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ReCreate

Reusing precast concrete for a circular economy

Vullings et al.

Guidelines for a BIM-aided pre-deconstruction audit

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Abstract

The BIM-aided pre-deconstruction audit process is mainly a process of collecting and digitalizing data of precast concrete elements in a donor building, from which they will be deconstructed. The digital information is stored in a database that architects and structural designers can use when designing a new building with reused precast concrete elements.

The ReCreate project tests the process of harvesting and reuse of precast concrete elements in four real-life projects in Europe. The goal is to gather knowledge in a wide range of topics directly connected to the reuse of precast concrete elements in structures of new buildings. By reusing these elements, they get a second life and the environmental impact of construction a new building is significantly reduced.

The insights gained in the pilot projects contribute to a kind of 'roadmap' for collection information on donor buildings and their precast concrete elements in what we call a 'pre-deconstruction audit' (as opposed to the more familiar 'pre-demolition audit'). The audit process contains all the steps necessary to start an efficient and (structurally) safe deconstruction process of a donor building.

The audit process starts by collecting data from various archives and the internet, such as Google Maps and Street View. The data is entered into a visual database, a 3D BIM model. This 3D BIM model offers great advantages in managing and validating the collected data. To validate the data, determine its reliability and complete missing data, a visual inspection is performed. Additional testing supports the data and the reliability of the data. The information obtained is incorporated into the 3D BIM model in order to create a final, complete and reliable 3D BIM database containing all the necessary information of the precast concrete elements.

The roadmap for collecting the data, creating a 3D BIM model (database), verifying and managing the data of the donor building and precast elements is laid down in this document as a recommendation.

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Contents

1. Introduction

1. 1. General

The aim of the ReCreate project, which this document originates from, is to reuse precast concrete elements from the structure of an existing building, the donor building, as structural elements in a new building. In order to do this safely and effectively, information is needed on the donor building and its structural precast concrete elements. To meet the requirements of new build, a variety of information needs to be retrieved. The physical dimensions of the concrete elements, such as beams, walls or columns act as the starting point. However, it is just as essential to uncover the load-bearing capacity, other (material) properties, as well as possible degradation.

This essential information will have an effect on the reuse potential of the deconstructed precast elements. In the best-case scenario, when all the needed information is present and reliable, the structural engineer has more options for reuse. If the information is limited and/or not reliable the use case of the elements is limited and more problematic. Structural reliability is a key factor in this process.

In this report, the process of information collection is discussed in detail as a BIM-aided pre-deconstruction audit process.

The research performed in ReCreate is strongly connected to pilot projects performed in Finland, Germany, Sweden and the Netherlands. These pilots entail a donor building (or buildings) of elements as well as new buildings that will be created. Because knowledge about the donor building is relevant for this report, in the next paragraph, a short description of the donor buildings in the several pilots is presented.

1. 2. Donor buildings

Precast concrete elements may be found as a part of the structural frame in many kinds of (hybrid) structures, also in conjunction with other materials. However, when using a donor building to harvest structural concrete elements, it is logical to look at building types with mainly precast concrete structures, such as ReCreate's donor buildings.

The donor building for the Finnish pilot project is an office building located in Tampere (Figure 1). The building is consisting of two wings, one with 7 floors and the other with one floor. The gross area of the building is 2940 m^2 and its volume is 14 500 m^3.

In case of the Swedish pilot project, the reused precast elements are derived from three different sources. Wall elements are from Helsingborghem's housing blocks in the Drottninghög neighbourhood (Figure 2). The concrete foundation slab is also retained from the previously demolished preschool 'Grodan', and it is reused in situ in Drottninghög, Helsingborg. Columns and beams come from Kv. Huggjärnet, a warehouse building in central Helsingborg. Reused hollow-core slabs are factory rejects from Strängbetong's factory in Veddinge, which otherwise would be crushed and mixed with new concrete to produce new elements.

The German pilot project uses a block of flats as the donor building. The donor building was located at the Otto Nuschke Straβe in Hohenmölsen (Figure 3).

The donor building for the Dutch pilot project is an office building located in Arnhem, named Prinsenhof (Figure 4). The building consists of two wings, one with nine floors and the other with five floors. The wings are connected by a core with a staircase structure. The structure is fully consisting of precast concrete elements. The structure of both wings is created by hollow-core slabs spanning of 13 meters between load-bearing precast façade elements.

Figure 1. Finnish donor building.

Figure 2. One of the Swedish donor buildings, during deconstruction.

Figure 3. German donor building.

Figure 4. Dutch donor building Prinsenhof.

1. 3. Types of precast concrete elements

One of the main purposes of the pre-deconstruction audit is to make an inventory of the elements available in the donor building. Several different types of precast concrete elements have been used in buildings (Figure 5 and Figure 6):

- Beams
- Columns
- Walls, load bearing and non-load bearing.
- Shear walls
- Facades (sandwich element)
- Stairs
- Stair landings
- Balconies
- Etc.

In principle, these elements can all be reused. This is best done by using precast element for the same purpose as it was designed for. This is because:

- The reinforcement in a concrete element is tailor-made for the element itself and for its original purpose.
- The detailing of reinforcement is subjected to regulation (Eurocodes). These regulations are different for each type of element.
- The connections of elements are tailor made for the specific use.

Figure 5. An overview of different types of precast concrete elements.

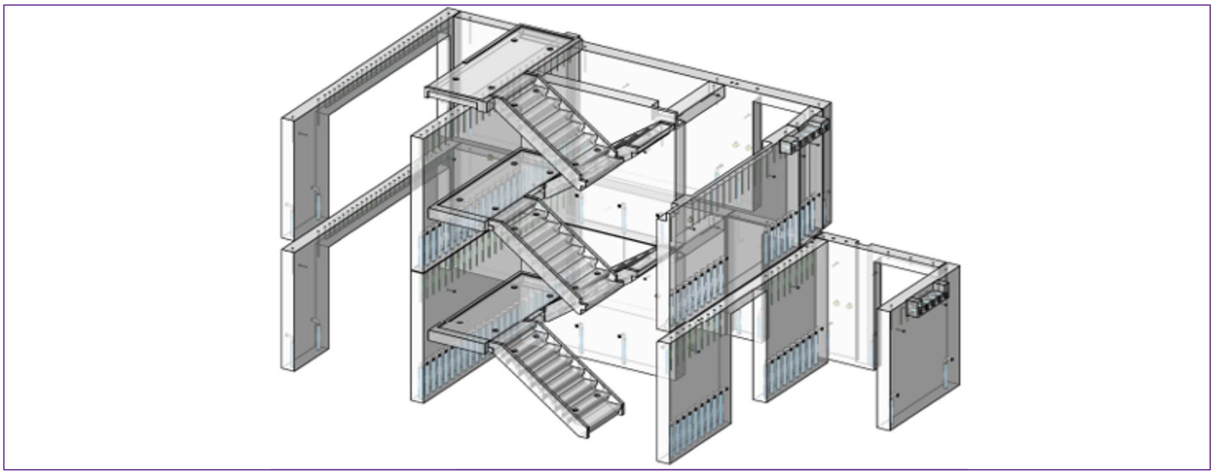

Figure 6. 3D BIM model of different precast concrete elements.

Even within the same element type, dimensions, connections and reinforcement may differ between individual elements. A structural designer must consider the fact that reused elements may have the same shape, but the structural details in these elements may be different.

All buildings may also include non-structural precast concrete element, for example off the shelf elements like lintels, drainage channels, drip sills, etc. (Figure 7). These products can also be harvested for reuse purposes, but are not the focus of the ReCreate project.

Figure 7. Standard self-precast concrete products (lintels, wall copings, drip sills).

2. Archival research

2. 1. General approach

After the selection of a donor building, the process of gathering information starts with the search for simple generic information on the donor building. Generic information consists of the main features of a building, such as its size, location, type, and age. This information is easily available and can be found by:

- Visiting the building.
- Google Maps and Google Street View are ways to get a simple overview of the building and it surroundings. Google makes regular updates, but the possibility that the information is not always up to date should be considered.
- An internet search of the address of the donor building or, if present, the name of the building. Consider the possibility that the information found is not up to date or 100% accurate.

After finding basic, general information on the donor building the search for additional information is the next step. For this, several archives can be used, such as:

- The archives of the owner of the building,
- The municipality archives,
- The archives of the contractor of the building,
- The archives of the architect of the building,
- The archives of the structural designer of the structure of the building,
- The archives of the manufacturer of the precast concrete elements part of the structure of the building.

In these archives, more detailed information may be found about the structure of the building and the precast elements themself. Due to all kinds of reasons and circumstances the required information is not always available, complete or up to date. Reasons being:

- Parts of archives can be lost due to fire, during a move to a different location or reorganisation of the institute that own the archive.
- In some cases, regulations stating that archives must be preserved for a certain amount of time and after this period the archived information is destroyed.
- Digital information is stored on a medium that is not accessible anymore due to decay of the medium or the absence of the necessary hardware and/or software application.

- The information in the archive was not complete in the first place. Usually only the self-created information is archived and this information can contain only a small part of the structure or certain types of precast elements.
- Information is not updated after making changes to the building during the initial construction and/or during a renovation/retrofit.
- The way information is recorded changes over the years. Forty years ago, it was general practice to write information on paper. At some point, typing was introduced. In 1979, the first word processor was introduced and information was digitalised. The same can be said about drawings of structures. AutoCAD, for instance, was first released in 1982.

It is very important to verify the authenticity, completeness and correctness of the information collected. This can be done by always using several different archives and verifying the information with an inspection of the building.

If differences are found between the (structural) information and/or the inspection of the building, extra investigation is needed to determine the implications of such discrepancies.

2. 2. Design and construction tradition

Today, many different parties are involved in the design and construction processes. The fragmentation of work performed in these processes also means the fragmentation of information. Therefore, collecting all the necessary information of a building can be quite challenging. Many different structural designers/engineers may work on one project. Most of them look at a different part of the structure(s). Usually, the engineering process of a structure involves for example the following parties and tasks:

1. **Principal structural designer**; designs the concept of the overall structure of the building, including the foundation, stability and robustness of the structure. Some key parts of the structure are checked by the designer in order to determine if the designed structure is feasible.
2. **Structural designer, foundation**; the designer performs research (including in-situ testing like e.g. penetration tests) into the soil parameters at the building site. The designer provides advice to the principal structural designer how to design the foundation of the building, based on information of the building given by the principal structural designer.
3. **Structural engineer, steel structures**; the engineer designs the steel structure, namely the components of the main structure designed by the principal designer. The detailing of the steel structure is done by the engineer, based on guidelines of the principal designer. All the necessary calculations and (shop) drawings of the steel structure are made by the steel engineer. The structural designer steel also assists in the manufacturing of the steel structure at the factory. In many countries the structural engineer steel has a liason to the manufacturer of the structural steel parts.

