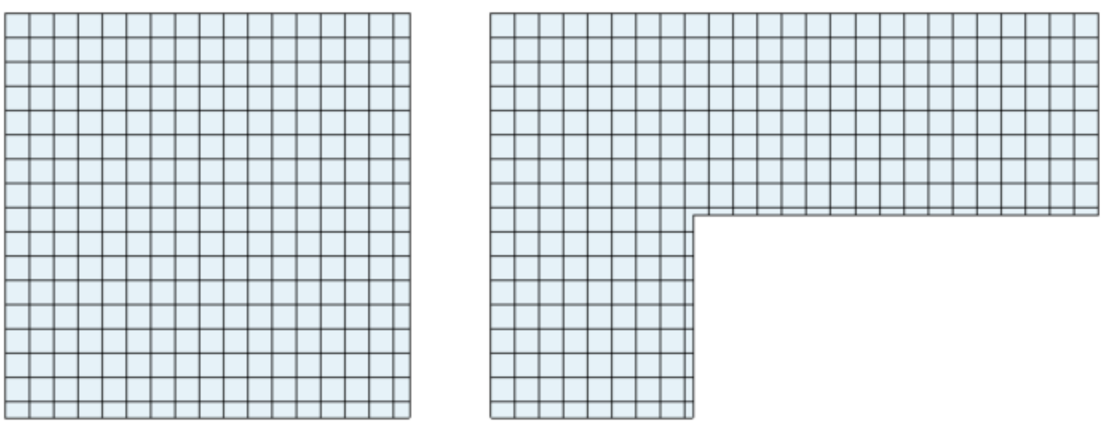
In other words, there is a trade-off to be found between the time required to create the model and its expected outcomes.

In order to construct a BIM model, you could first visit the building and start up from the plans to remodel it in 3D. Then you need to define the precision of the modelling . Do you need to remodel the façade precisely? Should you simplify the geometry? A simplified model could already be enough to estimate the number of bricks on a façade or the quantity of tiles in a room. This could be potentially more precise than a manual estimation thanks to the geometry within the model (Figure 56 & Figure 57). Although, this does not solve the biggest uncertainty which is the proportion of tiles you will be able to reclaim for reuse, this allows for a better estimate and eventually a better tracking of that proportion of reused materials.



Rough manual estimation: Room dimension : 25m² + 2.5m² (10%) tile dimension 30cmx30cm -> 0.09m² 25/0.09=277.78= 278 tiles 27.5/0.09 = 305.55 = 306 tiles (overestimation)	Rough manual estimation: Room dimension: 25m² + 2.5m² (10%) tile dimension 30cmx30cm -> 0.09m² 25/0.09=277.78= 278 tiles 27.5/0.09 = 305.55 = 306 tiles (overestimation)

Figure 56 *- Plan of two rooms having the exact same internal area but a distinguished geometry. A traditional manual estimation won't make a distinction between the room geometry to estimate the number of tiles. During a construction it means we have to overestimate the number of tiles to buy to be sure we have a sufficient amount on site to complete the room. In case of reuse, overestimating the number of tiles is counterproductive (it reduces certainty). Additionally, it is difficult to have a good view on the "dimension" of these tiles (full-scale or cut).*



Amount of units : 289 Amount of full size tiles: 256 Cut tiles: 33	Amount of units : 297 Amount of « full size » tiles: 264 Cut tiles: 33

Figure 57 *- The tile layout and estimation made based on the geometry of the BIM model allows to reduce uncertainties. The uncertainty is not in the estimation but rather in the capacity to mine these tiles back. It should be noted that the assessment of tile quality is not made using this technique and other solutions such as AI could also help counting the tiles, their dimension and state.*

Second, you may use other techniques than the standard BIM model to capture the reality (Scanning, photogrammetry) and use the BIM model only where useful. Additionally, one could also use the BIM elements (or family) alone, suppose a specific valuable item is part of the inventory. It is captured and modelled in 3D thanks to scanning techniques and then a BIM object is created in order to link the geometry and some metadata.

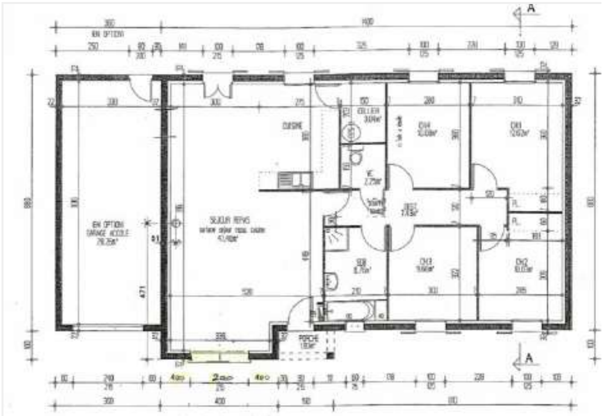
5.3.3. Setting up requirements and objectives

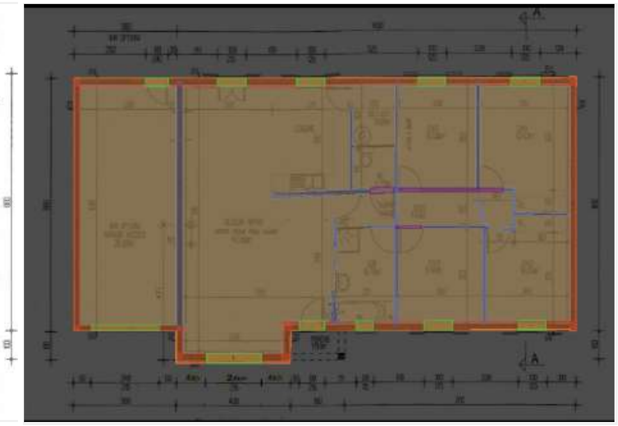
In the previous part we illustrated that although BIM approaches seem straightforward for new buildings, it might also have a potential for older buildings. However, as the context is different the use and the objectives might differ.

To define what could be the potential of BIM, one must list what would be expected from the BIM model:

- Model with a defined Degree of precision (precise or estimate);
- Consider the Potential use (mainly as a plan or a way to locate object, digital twin);
- Distinguish BIM model (the whole building in its context) and models of BIM elements separately (which could be used for reuse in new buildings or to populate online stores or database);
- Use the BIM for quantity take-off either to know the amount of material available or to plan the volume of containers needed. A series a tools such as the tile estimator presented above could help make estimations based on rough models;
- Use BIM to assess or plan the deconstruction (checking is a big element can be dismantled and moved throughout the building);

Based on this non-exhaustive list, the modelling approach of the BIM model might vary. If for some reason, a basic 3D model similar to an “extruded” plan is sufficient to count the number of tiles, estimate the number of bricks in a wall or organise dismantling process this type of 3D models can be quickly modelled and eventually automated. Indeed, creating a wall or a slab based on a line is already feasible in current BIM modelling software. For older plans, additional work might be done, either because there is no usable plan or because the picture of the plan must be transformed into vector files. This is also a topic where AI could help interpret old drawings to be able to automate the remodelling. Knowing that, “plan-to-BIM” and “scan-to-BIM” are two relevant topics to follow and further development in such techniques would greatly facilitate the creation of usable BIM models for existing buildings.





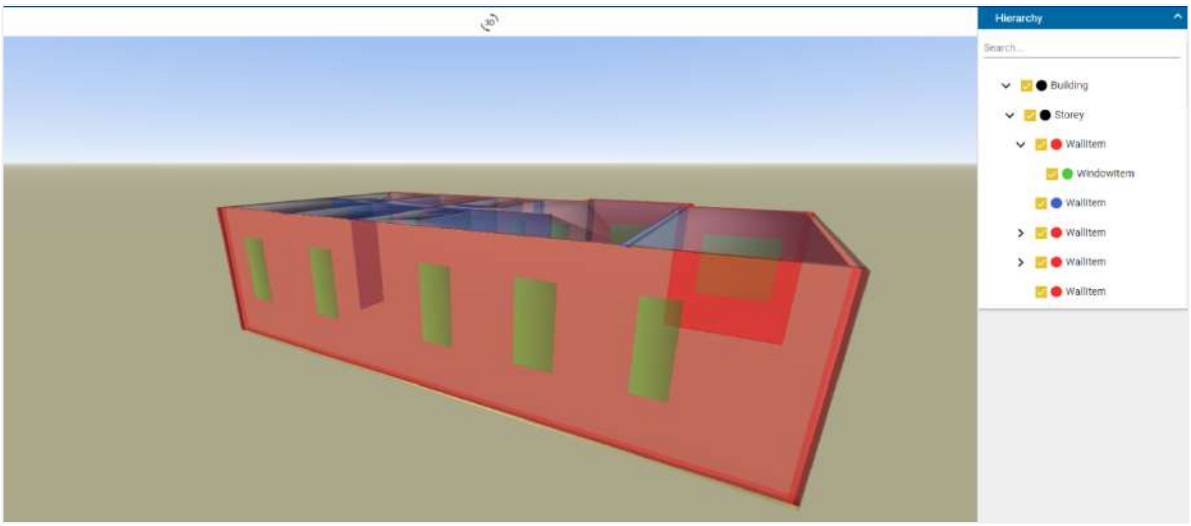


Figure 58 (top left), Figure 59 (top right) & Figure 60 (bottom) *: New services allows to use pictures of buildings plans to generate simple 3D models. The plan is analysed using computer vision (ai) which detects the walls, windows, doors, and partition walls.*
Source of the original plan layout: https://www.pinterest.fr/pin/578642252097339397/

To sum up the best way to use BIM for deconstruction is :

a. by defining the potential use case of BIM (model or data),
b. adjusting the efforts put in the modelling to be able to reach these and
c. the importance of linking data (notes, tests on material) and elements.

Thus, the importance of BIM elements should not be underestimated as this could have value for the future reuse of that element in a new building (which will probably be modelled in BIM). Facilitating the access of information or the use of reclaimed elements through facilitating their use in our current ways of working is also a factor increasing the reuse potential.

5.3.4. Do actors in the reuse/deconstruction sector currently know or use BIM?

The implementation of BIM tools in the construction sector is established and rapidly growing. Europe has been one of the leaders in global BIM adoption. However, countries are not following the same timeline or methods in their BIM adoption. Some countries have taken concrete steps to establish official guidelines and mandates for BIM use in construction, while others (such als Belgium) have chosen not to do so.

BIM tools can be used by all actors of the construction industry, notably architects, engineers and contractors, and different BIM software exist, tailored to the user's needs. The implementation of BIM requires investment to cover the high cost of BIM tool licences and training. This leads to the earlier adoption of BIM in large companies, while small and medium enterprises are less able to lift the barrier of investment. The integration of BIM education into university curriculums is seen as a way to bridge the actual needs of the construction industry and the skills of new graduates. This can potentially reduce the initial capital of big companies to outrun smaller firms with lower budgets.

In the deconstruction industry, the use of BIM tools is currently limited, and many actors of the deconstruction sector are unfamiliar or do not master the BIM. According to recent interviews with Belgian architects[8], the combination of BIM and circular economy is still very uncommon, as companies interested in the circular economy are not necessarily interested in BIM, and vice versa. In addition, waste management being a critical aspect of deconstruction, it has been identified that most of the existing waste management tools are not BIM compliant and while recent studies focus on BIM-compliant waste management tools for construction, the deconstruction sector lacks its own tools. More generally, EoL is currently not yet supported by an integrated BIM tool on the market, which limits the BIM-based EoL decision-making.

Although it is still an emerging science, BIM-based EoL have been identified to have a huge potential to facilitate the integration of circular economy in the building industry. Multiple EU-funded projects, such as HISER, ICEBERG and Digital Deconstruction have been or are currently investigating innovative BIM-based tools to facilitate circular EoL of building materials.

[8] A. Halbach and À. F. Université de Liège, "Le BIM as-built comme outil d'aide à la décision entre démolition ou déconstruction ?"", Jun. 2019. Available: https://matheo.uliege.be/handle/2268.2/6888.

5.4. BIM challenges

BIM as a collaborative approach has a huge potential in optimising and improving the management of the constructive process. However, its use also questions the traditional way of working and highlights the inefficiencies in processes and workflows. Hence, starting BIM is not necessarily always smooth and may generate challenges.

5.4.1. Challenge 1: A need for a standardised protocol

The key aspect of BIM being the collaborative approach, the process of managing the collaboration and the interaction between stakeholders remains the core of the BIM transition. One way to ease this collaboration is to generate agreements and consensus in the construction sector to ensure that every actor works in a way which is compatible with others. This can be done through sectoral agreements, laws and standards (at international level, or at national level) or directly between the partners of a project. Although having standards and protocols is very effective and efficient in creating a common ground between the different actors, one must consider that the construction sector is very wide and heterogeneous. Thus, creating one common protocol that fits all scenarios (new buildings, renovation, individual houses, apartment buildings, bridges,...) seems unrealistic. Therefore, many protocols discuss "how to define the rules'' rather than stating a very strict list of recommendations (COBIM, Belgian protocol). Indeed, this would allow us to adapt and adjust the protocols to the size, needs and requirements of a specific project. A distinction must be made between protocols and agreements facilitating the development of the project which must be rather flexible but structured and defined, and the legal or technical requirements defined by the sector or governments which ensure the reliability, fair access to public procurement, long term access to models.

