oPEN Lab

TARTU PAMPLONA GENK

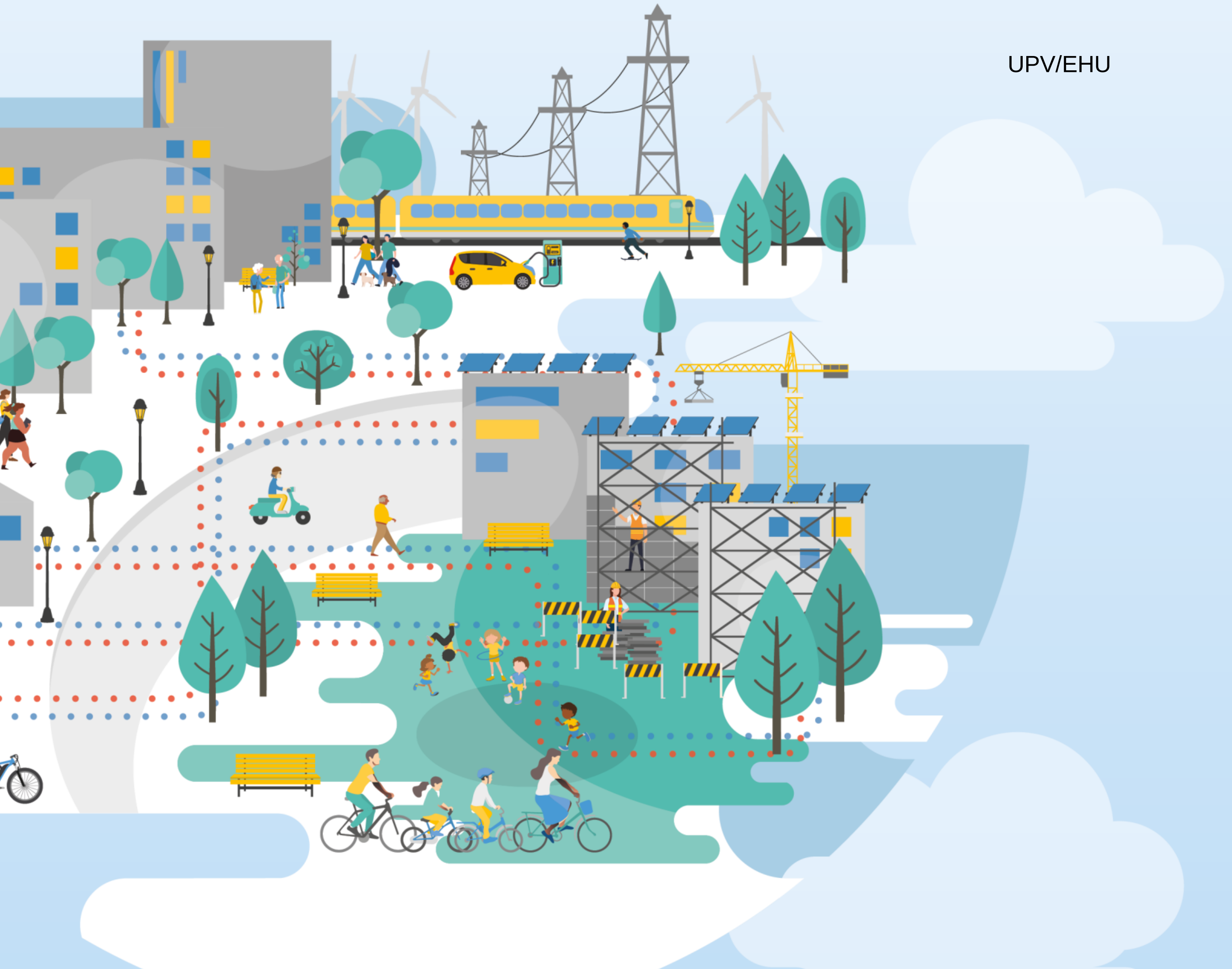
LEADING THE TRANSITION TO POSITIVE ENERGY NEIGHBOURHOODS

Optimization of the prefabrication process through digitalization

Deliverable 4.1

11/07/2023

UPV/EHU



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Abbreviations and Acronyms

Acronym	Description
BIM	Building Information Modelling / Management
CAD	Computer-aided design
CAM	Computer-aided manufacturing
LCA	Life cycle assessment
LCC	Life cycle cost
LOD	Level of development/detailing
GIS	Geographic Information System
BoM	Bill of Materials
BoQ	Bill of Quantities
ACs	Air Conditioning System
WMS	Web Map Service
WMTS	Web Map Tile Service
CNC	Computer Numerical Control
DSR	Design Science Research
IS	Information System
IFC	Industry Foundation Classes
CNC	Computer Numerical Control

Executive Summary

This report is the result of ongoing research work under the oPEN Lab project, with the main objective of optimizing the building renovation process through digitalization and focussing particularly on the prefabrication process.

As part of the Digital Twin developments, detailed geometric BIM models from existing buildings were available. This study focused on digitalizing the process, establishing seamless links between detailed laser scan data and computer-aided manufacturing (CAM) data. The main outcome of the work is a detailed workflow proposal named “optimized scenario: integrated renovation process” that allows for reducing time, resources, and environmental and economic impact in a renovation. The renovation workflow developed in this research work can be applied to different scale projects and prefabricated solutions, so it has a high degree of extrapolation and scalability.

The report includes a list of definitions and stakeholders that usually participate in building renovation. This can help to understand better the scope and the importance of the work done. The current knowledge and advances regarding digitalization in the prefabrication process and integration of digital software are collected in the state-of-the-art section, which might be used for further developments and studies. After carrying out a thorough analysis of a traditional renovation process named “Baseline scenario: traditional renovation process” some improvement opportunities are identified and applied to define an “improved scenario: integrated renovation process” that already integrates prefabrication concepts. This is further improved to achieve an “optimized scenario: Integrated renovation process” which is the main outcome of the work. A more detailed description of the three scenarios is described below:

- **Baseline scenario (traditional renovation process)**: a detailed analysis has permitted the identification of stakeholders, modelling tools, measuring tools, workflows, working methods, etc. involved in different project stages. Problems and improvement opportunities are detected mainly linked to duplicities, inaccuracies, and non- access to updated information on the project.
- **Improved scenario (industrialized renovation process)**: this scenario includes some of the improvement opportunities identified in the Baseline scenario analysis. The improved scenario already considers prefabrication and its benefits. The main improvement in this process is the introduction of automated production facilities and standardization. Problems and improvement opportunities are detected for further improvement mainly linked to digitalization. Hence, the role of CAD/CAM is discussed concerning the design and manufacturing of prefabricated modules.
- **Optimized scenario (Integrated renovation process)**: this scenario is the main result of this report and describes an integrated renovation process where all the stakeholders are involved from the early design stages. It includes relevant digital tools such as tools GIS, BIM, CAM, LCA, and LCC. BIM is the centralized source of information. Updated information and data of the project are accessible to all the stakeholders reducing duplicities and errors. Important time and cost reduction are achievable in this scenario aligned with OPEN Lab's main objectives.

The main outcome is a digitalized renovation workflow that has been tested in the three oPEN Lab Living Labs to make adjustments and gain accuracy. Recommendations for applying the integrated renovation process in the upcoming renovation works are provided. For evaluating and calculating the real impact in terms of time, cost, and environment, it is necessary to define Key Performance Indicators and evaluate the renovation of the three Living Labs. oPEN Lab is an ongoing project and the flowchart defined in this report will help achieve the main goals.

1 Introduction

Three scenarios related to prefabrication and digitalization have been studied: the traditional construction process, the industrialized construction process, and the integrated construction process. The study of the traditional renovation process (Chapter 4) and the integrated renovation process (Chapter 5) allows for highlighting the benefits, problems, and opportunities to develop the integrated renovation process (Chapter 6).