4. **Structural engineer, in-situ cast concrete**; the work of the engineer for in-situ cast concrete is more or less the same as the structural engineer steel, this time for all the in-situ concrete structures. Normally this includes the foundation of the building. Quite often this work is done by the principal structural designer; however it is possible that the reinforcement drawings are created by a drafting office on the basis of the analysis and sketches of the principal designer.
5. **Structural engineer, precast concrete**; the work of the designer precast concrete is the same as the structural designer steel, this time for all the precast concrete elements. The task of the structural engineer precast often consist of a general plan about how the structure is created by the several precast elements up to the detailed design of non-system precast elements. In some countries the designer has a liason to the precast concrete manufacturer.
6. **Structural designer, system elements**; specific types of elements like off-the-shelf structural elements are designed by the structural designer of the manufacturer of the elements, which also manufactures the structural elements. For example, this can include hollow core floor slabs, (precast) foundation piles, specific fastening systems, etc.

When the design work is scattered between different engineers as described above, normally the principal structural designer has an overall view and should make sure all the different components of the structure of the building are correct, according to their specifications and according to the codes. This is done by randomly checking the work (reports, calculations and shop drawings) of the other designers and engineers, which is the main source of reliable structural information.

Since 2000, more and more drafting of structures and structural components is done with 3D modelling or building information modelling (BIM). Before 3D modelling, most of the drawings were drawn with a 2D computer aided design (CAD) program like AutoCAD. 2D drawings have commonly been made with CAD since mid-1990s. Before that, the drawings were usually made by hand. Archives have stored paper copies or, in some cases, the drawings have been made into microfilms or digitized as pixel drawings (tif or pdf format), after which the original drawings have been destroyed. With 3D modelling came the possibility to integrate the engineering process with the production process. Furthermore, an increasing amount of factory processes are being automated. Machines 'read' the information in the 3D models and produce (parts of) structural elements.

The use of BIM and 3D modelling is common in several countries in the Europe, such as the Netherlands, Finland and Sweden. However, there are also countries (Figure 8) where the use of 3D modelling and BIM is not common in the engineering practice (Rabia Charef, 2019).

BIM and 3D modelling in the engineering process has an effect on the information available for precast concrete structures in buildings. Digital 3D models can give a better indication of where to find certain information and in what form/shape it is available. On the other hand, experience has shown that the fact that information is digital is no guarantee that it will be retained over time.

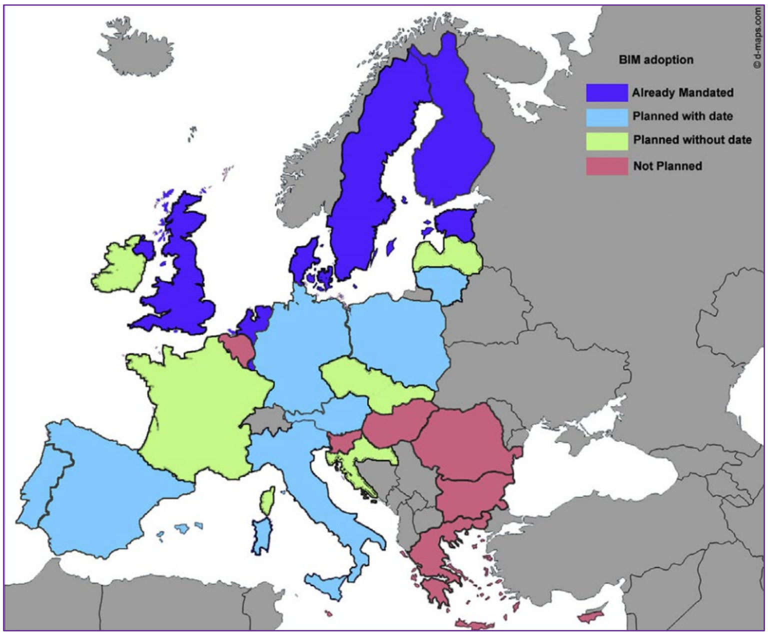

Figure 8. State of the Art of BIM adoption across Europe (May 2017). (Rabia Charef, 2019).

2. 3. Specifications

When a building is designed and built, responsibilities between parties, applicable construction codes and standards, material properties, and used products are defined. This is done in a specifications document, which usually is part of the contract between the client and the contractor. When the specifications of a building are available, relevant information about the properties of the materials and codes and standards applied in the construction stage can be found.

It should be verified whether the information in the specifications is consistent with that on the drawings, which is discussed next. When the information is consistent, it makes the information about the material properties more reliable.

2. 4. Drawings

In the design process of a building, many different drawings are made, such as floor plans, cross sections, elevations and detailing. Each party in a building project makes their own set of the aforementioned drawings, but their contents are different, as every designer generates drawings containing information pertaining to their field of design. An example of this is the difference between architectural detailing (Figure 9) and structural detailing (Figure 10). The architect will use minimal structural information (only the main dimensions of structural elements) and will denote the type of material, steel, reinforcement or concrete. The structural engineer, on the other hand, will only introduce structural elements in the detailing, nothing else.

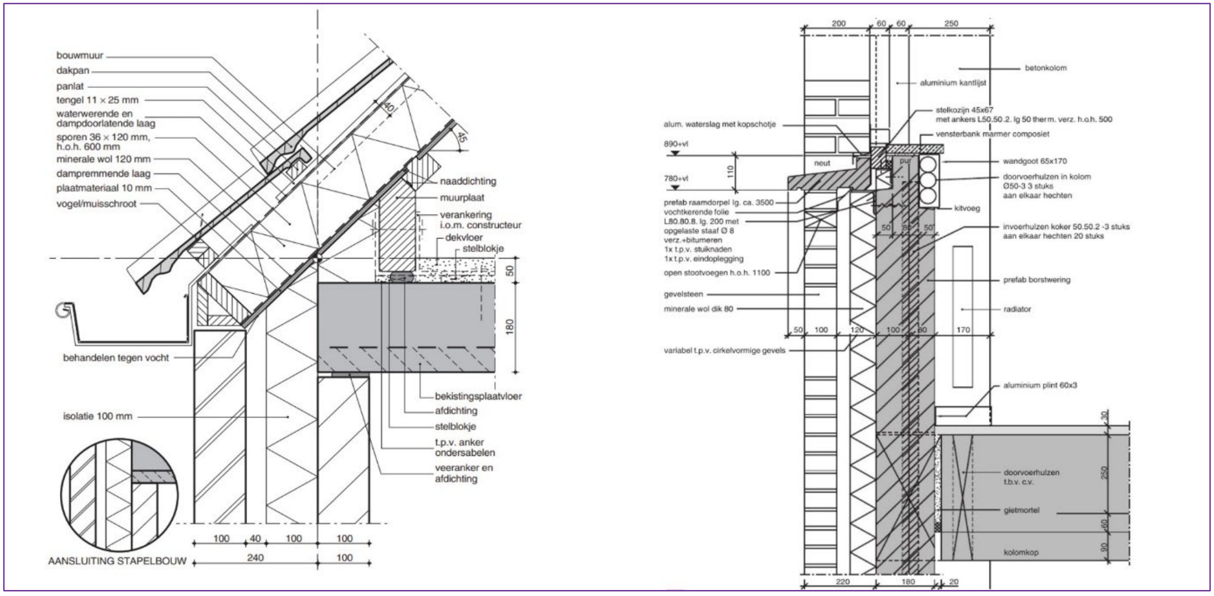

Figure 9. Typical architectural detailing of connections (Wentzel P.L., 2005) and (Boom van, 2005)

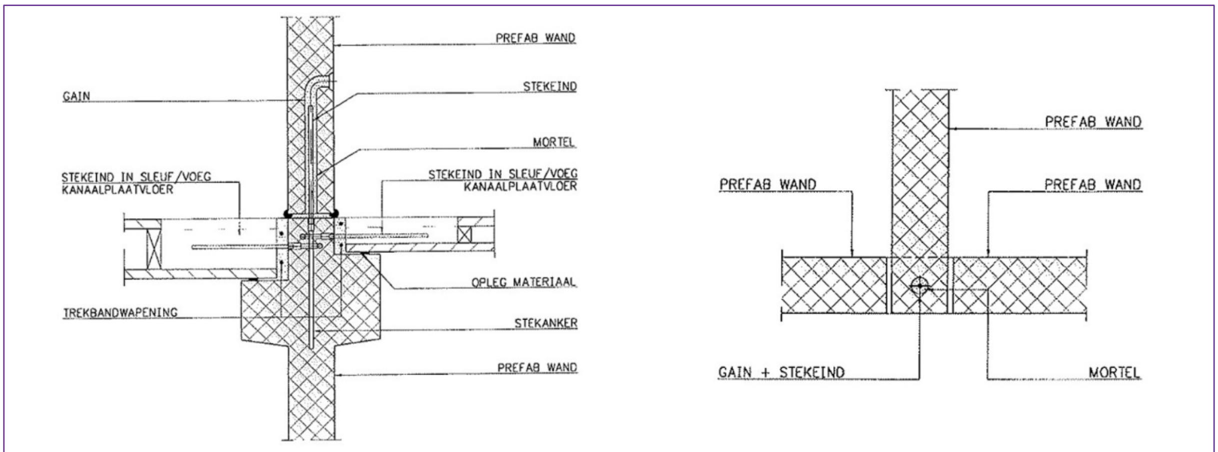

Figure 10. Typical detailing of structural connections (Belton, 2001).

For the reuse of precast concrete elements, information is needed about the elements themselves, the connections between them and other structures, and the overall location and role of the elements within the structure. Figure 10 shows the typical detailing of precast concrete connections, while Figure 11 shows a typical elevation drawing, and Figure 12 is a shop drawing of one precast element.

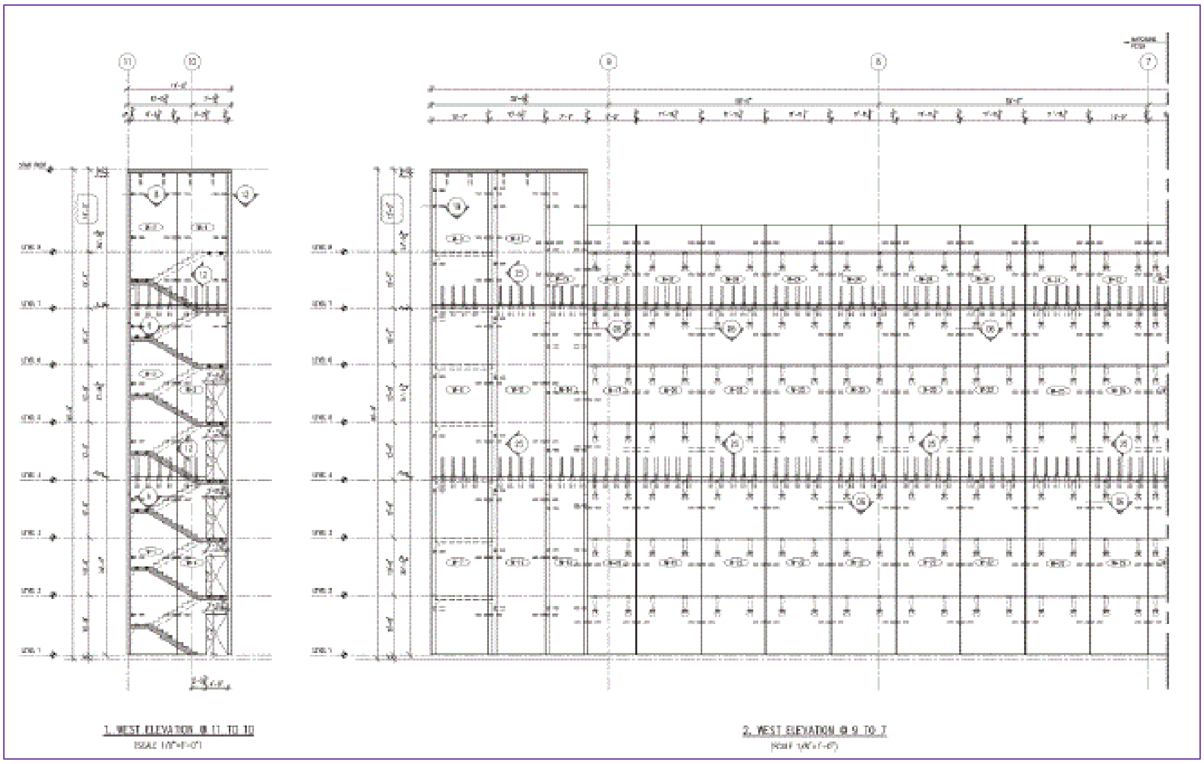

Figure 11. Typical elevation drawing for the erection of a building with a precast frame.