5.4.2. Challenge 2: A clear definition of needs and requirements

Many public procurement and private projects require to work on "BIM". However, asking for BIM without clearly defining the needs and requirements can be counterproductive. In general, it is advised to express precisely what are the purposes of the model and what are the most important needs to be addressed. Once these needs are defined, they can be translated into technical requirements such as modelling conventions, production tables (lists of elements to be modelled) or level of details (definition of the degree of precision of the modelling).

Prioritising the needs is also beneficial when several approaches are possible. As an example, windows can become a general category, whatever the respective dimensions of each window, or be treated as different categories depending on their dimension. If the former can facilitate automation, the latter would make it possible to count more accurately the windows of each type. Each approach has pros and cons, which should be aligned to the project's objectives.

5.4.3. Challenge 3: Knowledge and expertise to model BIM

Digital processes in general and BIM in particular are not only a piece of software. The transition towards digital tools requires training and expertise. From the collaborative approach towards collaborative tools passing by new modelling software, switching from a traditional paper-based process towards a more digital one will require new skills. Modelling using an object-oriented approach (each element is an object with a specific behaviour and not only a line or a block) requires to define naming conventions, modelling conventions, list of parameters attached per object.

5.4.4. Challenge 4: Changing management

Beyond the pure modelling, using digital processes induces change or adaptation of the workflow. Learning new tools and establishing new flows requires time. This will generate a reduction in work efficiency for some time but also might lead to small errors or mistake. Thus, the transition should be progressive. Starting with a set of limited but mastered needs which will serve as a robust base for the future expansion of the digital strategy is the first step.

5.4.5. Is BIM reuse-ready or should it be tweaked to favour deconstruction and reuse?

BIM tools and processes were designed at first to optimise design and construction processes, especially for buildings of a certain scale. This induces several limits:

- The elements used to design (wall, door, windows) are new elements created for the purpose of a specific project. BIM software is not designed to handle a library of elements inventoried and reclaimed from another project. Although it may be technically possible to establish direct connections between the design environment and digital marketplaces of reclaimed building materials, there would still be a lot of practical questions to tackle, notably regarding the availability of such materials in the long run (is downloading an element from such a database equivalent to buying it? Will the element be reserved for a specific period or can someone else still acquire it?). These practical questions need to find answers to ensure that reusing buildings elements does not generate more issues than expected (e.g. designing a building with a specific element on mind which happen to be “not available” anymore when the construction starts).

- The base parameters created per default are not considering deconstruction and reuse. In order to evaluate, assess or reuse the models for deconstruction and reuse, the key parameters must be defined, structured and generated per default.

On the other hand, the way the BIM models are structured also induce:

- An object-oriented approach with objects having different categories (walls, windows,...) organised in type (insulated wall x, brick wall y) and instance (the unique placed element) allowing to facilitate and structure inventory and enabling automation.
- A link between the objects (building elements) and their metadata (material, dimensions, composition, comments) which facilitates a precise qualification of the building elements’ properties.

5.5. BIM potential for facilitating reuse of building materials

5.5.1. Acquiring and organising information

What type of information can be generated from a BIM?

In order to use BIM to generate reclamation audits or to migrate data from one model to another environment (database, other software), it is crucial to consider which type of information should be collected and associated with the model.

A first type of information regards the **geometry** of the elements. The geometry can be either one geometry or an addition of several elements (each of them with a geometry and a list of parameters). Exporting the geometry could be useful to illustrate the inventory.

Another type of information regards the parameters attached to “types” and to “instances”. **Type parameters** are parameters which are common for every elements of the same type. On the contrary, the instance is the occurrence of one element and **Instance parameters** are parameters that are specific to one element. This can be illustrated by the example of a wall, which is usually made of different elements (structure, insulation, finishing). The general composition of the wall, its thickness and its thermal properties, for instance, are parameters that concern the ’type’ in general. On the contrary, the actual length or height of a specific wall are parameters related to particular ‘instances’. They indeed vary from one wall to another (within the same type). Once again, the border between ‘types’ and ‘instances’ parameters can vary according to modelling choices. For instance, all different sorts of windows can be assigned to a general type. The specific dimensions of each window would then be instance parameters. But it would also be possible to create different types of windows based on their respective dimensions. In this case, the dimensions become type parameters.

As an example, in our project we have 4 windows. Two are of type 1 which means they are 120x120cm triple glazing windows with 2 openings and two are of type 2 which induces they are 120x60cm with 1 opening. In this case, the general dimensions, number of openings and glazing types are type parameters which means every window with the same type will have the same value. Hence, window #2 will, although it does show any specific parameter, will be a 120x120-2opening triple glazing window. The sill height parameter is an instance parameter as the same type of window can be placed at various heights without considering it as a different kind of element. Thus, parameters which can vary throughout a type are generally good candidates for instance parameters. Alternatively, the sill height might be considered as a type parameter for glazed doors, as all the glazed doors might need the same value (for technical reasons) (Figure 61).

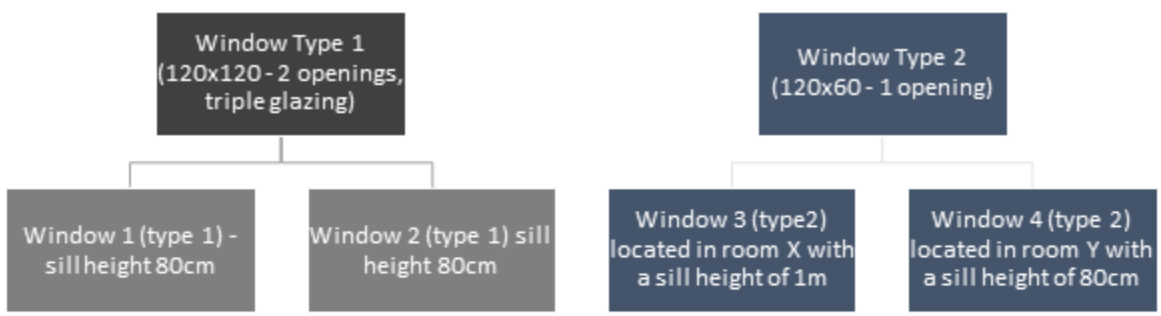


Figure 61: *Type and instance parameters are helping to structure the data within the BIM models. An efficient use of that structure might help organise inventories.*

It is possible to create simulations (energy consumption, space analysis…) by combining information from the different parameters. For instance, knowing the dimensions of the host of a window is useful to assess whether it will be easy to dismantle or knowing the distance between an element and the nearest exit, and its weight and dimensions is useful to plan the logistics of the dismantling.

What type and source of information can be added to the BIM?

The BIM model may not contain all the data which is required to assess the reuse potential of elements (be it for an existing building or in preparation of reusing materials in the future). However, it is always possible to add data to the BIM elements, either through the BIM interface, or by transferring data to the BIM from another source (excel sheets, apps, material database, etc.). The latter provides the opportunity to collect information with a user-friendly tool, while securing an automatic transfer of information to the BIM. This process is expected to facilitate the integration of information on the BIM model, especially for people who prefer to collect information on a specific interface.

Use case : Can data from reclamation audits be transferred automatically to the BIM ?
It is possible to automatically transfer data from a reclamation audit to the BIM, as long as a clear correspondence can be established between the inventory and the BIM, regarding element and element parameter identification. *Using the same identification number for the elements helps to identify them in both structures, thus link them and facilitate automatic data transfer. Similarly, data linkage may be easier if the name of the element parameter (ex: “composition”, “colour”, “condition”, etc) is the same in the inventory and in the BIM.* *It is also possible to automatically import data from any type of inventory table to the BIM, even though the nomenclature is different in both structures. Linkage scripts can be used for this (ex. with Dynamo software for Revit). This may be of use in the near future since there is currently no harmonised nomenclature for reclamation audits in North-West Europe. The digital supports are all different (excel sheets, apps, material database) and each auditor is familiar with their own support. As long as the inventory is structured in the form of a table, and that information needed for linkage can be obtained, data can be transferred to the BIM.*

In the BIM, information can be added either to a series of elements, by modification of type parameters. For example for a series of doors of the same type, parameters such as colour, brand or composition can be modified in *type parameters*. This allows you to add data to all elements of the same type in one action. Data can also be added to a specific object within a series, by modification of *instance parameters*. This can be useful when the series of objects is non-homogenous. For example, a door from the previous series may be contaminated with hazardous elements due to use, or in lesser condition than the other doors from the series. This can be indicated in the BIM by modifying contamination and condition in *instance parameters*.

5.5.2. Reuse inventory or Reclamation audit

Can useful data for reuse inventory be found in the BIM?

A pertinent use-case of the BIM in the deconstruction industry is the automatic extraction of information characterising BIM objects, to assess EoL scenarios. Such element characteristics encompass the identification of the object, as well as information regarding its general state, properties, composition and relation to other elements and to the building. The "Guide for identifying the reuse potential of construction products" developed through the course of the FCRBE Interreg [4] project describes such characteristics, and distinguishes them according to their vitalness into primary and complementary data.

Primary data correspond to product characteristics that are almost always required for assessing the reuse potential of existing building materials (same-site reuse, reclamation market or any other reuse path) :

- Item identification
- Visualisation : 2D (photo) or 3D (scan, 3D representation)
- Quantity
- Dimensions: length, width, thickness, volume
- Mass
- Location
- Condition : quality, damage

Complementary data is collected to consolidate the description of the identified item(s) and provide a better overview of its (their) reuse potential :

- Estimated value on the reclaimed market
- Item description : brand, colour, technical or mechanical performances, specific value or interest (historical, aesthetical, economic, scarcity, etc.), conformity or compliance with normative and regulatory framework, etc.
- Context : previous element use(s), accidents or incidents, etc.
- Assembly : number and type of connections, assembly method
- Environmental benefits
- Hazardous substances
- Additional documents
- Suggested applications

Knowing the importance of these parameters, their implementation within BIM software would facilitate the use of BIM models for inventory & fostering reuse. First, there is no limitation regarding the number of parameters that should be added to a project. Indeed, it is not because the parameters are not present by default that they cannot be added. Creating templates with specific parameters' lists is common in the AEC industry. Thus, having a "reuse" template with a specific set of parameters at various levels (projet, type and instance) seems relevant. Second, for more advanced parameters which require calculations or assessments, it is possible either to incorporate mathematical formulae directly within the parameters (e.g. the mass can be automatically calculated from the volume and the density) or, for more complex or dynamic calculations coding or visual scripting might help evaluate and encode values within a parameter.

Additionally, questioning and defining which parameters are "instance" or "type" parameters allows to organise the structure of the model and could facilitate the inventory and the evaluation of the reuse potential. Indeed, the distinction between type/instance parameters is not a distinction by "essence" but rather depends on the specific requirements of the project and the modelling conventions. The table below proposes and comments how the listed parameters above could be considered within a BIM approach:

Parameter	**Type / Instance**	**Comment**
Item identification	Instance	The software unique id can be used to identify objects / another parameter can be added at the instance level if needed. If an item identification is need for all objects of the same type this should be added as a type parameter
Visualisation 2D/3D	Not a parameter	Can be exported either per type/instance
Quantity	(Type)	Calculated by counting the number of elements of a given type
Dimensions/Mass/description	Instance/Type	If all elements of the same "type" have the same value -> type (e.g. height and thickness of a wall) If all elements of the same type can vary (e.g. length of a wall) -> instance
Location	Instance	Can be extracted from the model
Condition	Instance	As every item of the same type may have a different condition
Value	Type/Instance	Market value might be a type parameter; estimated value adapted from the condition might be an instance parameter
Context	Instance	Can use the premade "comment parameter"
Assembly	Instance	Except for structures, not handled by default; Some hosting properties exist (walls are hosting windows); Making a list of connections types and elements separated by commas might be a work around);

Table 4: *List of parameters attached to building elements.*

How can BIM be used to automatically generate a reuse inventory or reclamation audit?

In order to use BIM to generate reclamation audits or to migrate data from one model to another environment (database, other software), it is crucial to consider which type of information should be collected and associated with the model. Depending on the type of data (text, tables, pictures, 3D geometry) different approaches can be considered. In order to generate inventory of building elements for reuse, it is possible to extract the data sheet of elements and/or type of elements and extract the geometry of such elements. The example below shows the export of a BIM model. Every building element from the model has been exported automatically using a script. In the os explorer, several folders have been generated (Figure 62). Each folder regroups a category of elements. Inside each folder, every element subpart has been exported and numbered (a door is the assembly of three parts: the handle, the door panel and the frame).

This method allows to extract the geometry of each element and store it separately which makes sense while considering reuse (Figure 63). Indeed, the elements should be reusable in a new project. Additionally, this facilitates the generalisation of material databases. Finally, it is possible to export in a structured manner the data from every object within a datasheet which could serve as a basis to construct database tables (Figure 64).

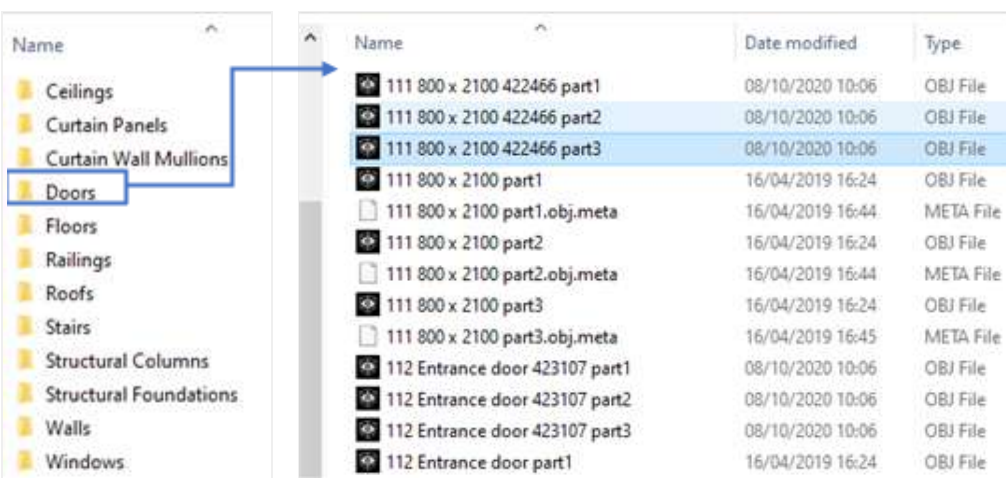


Figure 62: *The building elements composing the BIM models can be exported and sorted within predefined folders. This eases the creation of databases and platforms of reclaimed materials. The data structure (e.g. folders) and naming conventions can be adapted to the needs of the user.*

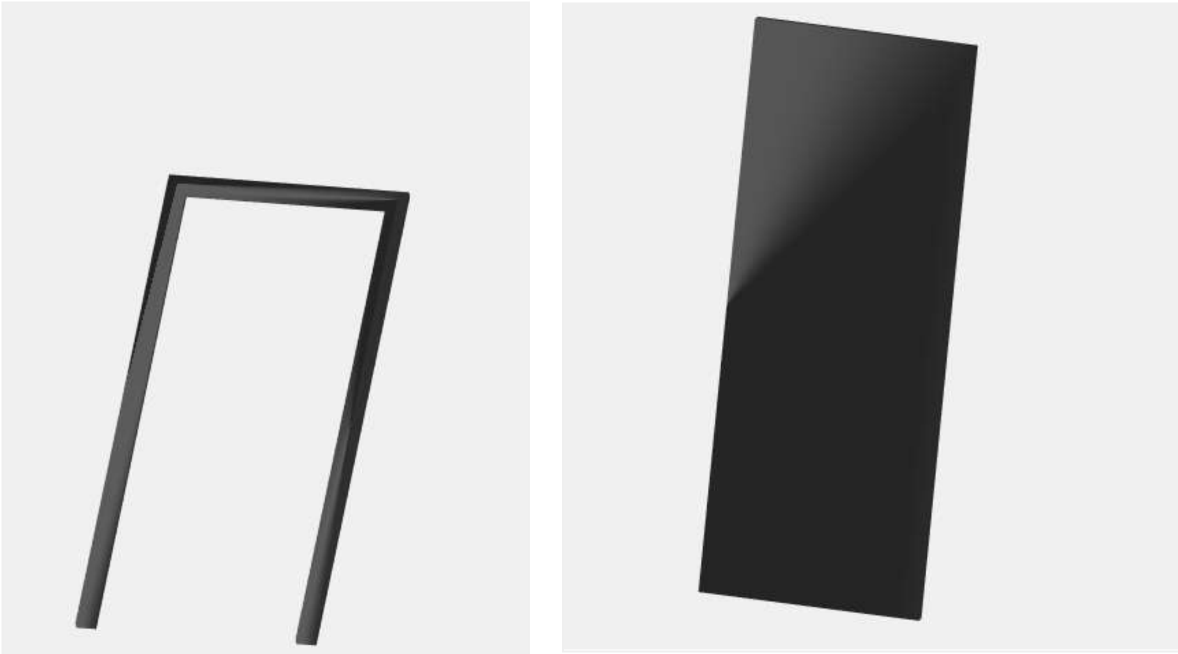
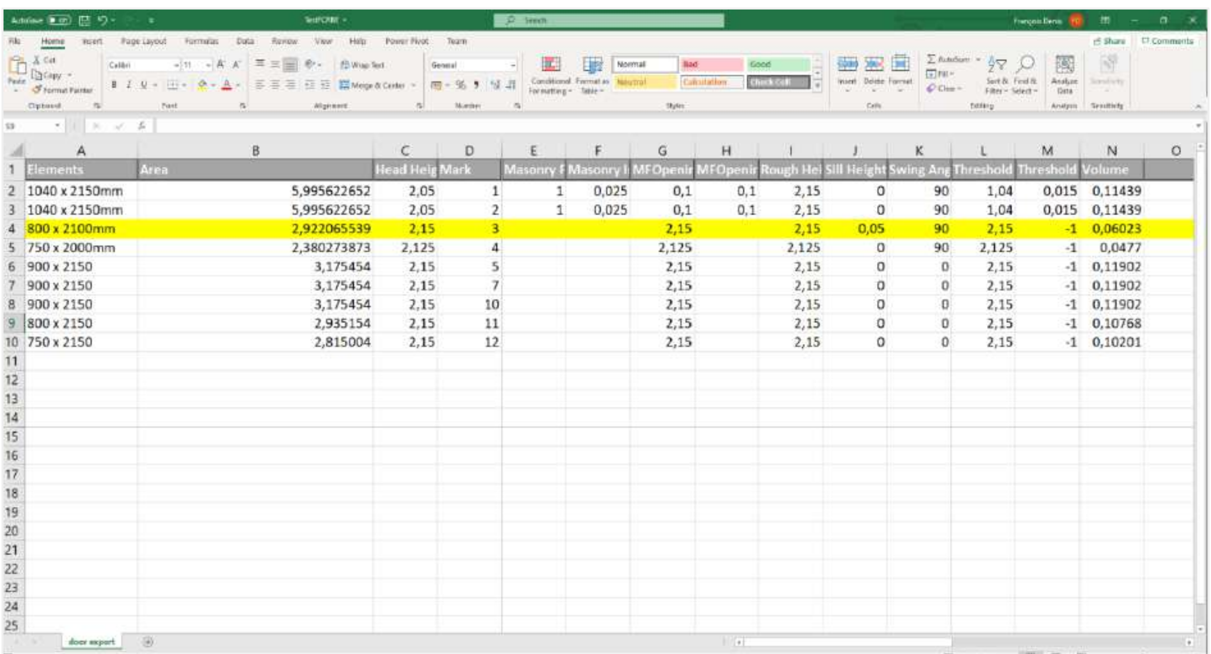


Figure 63: Model of a door and its frame automatically extracted as a .obj and sorted within a predefined folder.



Elements	Area	Head Heig	Mark	Masonry E	Masonry I	MFOpenir	MFOpenir	Rough Hei	Sill Height	Swing Ang	Threshold	Threshold	Volume
1040 x 2150mm	5,995622652	2,05	1	1	0,025	0,1	0,1	2,15	0	90	1,04	0,015	0,11439
1040 x 2150mm	5,995622652	2,05	2	1	0,025	0,1	0,1	2,15	0	90	1,04	0,015	0,11439
800 x 2100mm	2,922065539	2,15	3			2,15		2,15	0,05	90	2,15	-1	0,06023
750 x 2000mm	2,380273873	2,125	4			2,125		2,125	0	90	2,125	-1	0,0477
900 x 2150	3,175454	2,15	5			2,15		2,15	0	0	2,15	-1	0,11902
900 x 2150	3,175454	2,15	7			2,15		2,15	0	0	2,15	-1	0,11902
900 x 2150	3,175454	2,15	10			2,15		2,15	0	0	2,15	-1	0,11902
800 x 2150	2,935154	2,15	11			2,15		2,15	0	0	2,15	-1	0,10768
750 x 2150	2,815004	2,15	12			2,15		2,15	0	0	2,15	-1	0,10201

Figure 64: elements' parameters can be exported to generate a list of elements with their key parameters. This example shows only basic parameters available per default in the model. The more data is present in the model, the more data can be extracted or sorted automatically.

Opportunities and limits of BIM-based inventories:

The use of BIM technology to inventory building elements opens multiple opportunities for their circular EoL management. Not only does BIM provide a full and precise inventory of the building elements, useful for the building owner and the deconstruction company, but it also supports digitalization of these inventories in material databases, which publicises the availability of reusable elements and facilitates their integration in new construction projects. These two concepts are developed in the following paragraphs.

Having a BIM helps with automatically obtaining the building elements dimensions, properties, location and overall volume and mass of materials, to provide a full and precise inventory of the building components. It is possible to add supplementary layers of information on each BIM object in order to prepare them for the future EoL applications, such as deconstruction guidelines, guarantees, financial value, environmental assessment scores and legal requirements. For the building owner, who is usually responsible for the building waste, BIM-based inventories are useful to evaluate the material and element quantities, in order to start a reflection on their valorisation.

In addition, digitalisation of the inventory through BIM enables transfer of element information to a digital material database (MD), which acts not only as a digital storage of material information but publicises the availability of the reusable elements to the market. By linking the MD to a selling platform, actors demanding reuse elements can navigate the database online, search and buy elements to use them in other construction projects. In digital tender operations, blockchain technology can be connected to the selling platform, to guarantee element information authenticity. The digitalisation of building inventories in material databases, linked with selling platforms and blockchain technology lifts one of the main barriers for circular economy in the deconstruction sector, by identifying valuable components in advance and making their information available for potential buyers. As element information is made available before the deconstruction process, clients and their design teams can use this database to identify and specify useful components well in advance and include them in their new projects. This enables deconstruction actors to organise the deconstruction process accordingly, and to focus on the recovery of pre-sold elements, to recover them in good shape. Identification of valuable components in advance also changes reuse logistics, allowing just-in-time flows and reducing the need for physical storage, which is an important cost in the salvage industry. BIM-based inventories also facilitate the integration of reused elements in new projects, as reusable objects are already identified as BIM objects. In this way, architects designing with BIM can directly include reused BIM-objects in their design.

The potential of BIM-inventories for reuse dynamics are well established. However, non-BIM inventories also allow to estimate material quantities and digitalisation of element information in a material database can be done before demolition, without using a BIM, but by linkage of a digital inventory (ex. excel sheet) to the material database. The advantage that BIM-based inventories provide is the creation of BIM-reuse objects, which are expected to be easily included in new projects at the design phase.

The relevance of BIM creation to generate inventories must be studied for each project. For buildings which have a pre-existing BIM, or for renovation projects for which a BIM will be made anyways, using the BIM for the reclamation audit seems quite straightforward.

For most deconstruction projects, where a BIM needs to be created from scratch, it is necessary to evaluate the cost-benefit of BIM. Creating a BIM just for establishing a reclamation audit, if no other uses are planned and no additional information inserted, is probably not worth it. Creating a detailed BIM makes more sense if it is used for multiple applications (ex : environmental impact assessment, deconstruction planning, etc), rather than just for the inventory. The type of building is also important ; creating a BIM will require much less time to model (per m^2) for a big building with multiple redundancies and with elements which are already saved as BIM-objects, than for a small building, with all different elements which do not yet exist as BIM-objects. Moreover, the more accessible the information, the easier the BIM modelling will be.

5.5.3. Environmental evaluation of end-of-life-scenarios

The LCA can be used to encourage reuse at different building life stages

Life cycle assessment or analysis (LCA) is an internationally accepted method to assess the environmental impact of the products and elements used in a building and over a period of time from the extraction of the raw material to their end of life. With regards to the reuse sector, LCA can be of interest at two different stages.

Firstly, in the design process, to choose low-impact building elements, such as reclaimed elements, or elements and systems which are designed for disassembly and reuse. The application of LCA at the design stage can also be an advantage for companies that use it to respond to tenders that include environmental criteria. Indeed, in order to obtain a label that certifies a sustainable building, such as BREEAM, LEED and HQE, it is often required to use LCA to demonstrate the environmental performances of the building.