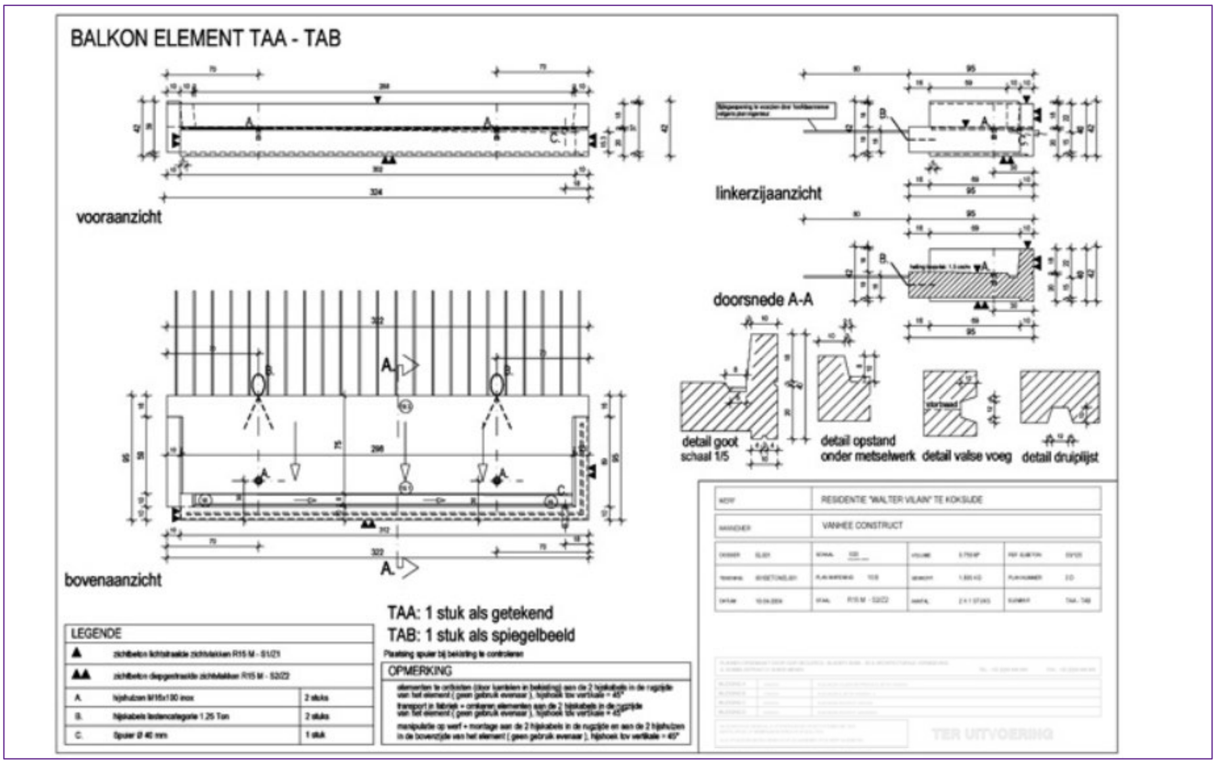

Figure 12. A typical shop drawing of a precast element, in this case, a balcony.

These documents, i.e. the elevation, floor plans, detailing and shop drawings contain, in principle, all the structural information of the precast concrete elements needed for the deconstruction planning of the donor building. They also contain some of the information needed for the design of a new building and reassembling the new building structure with the salvaged precast concrete elements, where the original connections can be reused (this is not always the case).

The precast concrete engineer is responsible for this type of drawings and information. For production purposes, the manufacturer of the precast concrete elements also has these drawings. The main structural engineer of the building generally is also in posession of these drawings, because they will check them during the engineering and construction phase of the project. The main structural engineer plays no part in generating these type of drawings, unless the main structural engineer is also the precast concrete engineer. Municipality will also review these drawings as a part of the building permit process.

As mentioned, the drawings may be available on paper (in A4, A3, A1 and A0 formats), microfilms, digitised formats (tif/pdf), or as digital 2D CAD drawings. From the 2000s onwards, BIM became more commonly used in structural design and manufacturing processes of precast concrete elements, so BIM models may be readily found only for relatively new buildings.

Best practice recommendation

Typically, the available information on buildings and structures is diverse and fragmented. It can be archived at different locations, incomplete and/or not up to date. Therefore, verification of the collected information is essential to determine the reliability and completeness thereof. Verification can be done by using different sources (archives) and always should include a visual inspection of the building. Several digital scanning techniques (such as 3D scanning) can also be help to verify the accuracy of the information collected through archival research (see the next section).

3. In-situ inspection

3.1. General approach

A visual inspection of the building and its structure can give a lot of information on the general state of the structure and gives a good indication of the reliability of the available technical information. By comparing the technical information from the drawings and the specifications with the building itself, it is relatively easy for a seasoned structural engineer to determine if they are consistent, if changes to the building have been made, and what the condition of the building and the elements are.

A visual inspection is also suited for collecting additional information about the general quality of the precast elements with regard to possible damage, cracking and/or degradation. This is discussed more in Chapter 5 and ReCreate's work package (WP) 4. Obviously, this information is not available in the drawings and specifications. It can only be obtained via an inspection or from previous damage and condition assessment reports, if any exist and are not too old to risk being outdated.

During a visual inspection, several methods and techniques can be utilised to collect data on the building, its structure, the precast elements, and the detailing of the structure and elements. An overview of different aspects of a visual inspection of a building is given next.

3.1.1. Visual inspection

The main goal of a visual inspection of the building is to verify the accuracy of the information collected in the archival research phase. This can be done by comparing the drawings with the building and by determining if the drawings are a good match. A visual review of the building can help to detect the most obvious changes that may have been made to the building as well as their extent. Simple measurements of the dimensions of the elements can also increase confidence in the archived data.

Aspects that can be viewed, surveyed, measured and scanned during an inspection are:

1. The general condition of the building, the structure and parts of the structure.
2. Verification of the available information on the structure and precast concrete elements.
3. The presence of visual degradation/damage in the structure and elements.[1]

[1] Reinforced concrete structures often have degradation/damage that is not detectable to the naked eye. A visual inspection is therefore not sufficient to determine the condition. A condition investigation with laboratory tests of material samples is needed (see WP 4).

4. Type of (structural) connections used in the structure (if visible).
5. General dimensions of the structure and elements. These can be verified by measuring them.

Figure 13 gives tools that can assist during the visual inspection, with measuring and scanning of the visible part of the building. Simple techniques can be used for measuring elements during a visual inspection of the building, such as a measuring tape, theodolite and total station. There is also equipment available that can help with visual inspections in locations that are otherwise not accessible, outside or inside of the building, such as an aerial platform or a façade wash system (Figure 14).

Figure 13. From left to right: measuring tape / ruler, theodolite, total station.

Figure 14. Aerial platform (left) and a façade wash system (right).

As a result, the first indications can be obtained of which precast elements may be suitable for reuse and how the deconstruction process can be expected to be like.

Best practice recommendation

When performing a visual inspection of a building, use copies of drawings to make notes and mark the elements that are measured or otherwise inspected. This technique should also be used for marking elements and locations that were photographed (see next section).

3.1.2. Photography and digital scanning

Photography

One of the simplest ways of collecting data during an in-situ inspection of a building is the use of digital photographing and digital video. This process is very accessible simply by using a smartphone and can be very valuable in providing extra information after the inspection. It can support the assessment of the structure and elements.

Digital pictures and videos of the building can also be very helpful in other ways. There are comprehensive digital techniques, such as photogrammetry, which can generate 3D data from 2D images and video. Software of this type include Agisoft Photoscan, Regard3D and VisualSfM, among others. These software packages can generate 3D models which can be used in 3D BIM modelling tools. The 3D models also can be used for 3D printing.

Machine learning capabilities for detection of cracking can be modified to detect other properties and geometrical information of precast concrete elements. Asset Hub (en.assethub.nl) has developed this for masonry structures, and this technique could also be extended to concrete structures.

As mentioned, a smartphone provides the lowest-threshold access to photo and video documentation. High quality cameras can be very small and therefore easy to mount on a drone. Drones can also access parts of the building which are otherwise inaccessible (Figure 15).

Figure 15. Photo and video cameras on a tripod or a drone.

3D scanning

Photographs can help with determining geometrical properties of the building and precast concrete elements. This technique is quickly evolving and becoming more accurate every year.

Another technique for getting geometrical data of a building is the use of 3D scanners. Light detection and ranging (LIDAR) is a method for determining ranges (variable distances) by targeting an object or surface with a laser and measuring the time for the reflected light to return to the scanner. Special 3D scanners can scan many points on a surface almost instantaneously and the result is a very dense point pattern, a so-called point cloud. See Figure 16 for apparatus, and Figure 17 for the results of a 3D Scanning of the Dutch donor building.

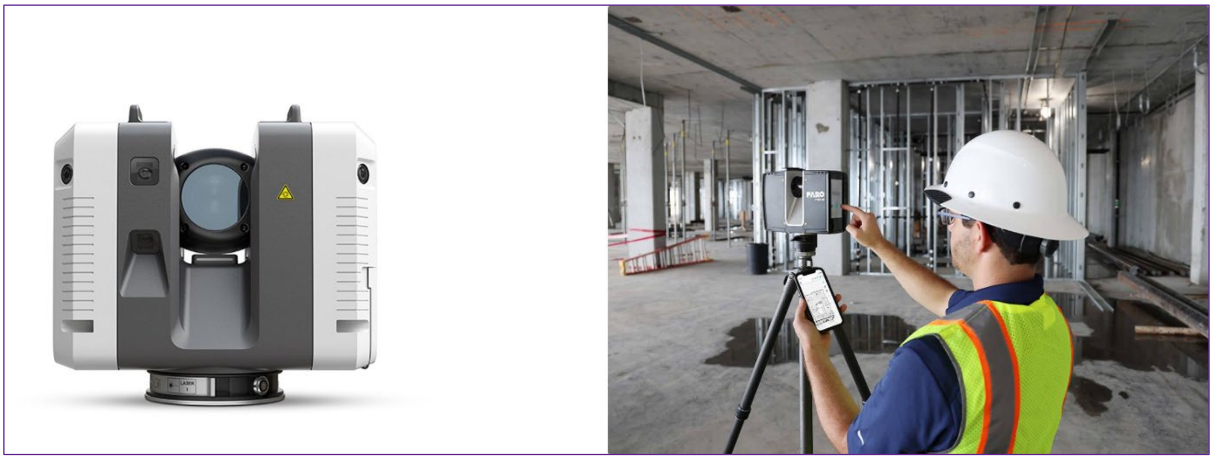

Figure 16. 3D scanners, stationary (left) and portable (right).