Secondly, during the demolition or renovation stage, LCA can be used to environmentally assess the EoL of materials according to different recovery scenarios. Even though it is expected that reuse, specifically on-site, is expected to have a lowest environmental impact than other EoL options, its quantification through an internationally accepted method such as LCA is pertinent for setting environmental targets, such as in tenders.

> *" Life Cycle Analysis (LCA) is an evaluation of the direct or indirect effects of a product on the environment, from the extraction of the raw materials used in its composition to its disposal." (Environmental Dictionary, 2019)*

However, it is important to draw attention that initially, LCA considers the "life cycle" of a product to be from resource extraction to landfill. This assumes that the material will necessarily end up in the landfill ("cradle to grave"), which is contrary to the "cradle to cradle" spirit of the circular economy. Indeed, most LCA studies of buildings are focused on the product phase and the operational energy use stage, and little of them include an in-depth analysis of the end-of-life phase. Some authors further indicate that reuse is not sufficiently taken into account in environmental assessments and requires new indicators in LCA methodologies, but as End-of-life modelling is becoming more important within circular economy policies, research developments are expected to address this issue.

Opportunities and challenges of LCA coupled with BIM

As the application of LCA in the construction sector can be complex and time-consuming, the possibility of LCA automation supported by BIM is perceived as an opportunity for more systematic and easier to perform LCA. Indeed, BIM can be a real enabler as it facilitates access to data. This could also help perform LCA earlier on at the design stage, allowing design decisions to be influenced by the consideration of LCA. The LCA could then become a design support tool instead of a fixed analysis result.

However, two arising questions need to be answered to comprehend if BIM and LCA are compatible: Do BIM models contain the data required to do an LCA ? Do BIM softwares support LCA ?

As an answer to the first question, BIM models usually lack LCA data, as some data required for an LCA are simply not needed in BIM (ex. recycling potential of element, machines and energy required for dismantling, etc). Additional efforts need to be made to directly integrate environmental properties useful for LCA analyses into a BIM object, In addition, sufficient level of detail in the BIM model is required to perform a meaningful LCA, hindering the applicability of LCA to low-detail as-built BIM for demolition or renovation projects.

The second question can also be answered by the negative ; BIM and LCA currently have their own software, standards and working methods, making it difficult to integrate a LCA in the BIM, One Click LCA has developed a plug-in for Revit, which however is not focused on the EoL assessment, while work is underway to link Totem, the Belgian environmental assessment tool for buildings, to BIM.

In what circumstances would the use of LCA coupled with BIM be most pertinent?

The application of BIM to an LCA will inevitably be limited by the amount and quality of useful data accessible in BIM. According to a One Click LCA specialist, performing an LCA from BIM can be faster, in theory. In practice however, it will only be the case if the BIM has a sufficient level of detail. Therefore BIM-based LCA is expected to be most pertinent at the design phase, when the BIM model is created in detail, rather than at the demolition stage.

Currently, it is not possible to conduct a LCA, with a thorough EoL assessment supported by BIM. However, it is worth considering whether the complex and time-consuming LCA method is the most appropriate for assessing the environmental impact of different end-of-life scenarios, specifically in preparation for demolition/renovation. Indeed, it could be interesting to use another tool; centred on the EoL rather than on the whole lifecycle, thus easier and faster to use. In addition, while LCA allows the evaluation of multiple environmental parameters, it may be easier yet very pertinent to focus on just one parameter, such as CO_2 emissions. For further automation of EoL environmental impact evaluation, BIM could be linked to such a tool, to provide quantity take-offs of materials in the building.

5.5.4. Assessment of the reuse potential of elements with BIM: case study of the Reversible BIM (RBIM) tool

Opportunities of the RBIM tool for the reuse sector

The Reversible BIM (or RBIM) is a tool under development by the Green Transformable Building Lab (GTB Lab). It is currently a prototype which is being tested on pilot sites in North-Western Europe, as part of the Digital Deconstruction Interreg project[9]. The tool is aimed to be a BIM-compatible tool that can assess reuse potential of building and its components.

The RBIM tool is based on the research of Durmisevic[10], which leads to the proposition of a model for calculating the reversibility potential (or transformation capacity), with the use

[9] https://www.nweurope.eu/projects/project-search/digital-deconstruction/

[10] E. Durmisevic, "Transformable building structures: Design for disassembly as a way to introduce sustainable engineering to building design & construction". 2006.

E. Durmisevic, P. R. Beurskens, R. Adrosevic, and R. Westerdijk, "Systemic view on reuse potential of building elements, components and systems: comprehensive framework for assessing reuse potential of building elements", U Twente, 2017.

of indicators of reuse potential, measuring functional, technical and material dependences on three levels of a building's composition (i.e. building, system, and component). The reversibility potential of a building is assessed by the independence and the exchangeability capacity of its components. More independence of elements means elements can be easily replaced, upgraded without damaging the whole structure or other elements. Exchangeability allows repair, replacement, and multiple uses of elements without creating waste or requiring additional raw materials. Ultimately, eight indicators of reversibility potential are established and provide a final score for the building (Figure 65).

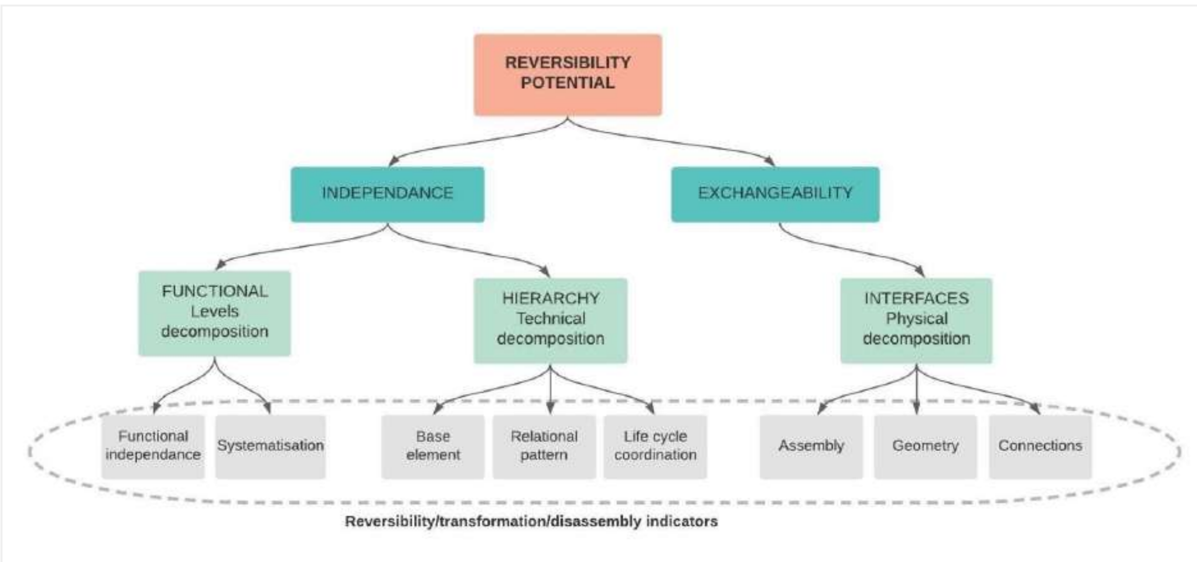


Figure 65: *Technical Reversibility Components, Elements and Building Level, E. Durmisevic and al. "Systemic view on reuse potential of building elements, components and systems: comprehensive framework for assessing reuse potential of building elements", U Twente, 2017, adapted by BBRI, 2020*

The assessment of the reversibility potential can be used at two stages. Either at the design stage, to assess the reversibility of buildings and provide a unique score, or as a decision tool for architects, to optimise reversibility. It can also be used at the deconstruction/renovation step, to assess which elements are easily dismantlable, thus fitter for reuse. In this way, it can serve as a decision making tool between demolition or dismantling. The combination of the tool with BIM allows automation, collaboration and visualisation ;

- **Automation** supported by BIM is perceived as an opportunity for more systematic and easier to perform calculations. This could help perform reversibility potential calculations early on at the design stage for all new buildings, favouring the widespread application of Design for

Dismantling (DfD) principles. This can stimulate the use of reusable elements in the future.

- At the dismantling step, the RBIM provides the additional **collaboration** opportunity, which is to select all the elements with high reuse potential before deconstruction and to create a library of BIM objects. Architects can then use these in their new designs.
- A colour code that represents the reversibility potential is used for each object. This v**isualisation** of the elements' reversibility straight on the BIM is made possible with the RBIM tool. By clicking on the objects, the user gets information not only about the reversibility potential, but also the dimensions, volume and even CO_2 emissions potentially saved.

Challenges and limits of the RBIM tool

The reversibility calculator tool is built as a plug-in for Revit, which automatically analyses the relationships between the elements of the building and their dependency on each other, calculates the *reversibility potential* of each element and aggregates this into a unique score for the building. If a BIM model is required, it remains unclear what are its requirements: what is the required level of detail, and does it require specific data which are not usually included in (as-built) BIM ? Indeed, data essential for RBIM calculations such as types, number and position of connections between elements are not always easy to acquire in an as-built BIM. In addition, supplementary analyses can be required, such as IR scan to identify the position of connections.

One limitation of the RBIM tool is that it allows the calculation of the reversibility (transformation, dismantlability) potential, which is not the same as the reuse potential. Indeed, the reuse potential not only includes reversibility (technical ability to be dismantled), but also other characteristics, such as element condition (state, hazardousness), market demand, value, etc. Technical capacity for dismantling is rarely the most important factor reuse, which is usually more market driven. Thus, the estimation of the reuse potential by an expert may be more pertinent than the calculation of the *reversibility potential* with RBIM.

In what circumstances is the RBIM tool most useful? What are its alternatives?

The use of the Reverse BIM tool developed by GTB Lab seems to be most suitable at the design stage, when a detailed BIM of the building is expected to be constructed anyways. RBIM could become a recognised tool for Design for Dismantling (DfD) optimisation, and potentially to score projects according to their reversibility potential. This way, targets could be set, which would favour reuse of building elements in the future.

Creating an as-built BIM for an existing building, with the only goal of assessing the reversibility potential of elements would imply high modelling costs at risk of low economic and environmental gains, especially if few elements have an actual potential for reuse. Instead, a rapid assessment of the reuse potential of elements by an expert (ex. salvage industry) is a pertinent action which can be done to evaluate if the potential of elements is worth more inquiry. In addition, there exists other ways to estimate dismantlability of a building, such as on-site visits, expert knowledge or extrapolating the rate of loss from on-site testing.

5.6. The use of BIM to stimulate the process and sequence of building disassembly

5.6.1. Opportunities of BIM-based disassembly

Having a BIM helps with automatically obtaining the quantities of each element category and material type, as well as estimating the inert and non-inert wastes. This data can be of great use in waste management and logistics. Furthermore, a BIM can be used for EOL planning, to stimulate the process and sequence of building disassembly, and to and evaluate optimal dismantling scenarios (economic, environmental, valorisation rate). This use is not yet widespread among the industry, and is currently at the research phase, as no commercial or academic BIM solution has fully used BIM for selective disassembly sequence planning nor deconstruction waste management. However, the use of BIM is a powerful tool for deconstruction planning. Its potentialities of **4D and 5D, data management, visualisation, logistics, automation and coordination** are developed in the following paragraphs.

The incorporation of **time (4D BIM) and cost (5D BIM)** as additional planning dimensions unlock great potentialities for BIM-based dismantling modelling. Indeed, the sequencing of selective dismantling steps can be used to optimise the recovery rate, as dismantling can be organised accordingly to the attachment and the location of recoverable building elements. Furthermore, as time required for each dismantling activity can be programmed in the BIM, as well as costs (labour, equipment, disposal fees or waste recovery, transport costs, etc), BIM can be used to simulate the economic performance of dismantling in order to decide on the appropriate end-of-life options.

In addition, it is possible to **add a layer of information** to each object in BIM in order to prepare them for the future EoL applications, such as deconstruction guidelines. Thus, BIM can facilitate deconstruction planning and execution by providing a digital space for deconstruction guidelines. Other characteristics such as resale value, disposal cost, and dismantling methods may be added to the objects. Linkage to a material database may facilitate and further automatise BIM construction.