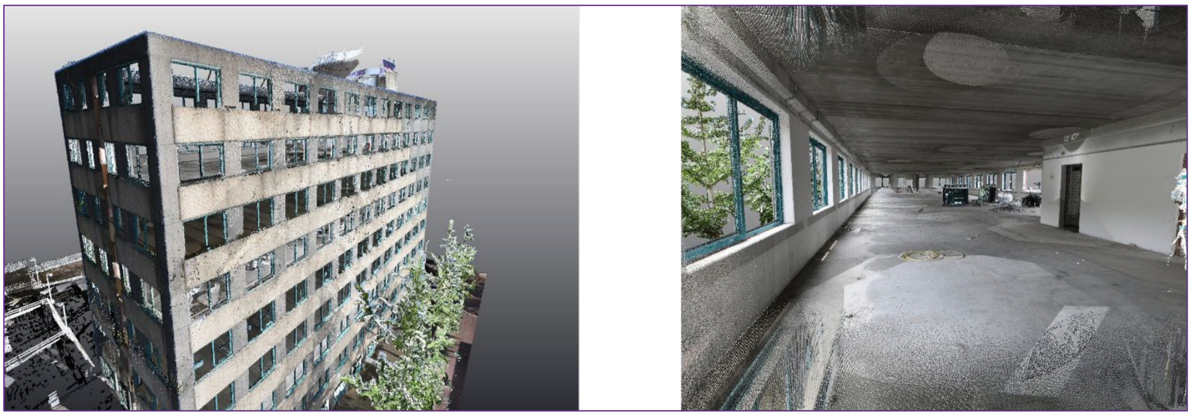

Figure 17. Point clouds of Prinsenhof (Arnhem, Netherlands), exterior (left) and interior (right).

Special software can use point cloud data to generate 3D models of a building. The 3D models can be used in 3D modelling software like Revit (Autodesk), which makes it easy to collect geometrical data of the visible parts of the precast concrete elements.

The 3D scanners can detect surfaces with light, but cannot penetrate items or elements. So, the interior of a structure or a part of a structure covered by other structures or materials are not visible for the 3D lidar scanner.

Best practice recommendation

In order to get good data of the structure of the precast concrete elements, it is imperative that all non-structural elements like (architectural) finishes are removed before making the 3D scan (Figure 18). These finishes entail ceiling tiles, tiling, wallpaper, moulding, wall panels, wooden finishes etc. The bare structure of the building must be visible in order to get the best results from a 3D scan.

Even so, the 3D models generated from such point clouds will still only show the visible part of the structure. For example, the connective parts of elements are typically covered by the adjoining elements. A 3D model of the building based on the point cloud is therefore not complete but additional information is needed.

Figure 18. The Dutch donor building. All the finishes have been removed, only the structure of the building is visible and can be scanned

3.1.3. Simple in-situ testing

For the structural design of the new building with the reused concrete elements, all relevant structural information needs to be collected or when not available to be determined. Obviously, collecting available information is easier than determining new data, however the collected data have to be reliable as well. Structural information can be collected from the specifications, (shop) drawings and/or in the original structural calculation reports of an element. There are two reasons to investigate the information from the structural calculations:

1. To verify if the information on the (shop) drawings or in the original reports is correct.
2. To determine the correct information, because the information is missing from the collected data.

ReCreate dedicates another work package (WP 4) for the determination of structural and material properties and the presence of degradation or damage, which is necessary information for structural calculations. However, this issue is mentioned here because during a visual inspection visit, it is possible to do certain simple tests to retrieve preliminary information that can help verify parameters obtained from the drawings or other original documents.

<u>Concrete cracking</u>

Concrete elements can exhibit cracking due to loading. Cracking can influence the durability of a concrete element. Therefore, the presence of cracking in elements planned for reuse needs to be determined. Measurements of the crack width (Figure 19) can result in any of the following conclusions, but this depends on the intended use and the exposure class that the element will be subjected to:

- It is not an issue when reusing the concrete element in the new building.
- It is an issue and the concrete element cannot be used in the new building.
- The crack width is measured and it is within limits, the element can be reused.
- The crack width is measured and it is just outside of limits and repairs can be done so that the element can be reused.
- The crack width is measured and it is outside the limits. Repairs are not helpful; the element cannot be reused.

When cracking is detected during an inspection, a simple crack width measurement can point out quickly the directions for reuse.

Figure 19. In-situ testing from left to right: crack width measurement, Schmidt hammer testing and cover depth measurement.

<u>Compression strength</u>

The compression strength of the concrete of the precast elements can be determined with a simple Schmidt hammer test. This non-destructive, indirect test can give a good indication of the compression strength. However, it should be noted that the Schmidt hammer test *per se* cannot be more than an indication.

This method can be useful to verify the compression strength indicated in the drawings. If no information is available in drawings, the test can give a good indication of the compression strength of the concrete. Together with a direct destructive compression test on cylinder core samples drilled from the concrete element and tested according EN 13791 (CEN, 2019), it provides a reliable result for the compression strength of the concrete of the elements. This is depicted in more detail in the outputs of ReCreate's WP 4.

The correct compression strength(s) can be used in structural verification of the concrete elements when applied in a new structure.

Concrete cover depth

The cover depth of concrete over the reinforcement plays a role in the durability of the concrete elements. It is also relevant for the structural analysis of the elements. The cover depth is indicated on shop drawings of the precast concrete element in question and in the original calculation reports of the elements. Measurements can verify the reported cover depth. If the cover depth is not known, it must be determined. This simple test can be done during a visual inspection of the elements (Selek, 2017).

Best practice recommendation

Incorporate simple non-destructive in-situ testing of elements, such as crack width measurement, Schmidt hammer testing and concrete cover depth measurements, to the building's visual inspection visit(s) to obtain preliminary information on structural and material properties.

4. Digital twin of donor building

The information of the precast concrete elements available in the donor building needs to be entered and categorized into a database. This becomes more obvious when more donor buildings are deconstructed and more elements become available for reuse in future buildings. The use of a digital twin, i.e. a 3D BIM model, as a database containing all information of the donor buildings and the precast concrete elements has many advantages, which as discussed in more detail in the next sections. In brief, this information is needed when a new building is designed with the reused precast concrete elements.

Another advantage of generating 3D BIM model of a donor building is its use during the deconstruction process of the donor building. By making a 3D BIM model of the donor building, this 3D model becomes a digital twin which can be used for different purposes, such as:

- Determining the best deconstruction order by modeling the disassembly sequence. In this way, quick insight is gained whether there are any potential problems during disassembly. These problems can be easily fixed behind the computer.
- Structural and human safety can be tested with a digital twin. Measures can be determined for unsafe situations before the unsafe situations even can occur on the construction site.
- A digital twin can support the structural engineer in preparing structural calculations required to obtain a demolition permit.
- With the digital twin, connections between different precast concrete elements can be considered to determine the right technique for the deconstruction, such as the orientation of a saw cut.
- The digital twin also allows for the development of disassembly and lifting techniques based on element preservation and safety. For the development of new tools and attachments, the digital twin can also provide assistance.

The digital twin contributes greatly to the preparation of a safe and efficient deconstruction plan for a donor building. A deconstruction plan is necessary not only for deconstruction efficiency, methodology and safety, but also for obtaining the necessary permits.

4.1. General approach

A Building Information Model (BIM) is a digital representation of a physical building in a 3D graphical environment, a 3D digital model (Figure 20), which can be created with various technologies. The 3D model visualises the 3D geometrical shape of elements, of a complete building and of the precast concrete elements in all its parts.

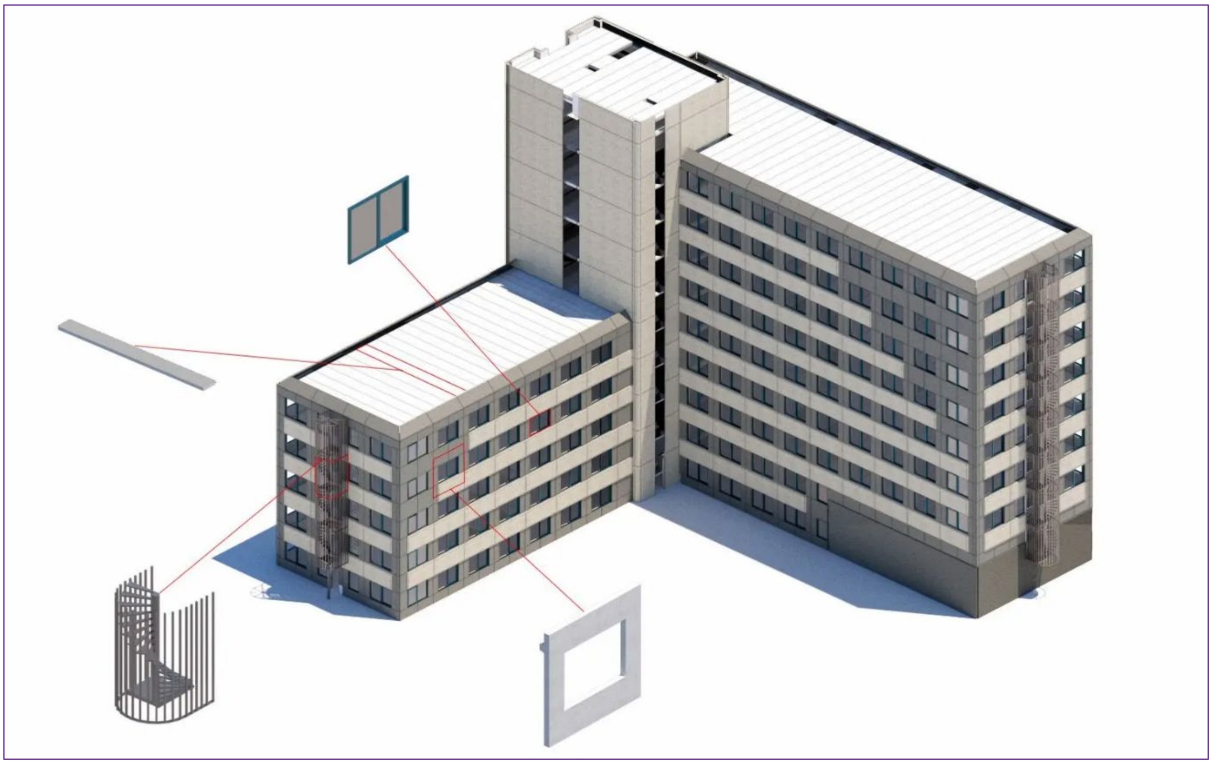

Figure 20. A complete 3D BIM model of Prinsenhof (Arnhem, Netherlands).

3D modelling software can be used to create and generate 3D models. If necessary, parts of the model can be parametric. Several 3D modelling software packages can be used, such as:

- Revit (Autodesk)
- ArchiCAD (Graphisoft)
- Tekla (Trimble)
- Allplan (Nemetschek)
- Solidworks (Dassault systems)

There are also special viewers available to view 3D BIM models, such as BIMcollab. These viewers are based on the universal file format called IFC. This is an open-source format which is commonly used in 3D BIM environments.

Special software is available to perform specific functions on 3D BIM models, such as Solibri. Solibri can generate all kinds of information based on the data within a 3D BIM model. One of the most advanced functions is clash detection in which it can detect if parts of the 3D model are colliding with each other (Figure 21 and Figure 22).

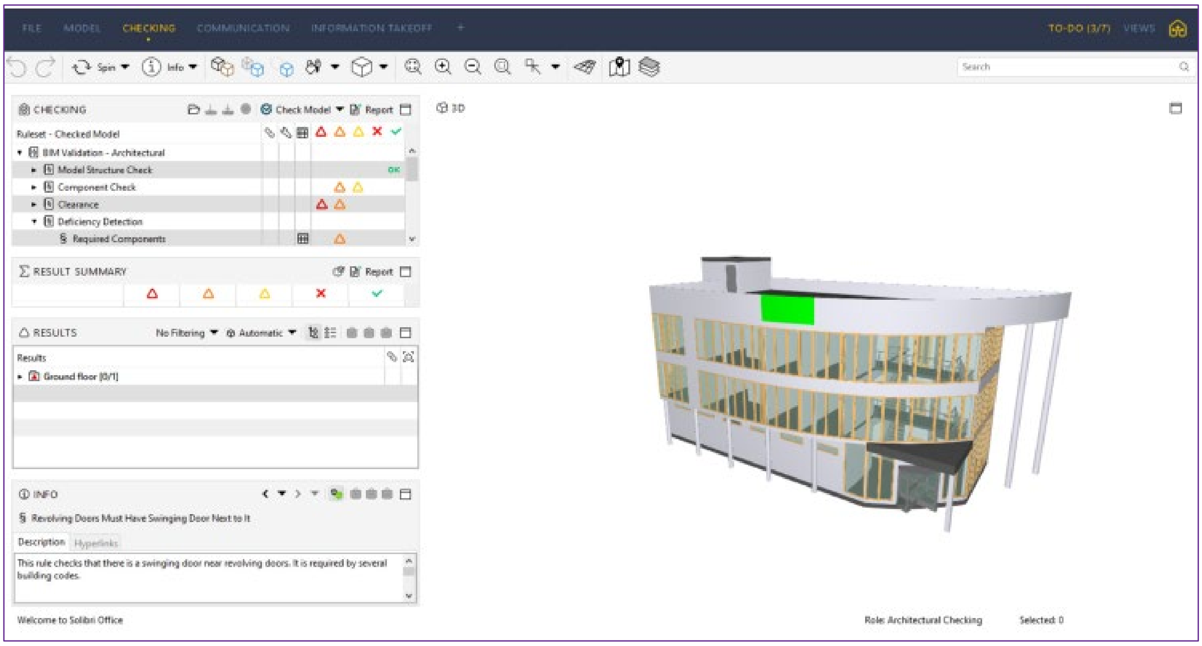

Figure 21. View of the Solibri software (Solibri, 2010).

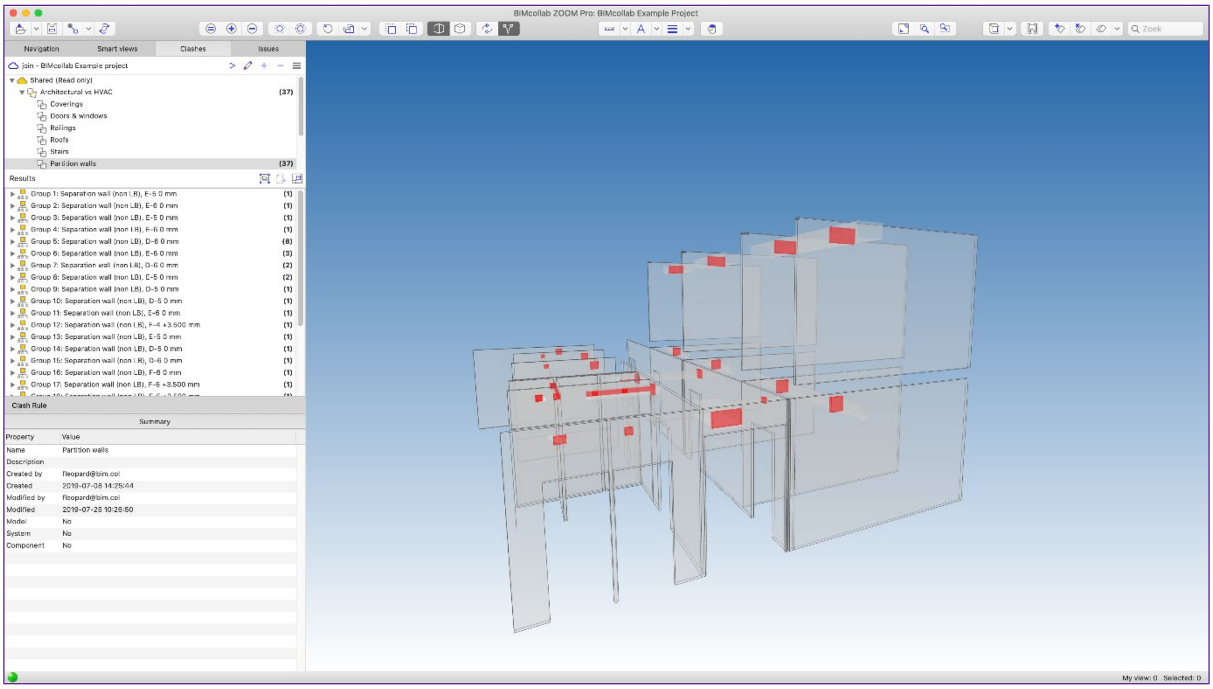

Figure 22. View of the BIMcollab software.

Representing building models in 3D is one of the main features of BIM modelling. Another feature is the possibility to combine this with adding information to the BIM model, or to each separate element in the model. This information can be generated by the 3D modelling software itself, like the volume and weight of each part of the model. Information can also be added to the model on different scales. For the building itself, information about its location, address etc. can be included in the 3D BIM model. At the element level, information about e.g. concrete compression strength or the quality of the steel (reinforcement) used in the element can be added. Special BIM viewers make all the information accessible and visible. For example, by hiding all the precast concrete elements, but only showing the elements with a certain compression strength, the user gets a visual overview of the result. This is much easier to analyse than looking through a spreadsheet, which the programme will also help to generate though. In BIM models for new structures, also the reinforcement that should be applied in the element is described in the BIM model. Also photographs and other documents (e.g. pdfs) with all kinds of information can be added to the distinct parts of the 3D BIM model.

Different kinds of software can utilise the information in 3D BIM models. Figure 23 shows the combination of a 3D BIM model with a Gantt chart of the building process over time. Each step of the building process is shown by the software, in which each element is added to the building at a certain point in time.

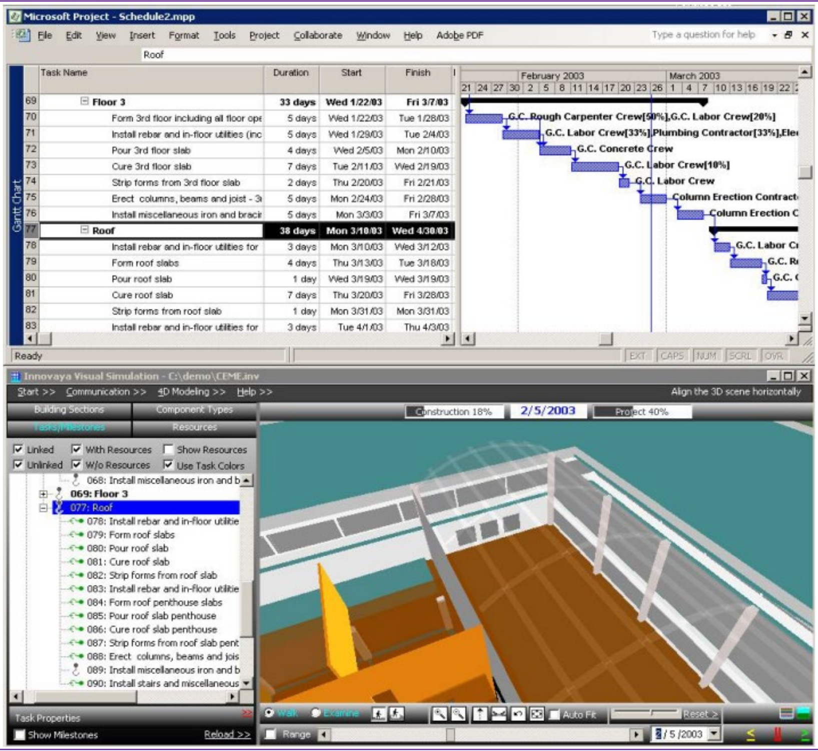

Figure 23. 3D BIM models combined with MS Projects (Autodesk, 2007)

Special software can also e.g. generate 3D BIM models from point clouds, or make structural calculations of the elements in the model.

This combination of 3D representation of physical elements and the use of information and special software makes BIM models very powerful and ideal for use in the process of reuse of precast concrete elements in new buildings. For this the BIM model should be created and filled with information during the audit process. And this should be updated and extended in the complete process of deconstruction and re-construction of a new building.

4. 2. Database of elements

3D BIM modelling software and 3D models can be used as a database of information on all precast concrete elements for reuse purposes. By modelling all the concrete elements, all the data of the elements is entered into a database in a visual way. This has several advantages:

- Visual 3D information is very easy to interpret and to check.
- Every kind of information can be added to each separate element and, with viewers, the user can easily access this information.
- Additional information can be added automatically, e.g. the volume or weight of an element.
- By modelling all the elements, visual checks can be made to increase the accuracy of the data. Automated checks, such as collision detection or comparison of the model with the point cloud of a 3D scan can be added to assist and provide an even higher level of accuracy of the information.
- A 3D BIM model can assist in the deconstruction process of the building, by reversing the logical building process of the building. The order of removing elements from the building can be visualised. This can be done in combination with planning software like MS Projects.
- A 3D BIM model can be combined with structural Finite Element Method (FEM) software to assist the structural engineer with structural analysis of the building during deconstruction and with the design of a new building with reused elements.
- The use of an open-source file format (IFC and IFC XML) makes it more flexible and accessible across different software platforms (also in the future).
- Easy to find certain elements and visualise the results. This makes the information in the database very accessible.
- The accuracy of the collected information can be checked with the help of a 3D BIM model. Special software like Solibri can be very helpful.