BIM allows **visualisation** of elements and their contextualisation in the built environment. This feature can be used to assist the preparation as well as during the execution of dismantling or deconstruction. Visualisation of the dismantling and demolition steps can be used during the planning stage, to view the objects to dismantle in relation to the building or for dismantling simulation. Visualisation can reduce errors and help optimise the dismantling process. For example, the dismantling and transport of large elements through the building can be stimulated visually. Another example is to colour-mark on the BIM specific object according to a chosen characteristic (such as recovery potential or hazardous potential), to visualise their location prior to dismantling, their storage location and their date of dismantling and to detect errors or optimise the dismantling process through its visualisation. The BIM-based scenario can also be used during the deconstruction, to help workers locate specific elements, choose the or easiest transportation route through the building to the storage area, or to plan health and safety measures according to the process.

BIM-based EoL planning can come in handy for sorting out **logistic** issues. Indeed, automatic estimations of building material volumes, weights and dimensions from BIM can be used in planning storage and transport. The number and the size of waste containers and the surface area required for reusable element storage can be estimated through BIM, as well as spatial planning (what goes where on the building site). In addition, when incorporating time as an additional BIM dimension, storage solutions can be planned and tailored accordingly to the deconstruction steps. Furthermore, transport of waste and elements can be modelled, which unlocks potentialities for just in time collection, reverse logistics or combined logistics. BIM-based EoL planning can be a pertinent facilitator for reuse through logistics planning and optimisation, as the lack of on-site storage space is a frequent barrier for reuse on deconstruction sites, specifically in densely built environments.

Like other digital tools, the use of BIM relies in the potentialities of **automation**. Indeed, coupled with a software/extension, programmed for the matter, BIM can be used to generate design documents and reports on the fly. These reports could include the quantities and date of material liberation, the cost of waste valorisation, the number of lorries required for evacuation, etc.

The c**oordination** capability of BIM can also improve deconstruction planning and execution. Additionally, the automation and accessibility of information reduce the guesswork of contractors during the deconstruction phase.

5.6.2. Use cases

Exporting a 3D inventory of building elements from a BIM model

As new buildings are conceived more and more using BIM models, considering the use of the model to elaborate an inventory is a question that will become more relevant throughout the years. Indeed, if the 3D models exists (Figure 66), making a quick inventory of buildings elements does not require intensive work.

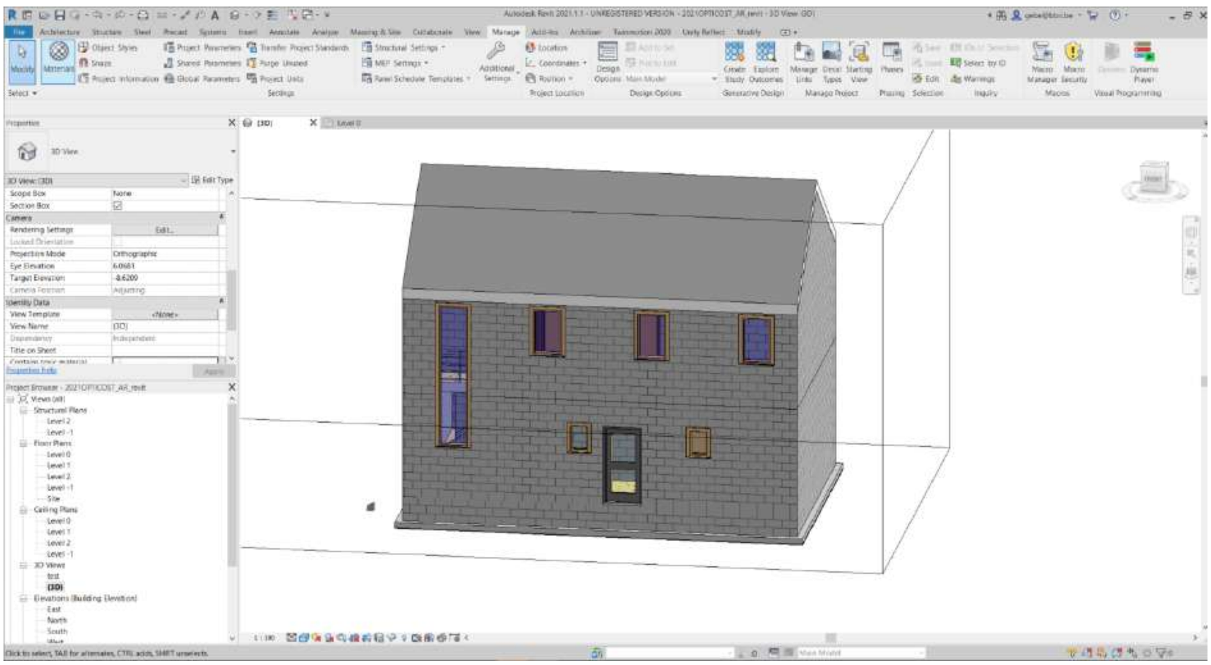


Figure 66 *- BIM model of a single-family house*

Although, it is possible to make a standard export of tables of elements, it is also possible, to extract the 3D geometry of element type and generate a visual inventory of elements (Figure 67). This summary export has the advantage of providing a visualisation of the listed elements organised by types (or another rule). Allowing to quickly select an element not only based on the parameters but also on its geometry.

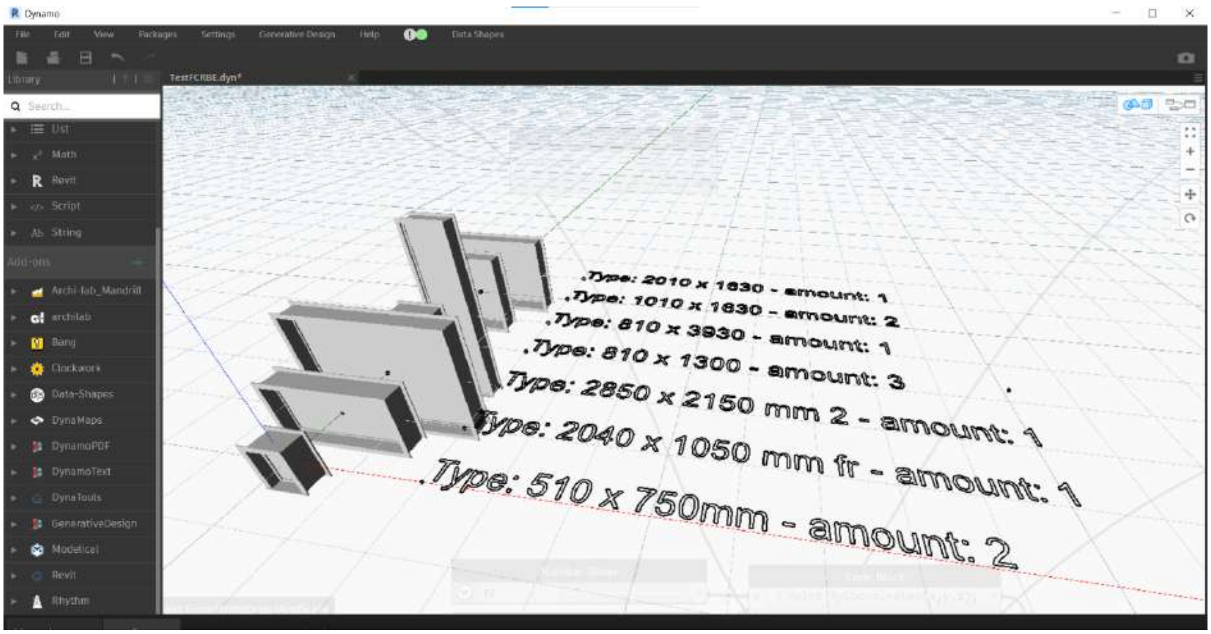


Figure 67 - *Windows' geometry is exported by type with their given dimension and number of similar elements.*

Additionally, a data sheet following the same structure has the visual representation (order of elements or sorting by type) can be extracted allowing to link the 3D object and its information (Figure 68).

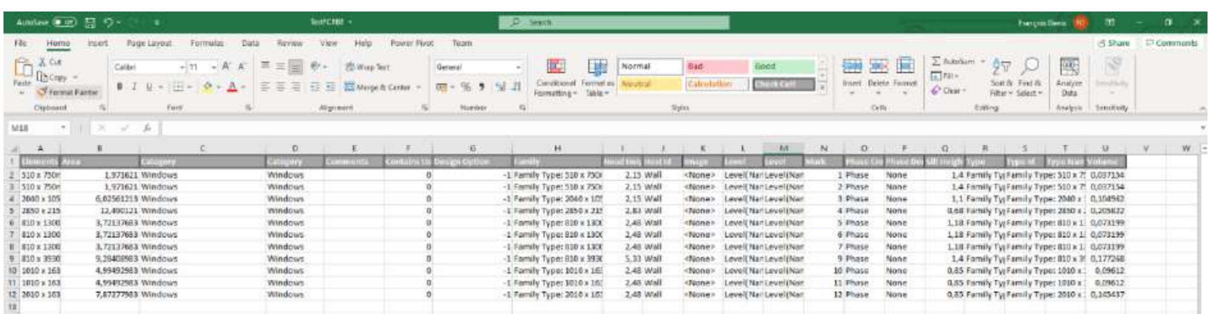


Figure 68 - *Every element's geometry can be linked to its datasheet using a defined naming convention.*

Evaluating storing space for reused building elements

Once we can export geometry as well as data for the inventory, it is also possible to use the information from the BIM model to plan or organise the dismantling of the buildings. For instance, extracting all the windows and doors of a building and estimate the volume needed to store them (Figure 69).

First, you extract the categories you want to list, in this case, doors and windows are extracted. In order to overestimate the needed volume, a bounding box is drawn around each element (Figure 70) and serves as the basis of the volume calculation (Figure 71).

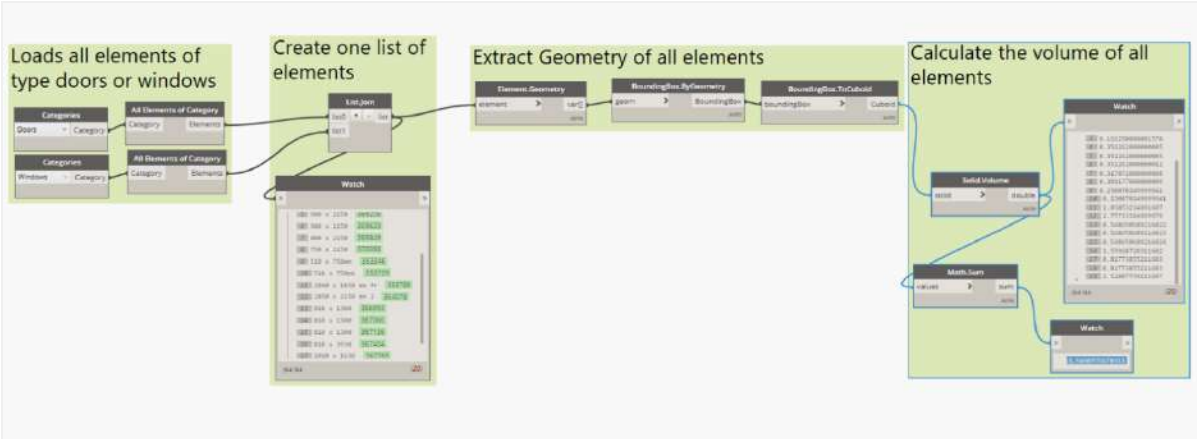


Figure 69 - *A short script can be used to estimate roughly the space needed to store elements.*