Because the use of BIM models is rather new, it is very likely that a 3D BIM model is not available of the donor building. Therefore, a new 3D model should be created based on all the collected information. Depending on the size of the building this can take 6 to 12 weeks. This also depends on the level of detail (LOD, Figure 24) used in the 3D Model. However, the extra effort to make the 3D BIM model will result in many benefits, as highlighted in the list above. It is one of the best ways to combine all the collected information (drawings, reports, photographs, test results, etc.) in one collective database.

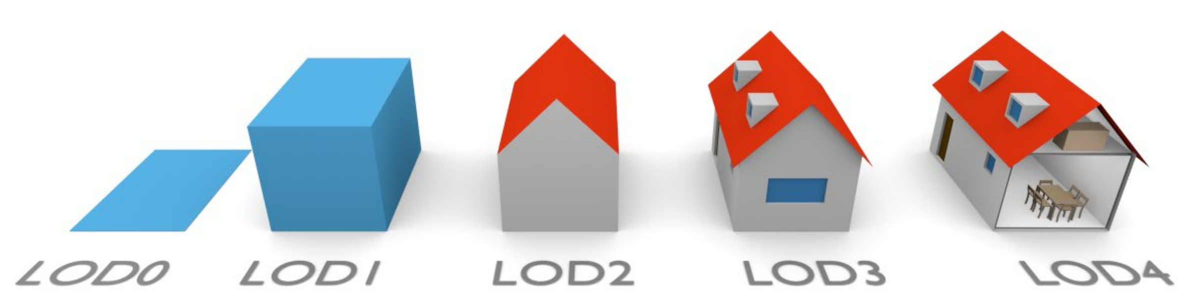

Figure 24. The level of detail from LOD0 to LOD4 (Biljecki, 2016).

4. 3. Evaluation of geometry

A 3D BIM model is very helpful with evaluating the geometry of the building and the separate precast concrete elements. The evaluation of the geometry can be used in different situations:

1. In the pre-deconstruction audit phase, when developing a 3D BIM model, checks can be performed on the digital model to verify the dimensions of precast concrete elements. This can be done by visually inspecting the 3D model and by using special software (e.g. Solibri) for collision detection. Together with the in-situ measurements, the checks will provide extra reliability of the collected geometrical information.
2. In the design phase of a new building, 3D models of the reused precast elements can be added into the model of the new building to construct digitally the new structure of the building. Evaluating the geometry is an important part of the design process, e.g. whether the elements connect correctly with each other.
3. Evaluating connections between elements and analysing possible deviations; not only with regard to the geometry of the elements and other parts within the connections, but also if ties are lined up between two elements.
4. Evaluating certain type of data (e.g. particular types of elements) in the 3D model and making it visible by highlighting elements in the model.

Evaluating the 3D model, the geometry of the elements and the (new) building the reliability of the model increases and therefore, so does the reliability of the 3D models of the elements themselves and that of the database. The reliability of the database is very important when the database contains elements from several donor buildings and if more than one designer uses the database.

4. 4. Incorporating additional information

Additional non-geometrical data can be added to the 3D BIM model, such as the test results of in-situ and/or laboratory testing, and the labelling that will be applied to the element in order to trace it later on through the logistics process.

In the Dutch pilot project for example, the extra information added to the data was an R-value related to the R-ladder (see Figure 25). According to the R-ladder strategy the reuse of elements can be prioritised and can help to make a decision based on environmental impact. A high R-ladder score means less impact on the environment.

The R-value was determined during a visual inspection of the donor building. It was based on several criteria and can depend on the situation. The value can be incorporated into the 3D BIM model and can give a quick overview of which elements are planned for reuse, which elements need to be refurbished and which elements cannot be used and will be shredded.

One of the criteria for determining the R-value is the new building itself and whether or not an element can be reused within the new building If a new building is not available, the determination of the R-value may have a different outcome. This also means that the initial assessment of the R-value during the visual inspection of the donor building can change when new information becomes available. This process is easy within the 3D BIM model.

Other types of information which can be added to the 3D BIM model include:

- Whether an element need to be refurbished in order to comply with current regulations. The needed refurbishments can be included in the BIM model.
- Whether an element need to be repaired. The needed repairs can be added to the information in the model.
- The location of the donor building, the storage of the elements and the new building. This information can be used to calculate (extra) transport costs and the additional impact on the environment.
- Etc.

The added extra information must assist in the process of reusing the precast concrete elements. The benefits can be technical but also deal with certain aspects of the reuse process, such as planning, budget estimates etc. The type of information to incorporate depends on the use case and if the extra effort results in benefits for the project. If the additional information can be used later on in e.g. the reuse process, or making a database of elements available in the urban mine, this might be worthwhile. Machine learning and automation can help make this process more cost-efficient.

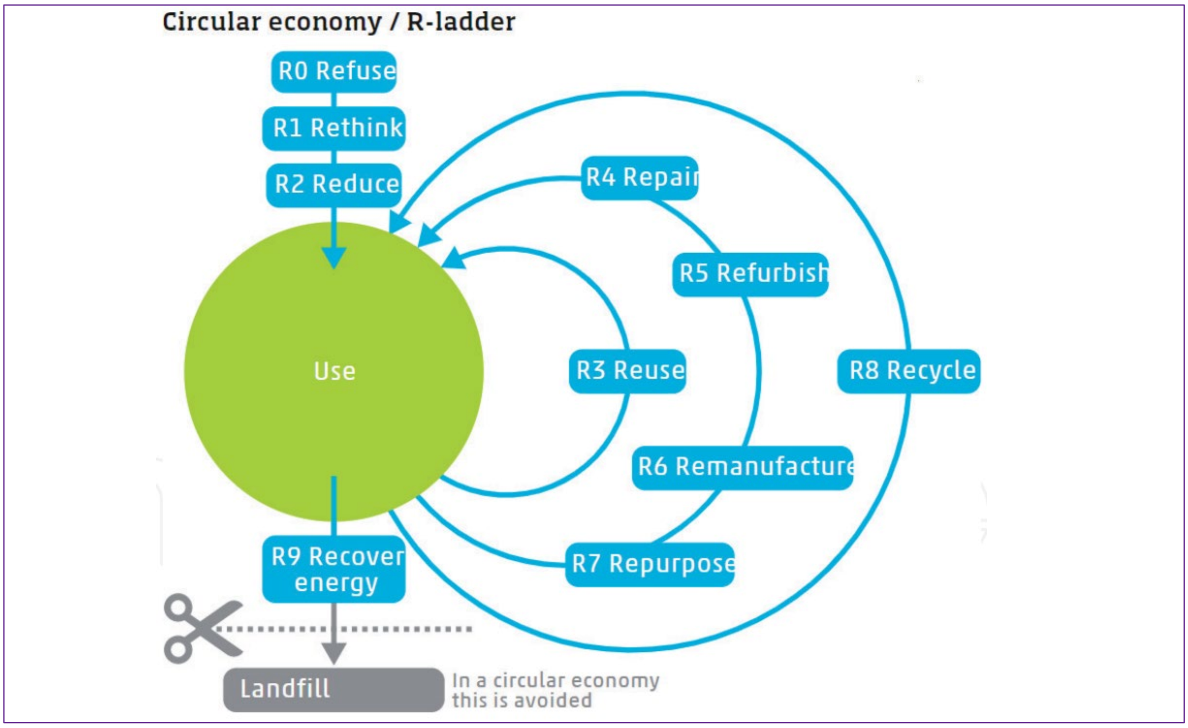

Figure 25. The R-ladder as used by Lagemaat in the Dutch deconstruction pilot (Minguez, 2021)..

4. 5. Phases of the BIM model

The 3D BIM model is generated in several phases. The first phase is the start of the 3D model and this represents all the information collected from several archives and other information sources, like the internet. An exploratory viewing of the donor building could be a part of the first phase. The level of detailing and extra information depends on the amount and quality of the available information. During modelling, the missing (geometrical) data will emerge and a can be listed in an overview. After the first preliminary model is completed and the list of missing data is compiled, phase two can start.

Phase two consists of collecting the missing data for the 3D BIM model of a donor building. The missing data is listed in an overview generated in the previous phase. This missing information is collected during a visual inspection of the building. During this visual inspection extra information can be generated by (on-site) testing, scanning and measurements as well. In this phase, not only the list with missing data is helpful but some simple drawings (floor plans, elevations and details) can assist with the gathering of information. The drawings can clarify items in the list of missing information. Notes can be added to the list and drawings. Photographs and video can be added to the new information. The drawings can be automatically generated from the preliminary 3D model (phase one).

Phase three is the final phase in generating a 3D BIM model during the audit phase. It is implementing the missing data from phase two into the preliminary 3D model (phase one). After completion, the 3D BIM model represents all the information. Model and geometry checking (collision detection, etc.) is included in phase one and three. If at some point new missing data emerges, the data collecting step of phase two can be repeated until a final model is completed, including all the addition information like material properties, test results, photographs etc.

4. 6. Software applications and file formats

There is a wide range of software packages which can create 3D BIM models (see Section 7.1). Most commonly used software packages are Revit (Autodesk), Tekla (Trimble), ArchiCAD (Graphisoft) and Allplan (Nemetschek). New applications are still developed and the functionality of these applications is improving regularly. Other types of applications also incorporate 3D BIM modelling capabilities, such as visual programming applications Grasshopper and Dynamo (Revit). Plugins, too, are developed for a wide range of applications. Plugins such as Blender (www.blender.org) and Lumion (www.lumion.com) are not normally used for 3D BIM modelling but can provide a wide range of extra functionalities, such as complex 3D visualisations (Figure 26).

Which application is used for 3D modelling of the donor building and the precast concrete elements is not restricted. The functionality of all commonly used applications is fair for this purpose. They all can provide readable IFC data. The interaction between all kinds of applications is nowadays good, too. There are some differences, but they are more focused on functionality and ease of use.

3D modelling software can produce and support different types of general, interchangeable formats (Table 1). The software packages also have their custom, proprietary file formats with file extensions such as .UEL for Tekla, .rtf for Revit and .ndw. However, the proprietary file formats typically are not interchangeable between software packages. The official general file formats are usable for 3D BIM model databases. These databases can be relational and easily can be queried and maintained. SQL (Structured Query Language) can be used for querying data in the 3D BIM database.

The general file formats are also used by digital tools, such as Solibri for collision detection and other functions. Additional desired functionality can also be achieved by developing plugins using programming languages, such as Java, C, C++, etc. For this, it is recommended to consider programming languages with SQL capabilities.

Figure 26. Visualisation of 3D models with Lumion and Blender.

Table 1. Official general file formats for 3D BIM models.

1.	STEP Physical File (SPF) with ".ifc" file extension This format is the most widely used format for IFC (Industry Foundation Classes) in practice. It is the most compact of the formats that can be read as text (ASCII file). IFC-SPF is based on the ISO standard (ISO 10303-21) for clear text representation of data models.
2.	Extensible Markup Language (XML) with ".ifcxml" file extension Extensible Markup Language (XML) provides enhanced readability and benefits from a broad range of software tools. ifcXML is based on the ISO standard for representation of STEP data in XML format (ISO 10303-28).
3.	ZIP with ".ifcZIP" file extension IFC data may be embedded within a compressed ZIP file. The embedded data may be encoded as either SPF or XML, where the resulting size is typically comparable.
4.	Terse RDF Triple Language (Turtle) with ".ttl" file extension ttl or ifcOWL provides a Web Ontology Language (OWL) representation of the IFC schema when using state-of-the-art web technologies for representing building data.
5.	JavaScript Object Notation (JSON) with ".json" file extension JSON provides enhanced readability and benefits from a broad range of software tools.
6.	Hierarchical Data Formats (HDF) with ".hdf" file extension HDF may store IFC data within hierarchical database, which provides high performance access to engineering data. HDF is based on the ISO standard (ISO 10303-26) for STEP data representation.

5. Connection to quality management procedures

Developing a reliable and robust quality management procedure for the deconstructed elements is the task of a dedicated work package, WP 4, in ReCreate, and it will produce specific deliverables about this topic. However, the quality management begins in the pre-deconstruction audit, which is why it is worthwhile to give a brief overview of the material and structural quality issues that need to be considered as a part of the audit.

5. 1. Basic structural qualities

During the pre-deconstruction phase, it is important to collect data on the shape, physical dimensions, possible damage and degradation of all elements. In case information is already available from archives, it is necessary to verify this information. In case no prior knowledge is available, this information should be determined during a visual inspection of the donor building and the precast concrete elements themselves.

Dimensions and shapes
For each precast concrete element, shop drawings are made which were used for the production of the element itself. These shop drawings contain the shape of the elements. Every little detail has a dimension in this type of drawings (Figure 27). The reinforcement of the element is often depicted in a separate drawing (Figure 28). Detail drawings of connections also provide information on the form of the elements.

These drawings can provide a good, reliable (after verification) and complete information about the precast concrete elements. If these drawings are not available, this information will have to be determined by other means, e.g. a visual inspection. Obviously, data acquired with these two methods will differ e.g. in the level of detail, because not everything is accessible in a visual inspection. Thus, the level of detail of the data will depend on the situation. A limited level of detail will have several consequences, such as:

- Extra time and effort is needed to get extra information.
- Less information translates directly into less (structural) reliability.
- The assessment of the elements for reuse purposes will be more difficult and will lead to more conservative results. The same can be said about structural analyses of the precast concrete elements.
- Less detailed information will result in less reliable 3D BIM models.

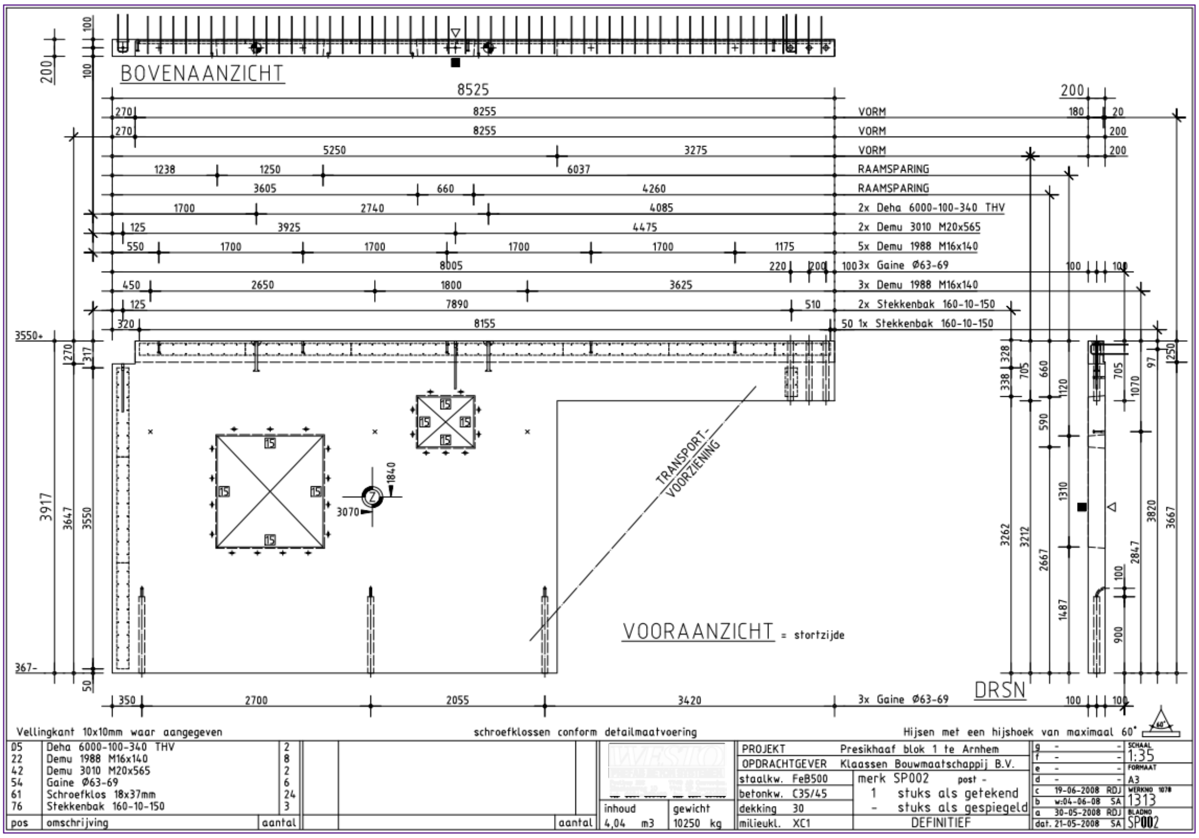

Figure 27. Shop drawing of a precast concrete wall, the shape of the element

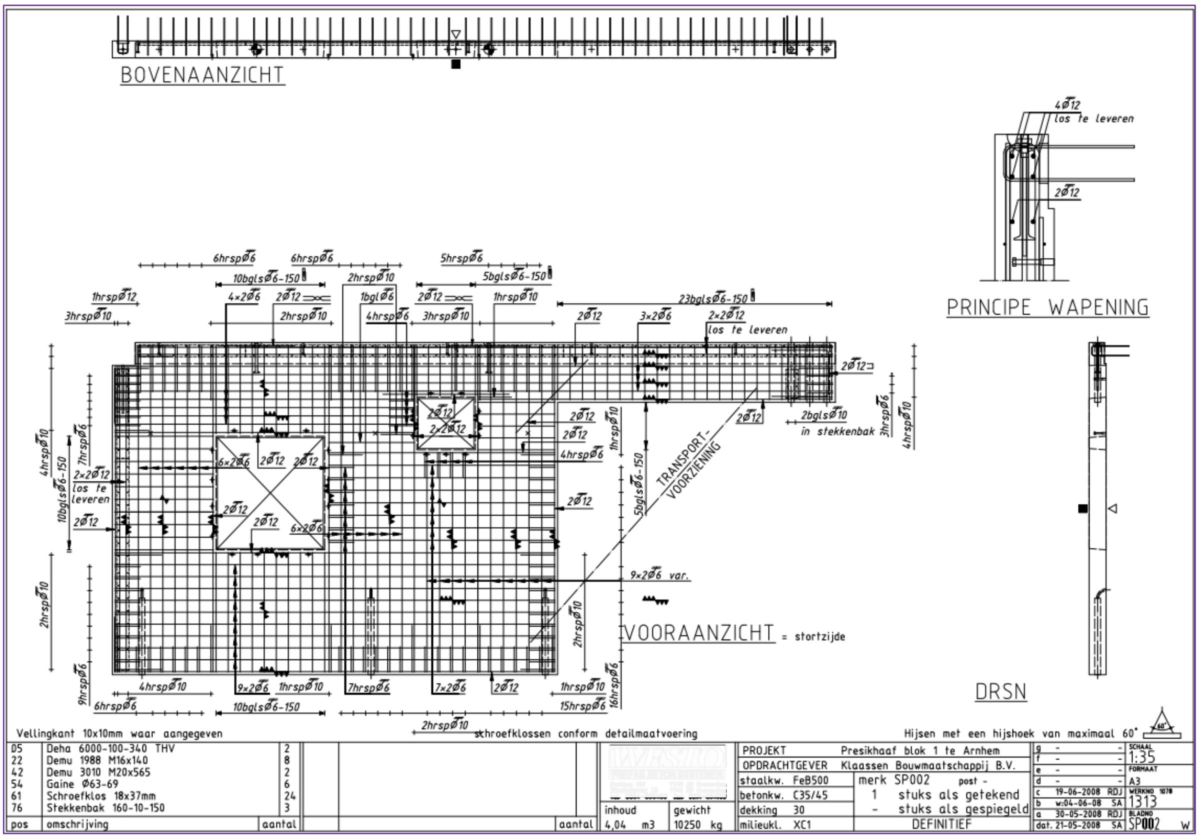

Figure 28. Shop drawing of a wall, including the dimensions of reinforcement.

The absence of information can ultimately lead to concrete elements becoming deemed not suitable for deconstruction. The minimum information required will be different for each situation. The pre-deconstruction audit should describe this situation and how to deal with it. Possible aspects could include:

- If information on concrete compression strength is missing and not verified by testing, take the lowest value for structural analyses and other considerations. This can also be applied to other material properties of concrete and steel (rebar).
- If only the main dimensions are known and no reinforcement information can be acquired reliably, reuse is only possible in non-structural applications.
- If the capacity of anchors in the concrete are not known and reuse of anchors is planned, only the lowest possible value can be used.
- If data is missing use tests to get additional information. E.g. test some concrete beams to determine the capacity of all equal-shaped beams. If a joint is unclear, do destructive testing on one joint. Etc.

These types of recommendations can be used in an audit plan. All this information must be included in the 3D BIM model, the element database. Information collected during a visual inspection is only possible when the donor building is still available. At some point the donor building will be deconstructed and all the precast concrete elements will go into storage. After a while the design of a new building will start. Depending on the case, this can be soon after the deconstruction of the donor building, or years later. The elements may come from different donor buildings. In all cases, it is necessary to have a reliable and complete database.

5. 2. Material properties and reinforcement

Material properties

The material properties of concrete and steel (rebar) need to be determined by testing. This is necessary for verification of available information or to determination of the properties if no information is available. In either case testing is necessary, only the number of tests may differ. Material properties that need to be verified are:

- Compression strength of the concrete (Chakiri, 2016).
- Yield strength and ultimate elongation of the rebar steel (CEN, 2005).

In general, normative tests must be used to determine these properties.

The number of tests can be done in accordance with the normative specifications. This includes also the correct statistical analyses. The number of tests will also depend on the specific situation, such as:

- Testing is only done for verification.

- A greater variance in test result will result in lower design values for tested properties. Extra tests can alter this.
- Destructive and non-destructive testing is possible for determining the material properties of concrete. Non-destructive methods are less reliable, therefore non-destructive testing is possible in combination with limited destructive testing. The number tests will depend on the reliability of the methods and the results.