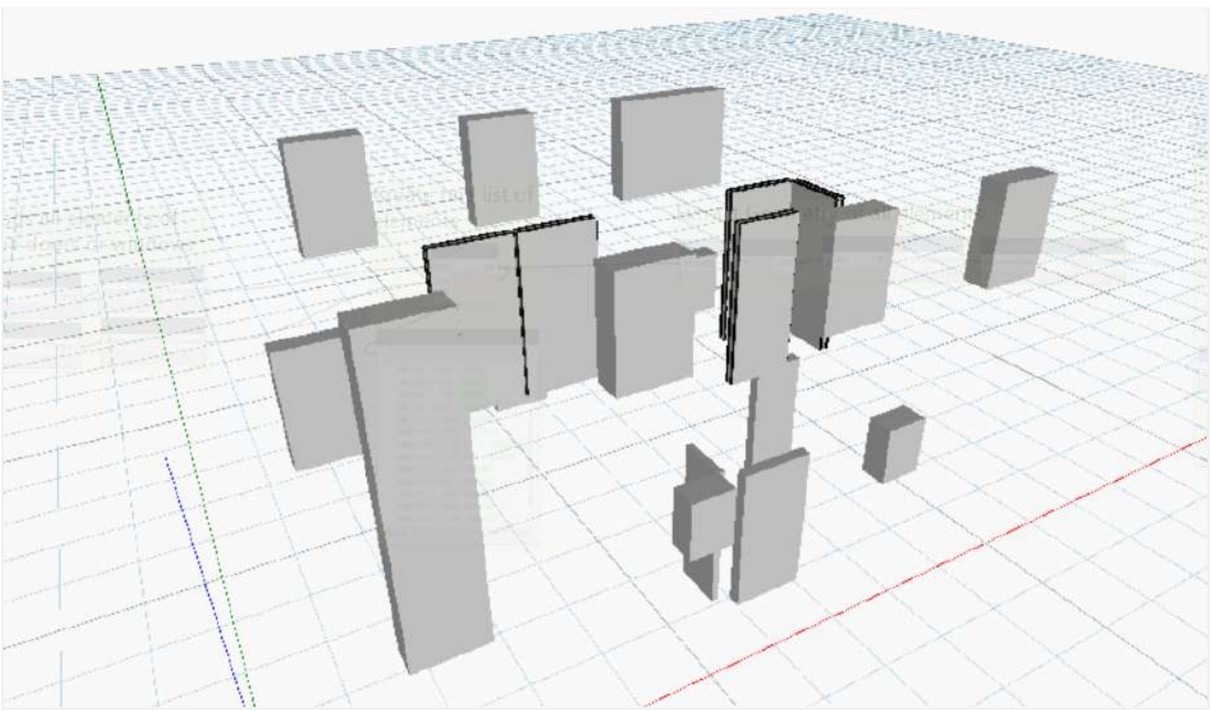


Figure 70 *- windows and doors' geometry exported from the BIM model.*

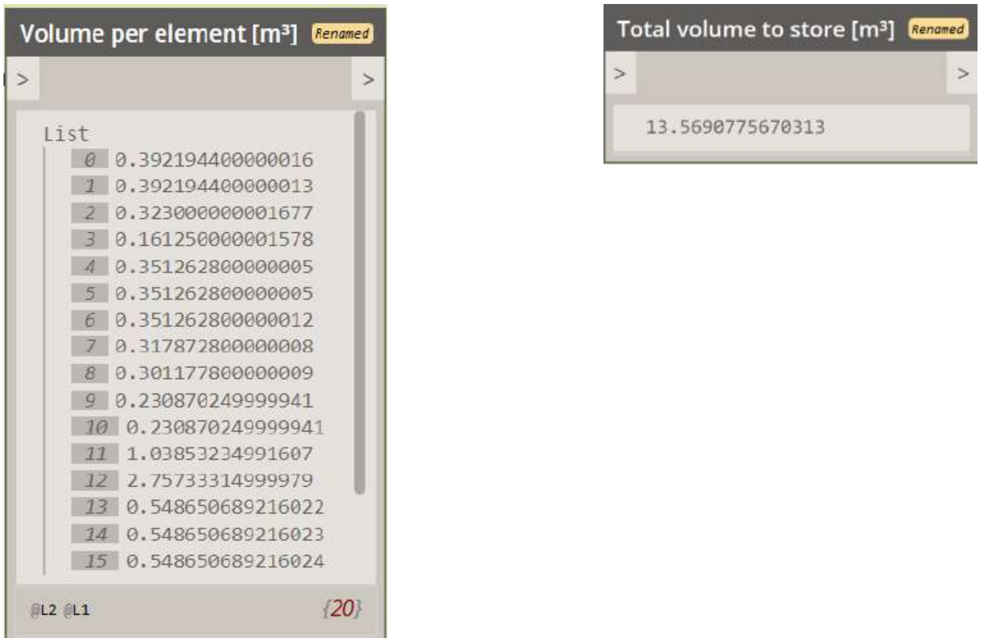


Figure 71 - *the volume per element and the total volume of the selected elements are calculated with the basis of the bounding boxes.*

Once this basic calculation is working, the script can be updated in order to extract the rooms of the project and compare the volume of the rooms with the volume needed to store. This could be useful to quickly identify the rooms which could be used as intermediate storing location (Figure 72 - Figure 73 - Figure 74).

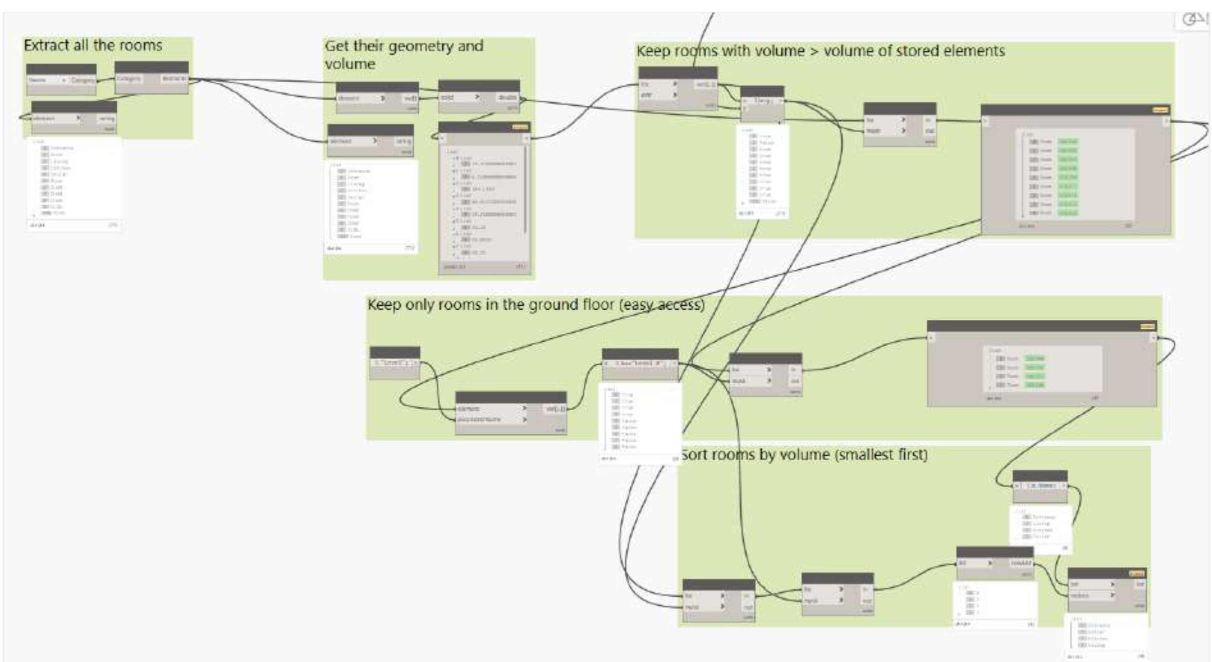
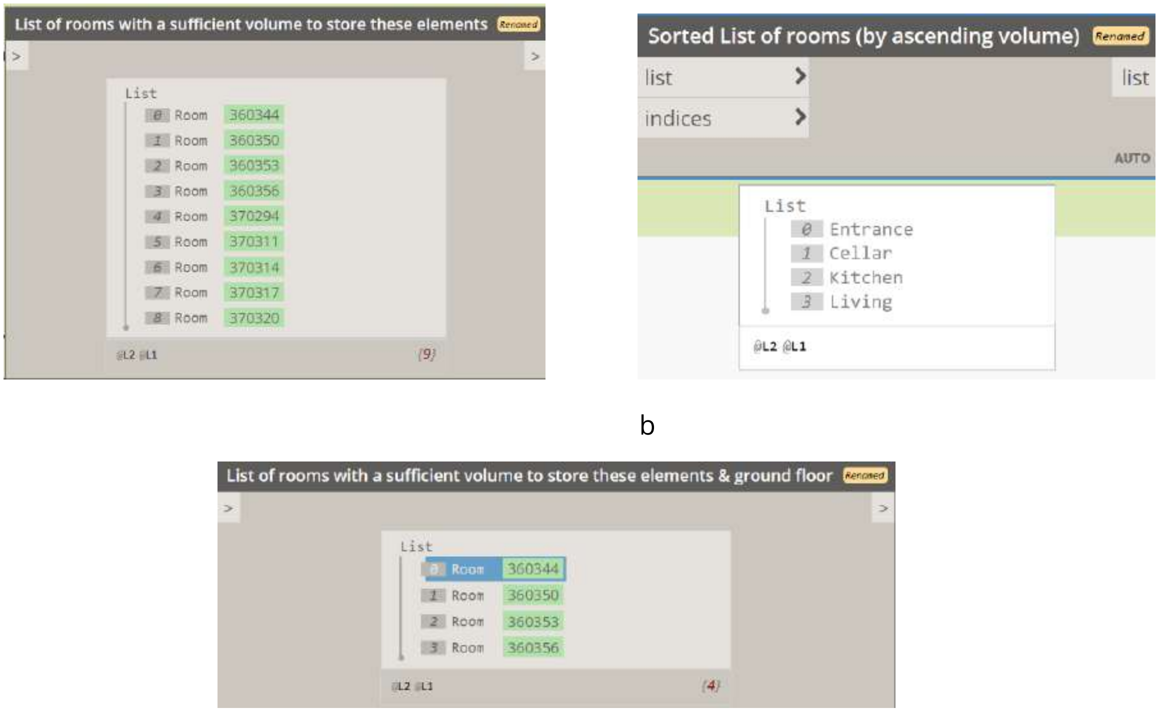


Figure 72: *updated script with extra functionalities.*



a

b

c

__Figure 73a__ : List of rooms with a sufficient volume to store these elements; __Figure 73b__: List of rooms with a sufficient volume & on the ground floor; __Figure 73c:__ Sorted list of room by ascending volume.

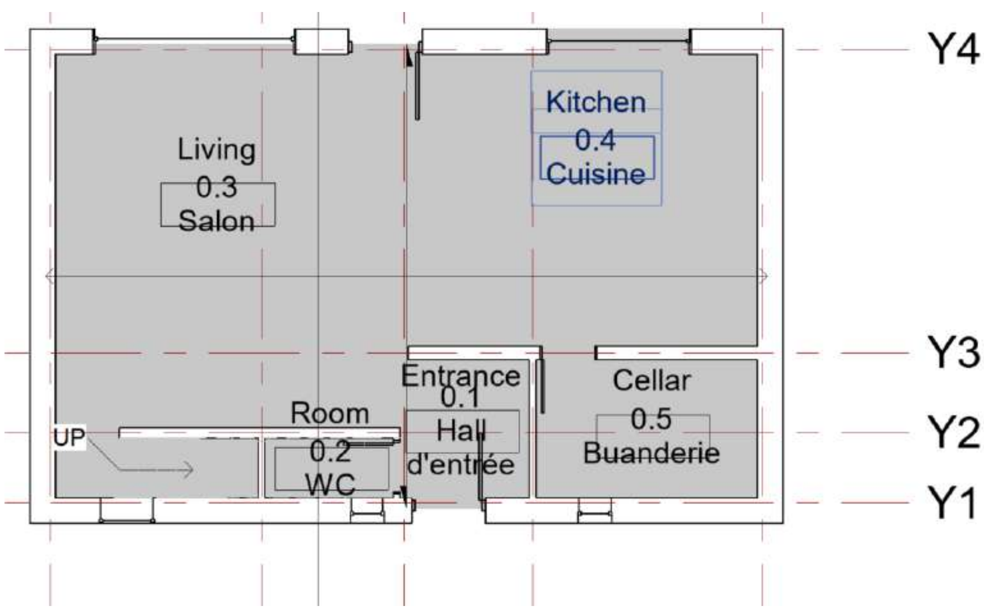


__Figure 74:__ Ground floor of a single-family house.

Filtering elements regarding their potential of toxicity

If we add the parameter “contains toxic materials” in building elements (this is a Boolean value), a script can be used to quickly visualise elements containing toxic materials (thus the one with the value “true”).