A description of the test and the test results can/must be included in the 3D BIM model.

<u>Reinforcement</u>

Besides material properties of the rebar steel, the location, cover and diameters of the rebar in the elements need to be determined, for verification or determination of the reinforcement. For this several methods are available:

- Concrete cover detection (ferro scanner or ground-penetrating radar [GPR], non-destructive).
- Point detection of steel rebar in concrete (ferro scanner or GPR, non-destructive).
- Surface detection of steel rebar in concrete (ferro scanner or GPR, non-destructive).
- Removing the cover in order to see and measure the rebar (destructive).
- Breaking down (crushing) one or more elements to make the reinforcement visible and accessible for measuring (destructive).

GPR is an alternative to ferro scanners. Other methods may be available, but each of them have limitations in its use case. When using these types of apparatus, the correct use techniques are determined by the manufacturer. Often experience is needed in order to do these types of testing properly, including the interpretation of the results.

A description of the test and the test results can/must be included in the 3D BIM model.

<u>Capacity of elements</u>

In some situations, the only way to get sufficient information about the capacity of an element is by performing tests, such as a four-point-bending test, to determine the moment capacity of a beam.

These types of tests are complex and can only be done by specialized testing facilities by professionals. In this type of testing, the aspect of time and costs need to be considered.

A description of the test and the test results can/must be included in the 3D BIM model.

Best practice recommendation

Various testing must be done even if all the information on the building and each element is available. A minimum of testing is necessary for verification of some information, like material properties of concrete and rebar. These will be defined in more detail in ReCreate's WP 4.

A description of the tests and the test results can/must be added to the 3D BIM model. Each tested element in the BIM model needs to have this information and must be easily accessible, by simply clicking on an element in the 3D model. The information can be directly entered into the model, or be data (pdfs, photographs and/or video) linked to the corresponding element in the model.

5. 3. Damage and degradation

Degradation of concrete structures can occur in different ways, such as cracking, deformation, corrosion of reinforcement and subsequent spalling of concrete, freeze-thaw damage, alkali-aggregate reaction, etc. Specialized expertise on damage and degradation mechanisms is needed in the quality management procedure. A best practice recommendation will be provided in ReCreate's WP 4.

In the pre-deconstruction audit phase, all available information on existing damage and degradation, such as previous condition investigation reports, must be obtained and recorded. Other forms of this documentation can include descriptions of observations, results of tests and digital photos and/or videos.

A part of the information can be determined by inspecting the elements themselves, however in many cases the location of the elements and their surroundings can hold valuable information, too. This type of information is only assessable in the donor building itself. For example, if cracking is detected in several elements this can be examined on the elements themselves, but if the structural engineer needs to know the origin of the cracking, this can only be determined in the donor building. Labelling will help to trace back the original location of individual elements after deconstruction.

A detailed description of the damage and/or degradation can/must be added in the 3D BIM model.

5. 4. Preliminary evaluation of reusability

The aim of the pre-deconstruction audit process is to make a decision if a specific precast concrete element is worthwhile to deconstruct for reuse purposes. The decision will depend on a series of criteria. Some of the criteria pertain to the quality, as discussed above. However, the main criterion will always be whether the element fits in the new situation in the new design.

This main criterion will be different for each new situation, and the quality information is essential in determining it. For example, an element will have different requirements when it is reused as an ornament in a garden of a new building. When used in a building, the requirements will be more demanding when the element is reused as a part of a bracing shaft, i.e. a central core (shear wall) of the new building. The criteria will be very different from the reuse in a 'normal' (non-bracing) structural role. When the targeted reuse in the new building is known, the list of criteria can be made based on the type of the building and possible use cases. It can include very specific criteria for specific situations or it can be quite general. This will always depend on the situation, and it will be explored more in ReCreate's WP 5.

The archival research and visual inspection (Chapters 2 and 3) help to make a first assessment of the precast elements in the building to establish preliminarily which elements are most favourable to deconstruction. The non-destructive and destructive testing, part of the quality management procedure, will further help to determine if the deconstruction of an element worthwhile or not. These considerations and the decision should be recorded in a summary. This information can be included in the 3D BIM model.

6. Recommendations

This report has discussed the BIM-aided pre-deconstruction audit and how information obtained from this audit is handled. Experience with the pre-deconstruction audit work and the usefulness of information obtained from it in the later phases of the pilot projects show that producing BIM models based on the achieved information is useful. The BIM model not only helps to inventory the elements available for reuse, but the model can also be used in the design of the deconstruction process. In addition, the BIM objects of the precast elements can be extracted from the donor building's model and imported into the BIM model of the new building design.

Best practice recommendation

For the purpose of conducting a BIM-aided pre-deconstruction audit, the following procedure is recommended:

1. Gathering information such as specifications, drawings and calculations from the available and accessible archives.
2. Conducting an exploratory site observation whereby:
    a. assessing whether there are any discrepancies due to changed construction or alterations;
    b. missing dimensions are recorded and known dimensions are verified;
    c. checking for damage in the form of fracture, cracking or deterioration of material properties which could limit the possibility for reuse.
3. Preparing the first BIM model of the donor building.
4. Carrying out a further observation which is focused on how the structure is divided into in precast concrete elements and how these are connected. In this
    a. a verification of the geometry of the reinforcement in the elements;
    b. a verification of the material properties of both the concrete and the reinforcement steel;
    c. further inspections after damage in the elements;
    d. a verification after the way the several elements are connected.
5. Performing a 3D laser scan of the donor building and use the results to verify the BIM model of the donor building, if necessary.
6. Adding additional information to the BIM model such as:
    a. the distribution of the several elements over the structure;
    b. import of standardized precast elements in the model;
    c. create non-standardized precast elements in the model;
    d. adding a unique label to all the elements for tracing purposes;

e. adding material properties to the elements;
f. adding available data of the reinforcement to the elements;
g. adding available information on severe cracking, spalling and material deterioration.

It should be noted that this is an iterative process, so e.g. the archival drawings and the site (the building) must be revisited several times to complete the information.

7. References & further resources

7.1. References

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7. 2. Sources of figures

Figure	Description and source
1	"Finnish donor building" Photo Heikki Vuorinen
2	"One of the Swedish donor buildings during deconstruction" Photo Helsingborgshem
3	"German donor building" Photo Brandenburgische Technische Universitat Cottbus-Senftenberg
4	"Dutch donor building Prinsenhof" Photo Hergebruik kanaalplaten: meer dan een technische uitdaging (cementonline.nl)
5	"An overview of different types of precast concrete elements" Photos M. Vullings
6	"3D BIM model of different precast concrete elements" Figure M. Vullings
7	"Standard self-precast concrete products (lintels, wall copings, drip sills)" Hercules Betonlatei 60X100mm Sw, Met waterhol, Diverse lengtes allesvoorbouwen.nl Muurafdekkers mw | Bos Sierbeton (bosbeton.com) Betonnen raamdorpels uit eigen fabriek | JS Prefab Beton - JS Beton
8	"State of the Art of BIM adoption across Europe (May 2017)" Rabia Charef, 2019 (page 15)
9	"Typical architectural detailing of connections" Drawing Boom van, 2005 (page 150) and Wentzel, 2005 (page 283)
10	"Typical detailing of structural connections" Drawing Belton, 2001 (page 73 and 84)
11	"Typical elevation drawing for the erection of a building with precast frame" Drawing M. Vullings
12	"Typical shop drawing of a precast element, in this case a beam" Drawing M. Vullings
13	"From left to right: measuring tape / ruler, theodolite, total station" Photos HBM 100 m x 13 mm Fiberglass Meetband, Meetlint, Landmeter (hbm-machines.com) Theodoliet huren | Met afstandsmeter | Boels Total station verhuur | Voor professioneel gebruik | Boels
14	"Aerial platform (left) and a façade washing system (right)" Photos Elektrische schaarhoogwerker huren | Direct beschikbaar | Boels Pontsteiger Amsterdam | Ecotec BV Gevelliften
15	"Photo and video cameras on a tripod and a drone" Photo Façade Inspections Using Drones - The Constructor
16	"3D scanner, stationary (left) and portable (right)" Photos Mobile mapping | Momaso FARO Focus Laser Scanner| Hardware | FARO

Figure	Description and source
17	"Point clouds of Prinsenhof (Arnhem, Netherlands), exterior (left) and interior (right)" Photos E. de Bruin of Unite2Build
18	"The Dutch donor building. All the finishes have been removed, only the structure of the building is visible and can be scanned" Photos M. Vullings
19	"In-situ testing form left to right: crack width measurement, Schmidt hammer testing and cover depth measurement" NON- DESTRUCTIVE TESTING OF CONCRETE | NDT Inspection Connection
20	"A complete 3D BIM model of Prinsenhof (Arnhem, Netherlands) Model Hergebruik kanaalplaten: meer dan een technische uitdaging (cementonline.nl)
21	"View of the Solibri software" Figure Solibri, 2010 (page 11)
22	"View of the BIMcollab software" Figure Quick Start Guide BIMcollab ZOOM
23	"3D BIM models combined with MS Projects" Figure Autodesk, 2007 (page 4)
24	"The level of detail from LOD0 to LOD4" Figure Biljecki F. 2016 (page 2)
25	"The R-ladder as used by Lagemaat in the Dutch deconstruction pilot" Figure Minguez R, 2021 (page 20)
26	"Visualisation of 3D models with Lumion and Blender" Photos Architecture Rendering Tips, Stories and More | Lumion 10 Rendering Blog interior scenes | 3D Shaker
27	"Shop drawing of a precast concrete wall, the shape of the element" Drawing M. Vullings
28	"Shop drawing of a wall, including the dimensions of the reinforcement" Drawing M. Vullings

7. 3. Resources on BIM and related topics

General information on BIM and BIM modelling

1. www.designingbuildings.co.uk
2. www.buildingsmart.org
3. www.eubim.eu
4. www.bimportal.be (Dutch and French)
5. www.bimloket.nl (Dutch)
6. www.autodesk.nl

BIM data structures, e.g. Open IFC & IFC (Industry Foundation Classes)

1. www.buildingsmart.org
2. www.iso.org (ISO 16739-1:2018)
3. www.ifcwiki.org

3D BIM modelling software

1. Revit
2. Revizto
3. Navisworks
4. ArchiCAD
5. Vectorworks Architect
6. Midas Gen
7. Autodesk BIM 360
8. SketchUp
9. Buildertrend
10. Trimble Connect
11. BIMobject
12. Civel 3D
13. BricsCAD BIM
14. Sefaira
15. Hevacomp
16. Kreo
17. VisualARQ
18. The Wild
19. Allplan Archtecture
20. AECOsum Buidling Designer
21. ActCAD BIMBIMx
22. dRofus
23. Procore
24. ArCADia BIM 11
25. Tekla BIMsight

26. BEXEL Manager
27. PriMus IFC
28. IrisVR
29. Free BIM soloutions
30. Microstation
31. Edificius
32. Infurnia
33. Onshape

For up-to-date information, see https://revizto.com/en/best-bim-software-tools-2021/

3D BIM tools

1. www.bimcollab.com
2. www.solibri.com
3. www.bimvision.eu