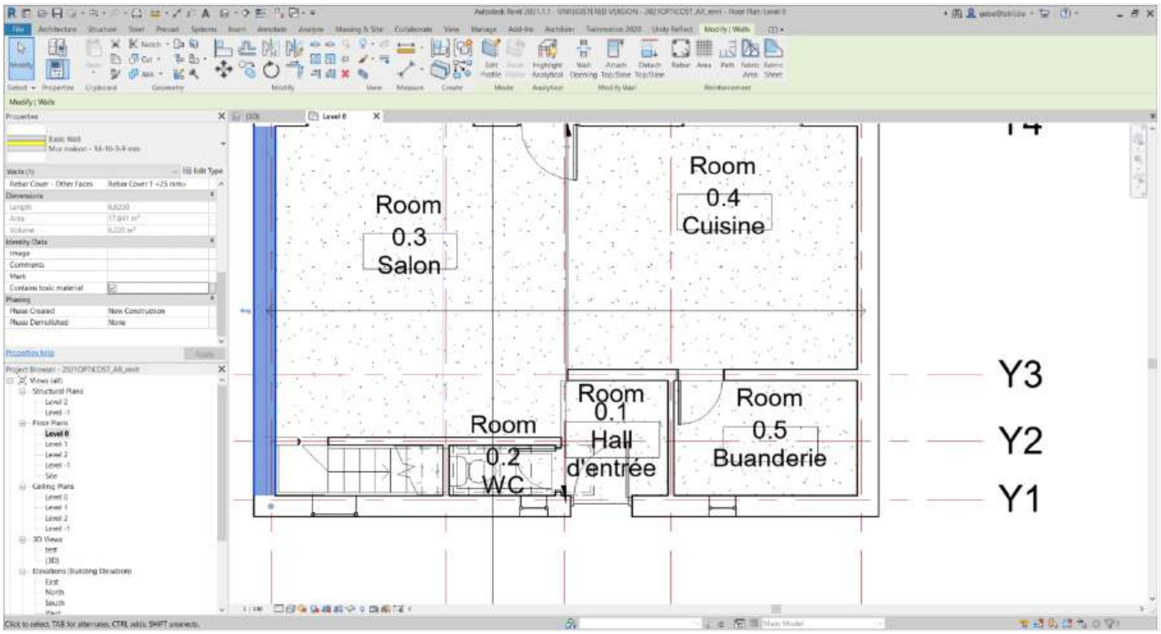


Figure 75: *Example of a wall with the parameter “contains toxic material”*

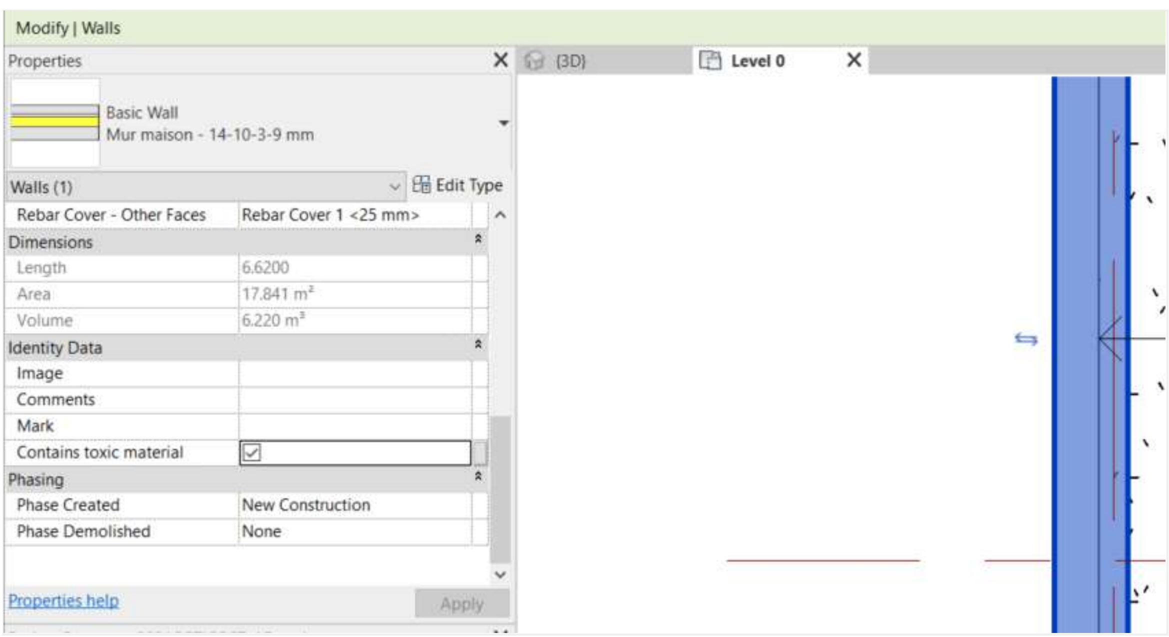


Figure 76: *Example of a wall with the parameter “contains toxic material”*

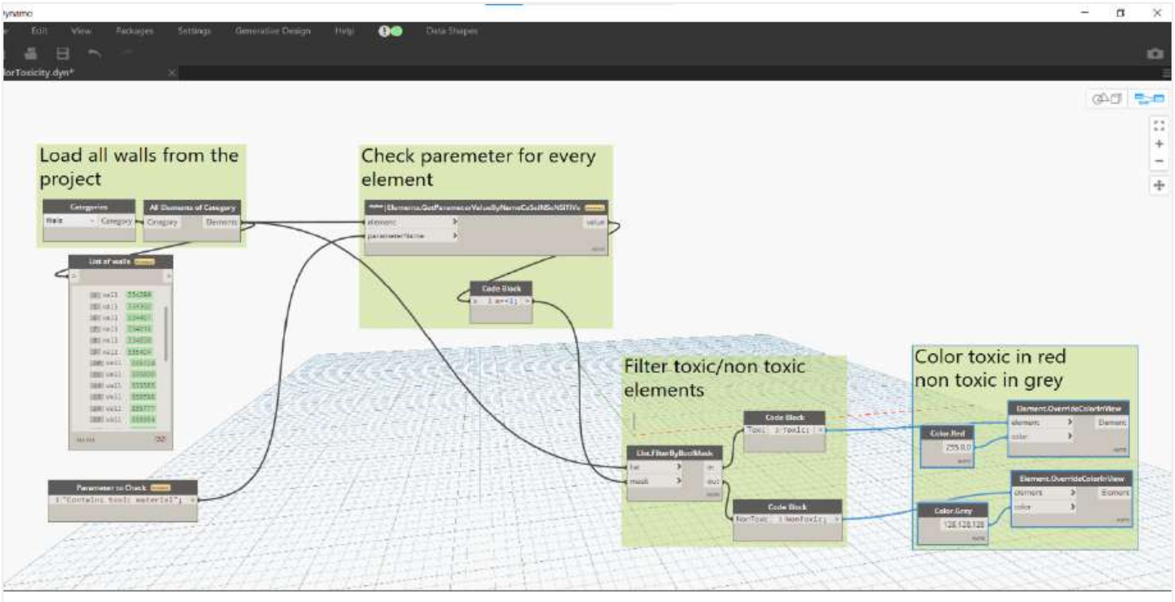


Figure 77: *Illustration of the script checking the toxicity parameters; The script has been coded in 15 minutes.*

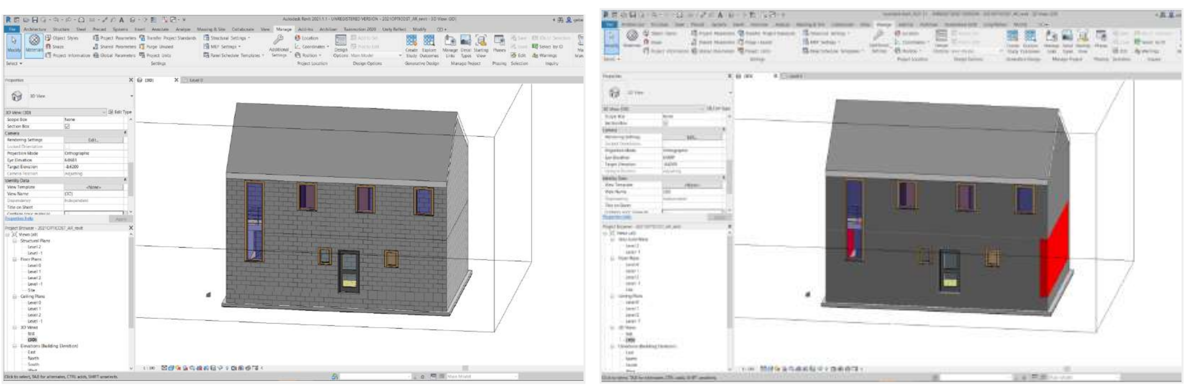


Figure 78: *the walls containing toxic materials are coloured in red.*

Figure 70: *List of walls sorted between containing or Not toxic materials*

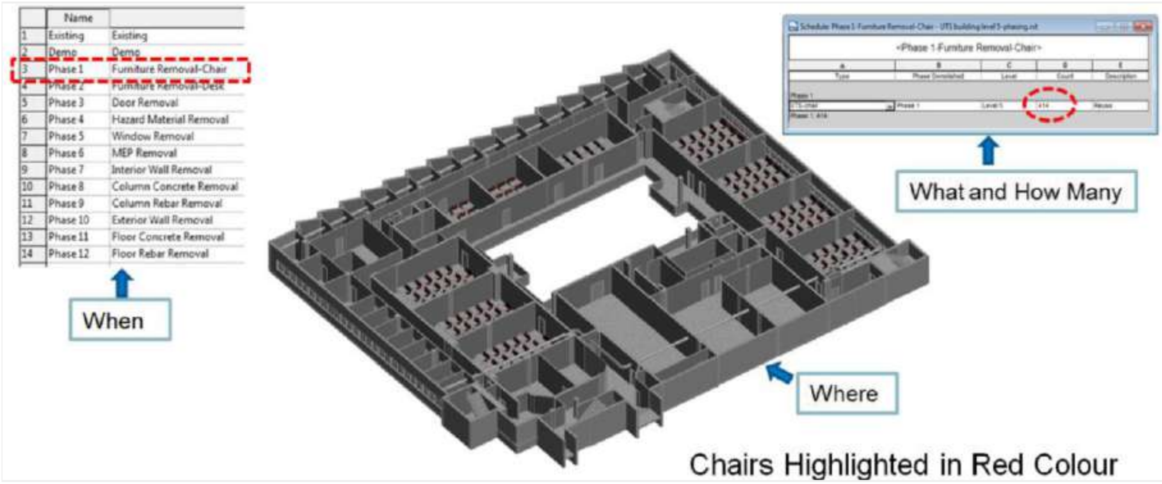
Bim-based plan for deconstruction waste management: the use of 5D BIM in a case study

5D BIM (including time and cost parameters) can be used to plan a deconstruction scenario. Quantities of materials recovered, as well as time and cost calculations can be conducted automatically to compare deconstruction scenarios. The deconstruction steps can be visualised on the BIM. BIM-based deconstruction scenarios are most interesting for big buildings, when optimisation of the demolition has to be conducted (according to time, cost and rate of valorisation).

The prerequisite to use this tool is that the as-built BIM needs to be constructed. In the case study developed by Ge and al (2017)[11], the BIM of one storey of a University building was constructed with a semi-automated approach, based on 3D point clouds and 2D plans and sketches. It was fully developed, up to including objects behind other objects, as well as relationships between components. Object properties relevant to EoL planning were added (material type, demolition cost and recycling method). No commercial solution exists for 5D BIM-based deconstruction. Revit software was used in this case study.

The as-built BIM was used to perform simulations of the demolition process. The simulations consist of not only demolition sequences, but also a scheduled number of days required for demolition in each of the phases. It also allows visualisation and quantification of the elements to be dismantled at each step (Figure 80). As a result, labour costs required and quantities of demolished material and number of trucks required for transporting the demolished material could be estimated (Figure 80).

[11] Ge, Xin Janet, Peter Livesey, Jun Wang, Shoudong Huang, Xiangjian He, and Chengqi Zhang. 2017. 'Deconstruction Waste Management through 3d Reconstruction and Bim: A Case Study'. *Visualization in Engineering* 5 (1): 13. https://doi.org/10.1186/s40327-017-0050-5.



<Wall material takeoff>					
A	B	C	D	E	F
Material: name	Type	Phase demolis	Material: volume	Unit cost ($/m3)	Cost ($)
Asbestos					
Asbestos	Hazardous materials	Phase 3	0.42 m^3	300	124.874983
Asbestos: 26			0.42 m^3		124.874983
Brick, common					
Brick, common		Phase 7	508.92 m^3	300	152,675.861538
Brick, common: 60			508.92 m^3		152,675.861538
Concrete masonry Units					
Concrete masonry units	Atrium wall 100	Phase 7	10.06 m^3	300	3019.045148
Concrete masonry units	UTS-exterior-wall-240	Phase 10	180.48 m^3	300	54,142.794872
Concrete masonry units: 69			190.54 m^3		57,161.84002
Gypsum wall board					
Gypsum wall board	UTS-exterior-wall-240	Phase 10	18.05 m^3	300	5414.279487
Gypsum wall board: 57			18.05 m^3		5414.279487
Grand total: 312			717.92 m^3		215,376.856029

Figure 80: *Visualisation and quantification of the dismantling in BIM and b Estimation of labour costs required and quantities of demolished material and number of trucks required*[12].

5.7. Conclusion: addressing user's needs

BIM is a tool allowing to link geometry and data throughout the lifecycle of a project. Although, it was first conceived to optimise the construction process, the possibilities allowed by the technology present a huge potential in quantity evaluations, assessments or even scenario planning. The combination of both geometry and information allows to make more advanced evaluations in a shorter amount of time. However, in order to be effective a BIM model is dependent on the level of detail and information. Defining the BIM uses and thus, the requirements is and remains key in the whole process. Having a BIM model is

[12] Source : Ge, Xin Janet, Peter Livesey, Jun Wang, Shoudong Huang, Xiangjian He, and Chengqi Zhang. 2017. 'Deconstruction Waste Management through 3d Reconstruction and Bim: A Case Study'. Visualization in Engineering 5 (1): 13. https://doi.org/10.1186/s40327-017-0050-5.

never sufficient to address a problem, the question is rather what is inside of it, how it is structured and how can we extract information and which information.

This is why, although buildings that are being reused today might not have BIM models, it is important to question and investigate further the specific BIM needs and requirements to allow or facilitate reuse either for new buildings (facilitate the future reuse of the materials installed in new buildings) or for deconstruction (facilitate the evaluation of the reuse potential of existing building materials). Defining the parameters needed for a digital inventory as well as the data structure would allow us to generate data templates which could be used for BIM project, ensuring that the buildings we built today will provide reusable elements in the future.

Additionally, BIM is a multilevel approach. BIM is often associated with big international projects. However, there is not a single "fit for all" BIM approach but rather a range of possibilities from easy and quick modelling allowing quick, basic but limited estimations to very detailed remodelling of a building allowing precise estimations or simulations.

To sum up, pushing the use of BIM at all costs in a generic, unique and standardized way for every building type, phase or scale might not be beneficial and counterproductive. Considering that BIM is only fitted to one specific type of project is too limiting. There a several types of BIM uses, requirements, software and platforms. Adapting the BIM approach to the added value generated by the deliverables and extracts might be more relevant than applying either 0% or 100% of BIM approaches blindly.

The use of BIM to support circular economy: the digitization of existing and future buildings is key to support the emergence of sustainable models and accelerate the transition to a circular economy. BIM (Building Information Modelling) is considered as one of these tools. The BIM is an object-oriented model, which not only allows data storage, but also helps with more transparency and information exchange between actors, which improves collaboration. Additionally, the automation of tasks through BIM reduces guesswork and errors and can be used to generate scenarios, calculations or reports on the fly. The intrinsic advantages of the BIM make it useful in the context of reuse, where transparency and collaboration are key, and where automation has the potential to reduce labour costs. The potentialities of BIM for the reuse sector are numerous :

Data on building elements in the BIM can be extracted automatically (e.g. using scripts in Dynamo for Revit) to generate a **reclamation audit or reuse inventory** (e.g. in Excel format), and the BIM can provide fine estimations of element quantities (e.g. bricks, tiles). Digitalisation of the reuse inventory also opens the potential of linking BIM to a Material database and to reselling platforms. BIM also has the potential to support calculation tools, which can be used to compare different EoL scenarios. For new buildings, BIM can support **design for disassembly**, to facilitate future reuse. At the design or at the transformation stage, BIM-based **reversibility potential** calculations can be done to evaluate if building elements are technically removable from a building. In addition, by linking BIM to Life Cycle Analysis (LCA) tools, **environmental impact assessment of EoL scenarios** could be automated. At the transformation stage, the use of 4D (time) and 5D (money) can also support reuse by simulating the process and sequence of disassembly.

Addressing limitations and challenges : in new constructions, where BIM approach is becoming the norm, BIM-based EoL decision tools are seen as an opportunity to create a framework for buildings designed for reuse, although consistency in data storage and exchange must be addressed. Maintaining the BIM in use throughout the building life and adapting it as a digital twin is imperative for its effectiveness in the future.

For old buildings however, the pertinence of creating a BIM for EoL management is questioned, more so for deconstruction than renovation, the latter allowing further use of the BIM as part of the building is maintained. Indeed, the BIM methodology does not always allow to integrate the full complexity of the existing built environment, but it also imposes important modelling efforts and costs, especially for highly accurate models. As most of the existing building stock is not entirely suitable for reuse, and as the reuse business model is still fragile, low-tech digital solutions may prove to be more economically viable solutions than BIM. However, in cases where pre-existing BIM-objects can be used, for “conventional” buildings (e.g. all the walls are straight), which contain structural repetitions (e.g. similar levels of a multi-storey) and where element information is available (e.g. blueprints, technical data, etc.) BIM generation will be facilitated and may prove to be pertinent. Moreover, the development of plan-to-BIM or scan-to-BIM technologies, which are still at their premises, open new horizons for semi-automated BIM generation.

Lack of standardisation of the BIM tool is often considered as a threat to it widespread. Indeed, BIM lacks a standardised classification tools for EoL, in order to allow data exchange and easier collaboration between actors. A reflection is needed regarding element classification, including clarity of information and their encoding from one file to another (Excel to BIM), as well as linking digital tools with each other.

In addition, BIM tools lack interoperability with LCA and other EoL management tools, which further limits the open data exchange between BIM tools and external EoL tools, as well as material databases.

However, achieving uniformity of the tool will be difficult given the Belgian market and its policies. In addition, too much standardisation of the tool is a threat to BIM accessibility. The BIM should indeed be kept open and flexible, so that it can be developed according to the project requirements, otherwise it could close the doors to certain players.

Indeed, it is crucial to build a BIM which is adapted to the transformation strategy and to the needs and expectations in terms of circular economy. Detailing the usage of the BIM in order to define the type of information which it should contain, its level of detail, and its accuracy should be done prior to BIM generation. This will allow to evaluate BIM model generation costs, which usually increases with the amount of information needed per material, and to compare it with the benefits which it provides. In some cases, it may be more pertinent to model only parts of the building instead of the whole building.

Another challenge for the use of BIM in the deconstruction industry is the lack of knowledge of the tool. As the potentialities of BIM are not well apprehended by the sector, it is difficult to target their needs, and translate them into a precise demand for BIM. In addition, as the sector does not yet master the basic digital tools, it is difficult to offer more high-tech solutions such as BIM. In this regard, simpler solutions, allowing information exchange to and from the BIM with Dynamo (for Revit) may help widespread use of BIM.

6. Applications and Materials databases in the support of reuse in the deconstruction industry

Applications and software can be used to facilitate the recovery and reuse of construction products. They offer a large range of uses : assistance in the creation of material inventories, for database creation, environmental impact assessment (LCA) or assessment of feasibility of deconstruction techniques.

6.1. Applications

Apps supporting the digitalisation of the inventory process: Filling out an inventory can be done through an application. A digital inventory offers the following advantages relative to a non-digital inventory :

- Time gain due to automation (ex : product quantification and qualification, creation of reports on the fly) ;
- User-friendliness (ex : easy photo addition, drop-down menus and checkboxes) ;

- Accessibility, collaboration and appropriation of the inventory by multiple actors (project manager, project owner (de)construction companies, etc), from different locations ;
- Identification, characterisation and precise location of construction materials and elements ;
- Anticipation of reuse/recycling and organisation of dismantling works ;
- Linkage to a material database or online selling platform ;
- Monitoring and traceability of material fluxes during the deconstruction/transformation project ;
- Facilitate the evolution of the inventory with application updates (new features).

Currently, there exists a few apps which are used to collect information and generate inventories, such as the Rotor app (used in-house) and Bellastock (web-application), but none of them are used at a wide scale. There is a need to develop an "inventory app", which would combine the following principles :

- It should be user-friendly, with an interface kept as minimal as possible to keep it easy to use (such as in the form of an excel sheet) ;
- It would combine automatically all the tools used now : gathering notes, photos, plans, quantities, comments, etc. in one interface ;
- It should be customizable because each organisation has its own way to work, and each building and project is different. However, it could be interesting to have some sort of standardisation ;
- The app could have a number of templates containing typical parameters (ex : by linkage to a database), through which the user could preselect some options. Remaining information to fill in could be highlighted to grasp the user's attention. In addition, it would be of interest if the user can create a new template (ex. for a tower with similar elements inside, the user could save one floor as template, to use it for the other floors and modify when needed) ;
- The structure of the app should allow to perform a demolition inventory (material-oriented), combined with a reuse inventory (element-oriented). The combined structure of both inventories is yet to be developed ;
- The app should include a feature to allow data transfer (ex: to a material database, selling platform, etc.) and data storage.

Applications and softwares could also be of interest to guide a user through the information collection process. Such a tool currently does not exist.

6.2. Material databases

A digital database is an organised collection of structured information (data), which is stored electronically. Being digitised, the data can easily be accessed, modified, managed and organised. The use of a digital material database (MD), which contains data on building materials and elements, is of practical interest to the reuse industry for multiple reasons.

Current material database technologies include : Cirdax[13] (NL), Concular[14](DE) and Upcyclea[15] (FR).

Material databases provide a structure for material documentation, in a systematic manner: one of the difficulties in the reuse sector is to find documentation about the products in the building stock. There is no general library about 'old' materials. The material database can help overcome this issue by providing a structure for an online library, collecting technical documentation of existing building materials. Preferably open-sourced, the database can allow easy access to all the available information on the products which are still present in the building stock. Other information such as product identity can be collected in the material database, which can be of use to different actors of the reuse sector, who do not use the same nomenclature. For example, in the material database, an element can be identified by its function in the building (ex. door), materials (ex. wood), by the corresponding EURAL code (ex. 17 02 01), and more.

The challenge in the material database is to structure the information in a harmonised manner. For optimal functioning, building elements should be described systematically in the database (qualitatively as well as quantitatively) . It may be pertinent to set guidelines for classifying and describing elements and to help users encode information properly.

Material databases support digitalisation of reuse inventories and publish the available reusable elements on the market : for existing buildings, the data is to be obtained through reclamation audits and inventories. At the individual level, such a database could provide digital support for audit information, which is easier to share, modify, access, and can be stored digitally. However, at a larger scale, the material database can be used to collect data from multiple audits, creating a timely array of information.

On a global scale, harvesting data from demolition and reclamation audits would create a far larger variety and quantity of available components, and a more fertile database from

[13] www.cirdax.com
[14] www.concular.de
[15] www.upcyclea.com

which to meet a new project's needs. In this way, material databases can be used to publish the availability of reusable elements to the market ; potential actors in demand of reused elements could navigate the database online, search for specific components, and agreements could even be reached prior to demolition, facilitating logistics.

By making the Material Database BIM-compatible, architects and design teams can search through the MD and directly compare BIM objects from demolition projects and construction projects to see if materials would match. Linking the MD to a marketplace opens up the possibility of selling reclaimed materials for future construction projects. In addition, the material database can be backed by Blockchain technology, which builds trust between parties that are unknown to each other, since it prevents damages or forgery of the MD.

In the long term, Material Databases enable anticipation for the reuse sector: Material flows (including reusable materials) can be anticipated in the very long term. Current trends show a sometimes very short lifespan of around twenty years (mainly for offices), while other buildings or elements are expected to last longer. The reuse process is based on the transformation of existing real-estate, which is estimated to have a lifespan of 20 to 100 years. For these present and future buildings, information can be inserted in the MD at the construction phase (probably directly from the BIM), and can be adapted during the lifetime of the building (the BIM as-built is expected to be kept up-to-date following alterations, maintenance or transformations) or at its end-of life.

A materials bank created today from contemporary buildings, must be designed to remain effective over the next 100 years or be upgradable to ensure compatibility with future technologies. If data on all new-builds is added to this database, there will be sufficient choice to integrate a large number of reuse elements into new structures.

At a large scale, material databases support data-driven circular economy

At a larger scale (building and regional context), MD can be used to map the flow of products and materials. It can be combined with big data analysis and provide information on current and future material flows at the city or regional level. Researchers and entrepreneurs can use the database to identify underused components, for which environmental and economic improvements upon conventional waste management can be developed, and, in due course, deliver upcycled or reused products.

7. Conclusions and outlook

The idea behind digitalization is that data can be made available, and processed into information, knowledge and wisdom. Through digitalization, data can be shared to provide better insights and to make better decisions; data and information can be put available to others, to allow more transparency and cooperation; data allows to measure and evaluate certain parameters and to do calculations; and data and information allow to optimise certain processes, eg. by automatization of repetitive tasks.

In this sense, digitalization offers a lot of potential to aid and support a more circular economy, and to foster the reuse of building elements as a subpart of the circular economy. As well BIM, image techniques, AI and dedicated softwares can have interesting use cases that have been explored in this report. The fact that information can be created, edited, shared in the value chain, … is a crucial next step to better organise the current material EoL-chain, and will allow for better understanding, better decisions and better cooperation in the future.

However, when looking back, it is clear that most of the existing tools and approaches are not developed for the deconstruction and reuse sector itself. BBRI has mainly used and encountered technologies developed and already proven useful in other domains of the construction industry (eg. BIM for new construction, image technology for renovation, …) or developed in other application domains (eg. AI, software for maintenance) and thus no solutions specifically made for urban mining.

An important next step will be thus to work closely with the actors in the deconstruction, demolition, reuse and recycling chain and ecosystem, to better identify their needs and problems, that in the next step can be addressed by digital tools, methods & data specifically developed for them. This can be done by gathering people in working groups, testing solutions in the field, with the concerned actors, ….