The third scenario, “optimized scenario: integrated renovation process” (Chapter 6), is considered optimal and the main outcome of the work. It has a digital flowchart based on prefabrication and digitalization that links from the point cloud to the CAM process to develop. The key benefits are characterized by being less time and cost-consuming in comparison to current renovation processes (see *Figure 1*). A higher quality level of the process outcomes is also achieved in the integrated renovation process.

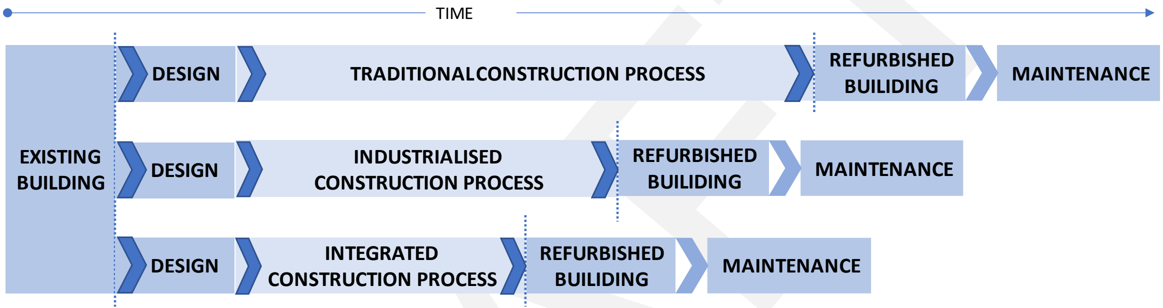


Figure 1. Comparative analysis between traditional construction process, industrialized construction process, and integrated construction process (listed from top to bottom), by authors, 2023. Copyright 2023 by oPEN Lab.

Finally, in this report, partial results of the testing of the optimized process in three case studies belonging to the three living labs of the Open Lab are presented, mainly at a prototype scale. At the finalization of this report, it has started the application and adaptation of the integrated renovation process to the renovation works of the three Living Labs.

1.1 Structure of the report

This document starts with an analysis of the state of the art. It follows with the objectives and the methodology pursued to achieve them. Then, the different scenarios considered in the research work (baseline, improved, and optimized) are described. It continues by describing the testing of the optimized scenario in three case studies. The document ends with the conclusions and suggestions.

1.2 Main challenge and application of the study

The main challenge of this study is to be able to define an optimized, replicable, and scalable digitalization workflow for renovation works, where all the stakeholders are involved from the early design stages and use relevant digital tools (from scan to CAM), achieving a reduction in time, resources, and both environmental and economic impacts.

For this purpose, this study incorporates data related to:

- The exploration of tools and data sources to enable seamless data integration in the design process and data exchange among stakeholders; and
- The obtained data using technologies such as laser scanner, LIDAR, BIM model, GIS, etc.

Regarding the scope of application of this study, the work executed will serve as input to feed the activities to be carried out in the planned research related to the improvement of the timing and working system of the off-site prefabrication and assembly process.

Finally, the results obtained during this task will provide information to define the Business As Usual (BAU) of the PENs, especially concerning the mapping to be done on how the innovative technologies and participatory processes applied can contribute to the implementation of the Renovation Wave strategy and to feed the oPEN Lab toolbox.

1.3 State of the art

In this chapter, a detailed analysis of the current context, definitions, and state-of-the-art knowledge is collected.

1.3.1 Definitions

1.3.1.1 Industrialization of Construction

Industrialization of construction involves the application of the best methods and technologies throughout the whole building process: design, manufacture, transport, assembly, use, maintenance, demolition, etc. Those methods imply a different and innovative way of thinking (Alaloul Wesam et al., 2018)

A building will not have a greater or lesser degree of industrialization depending on the level of perfection of its construction elements, but rather it will be the entire construction process that will establish the level of industrialization.

An industrialized construction system is understood as an innovative process that is carried out in the factory or on-site in a controlled environment, in a simplified way, planning is integrated into the whole process, using available technology, with a high level of work organization, standardization, and bringing mechanization and replacement of manual labor (Xie et al., 2023).

1.3.1.2 Prefabrication

Etymologically it means manufacturing previously and implies different assembly actions of construction elements that are carried out outside the construction site.

An element or system is prefabricated when it is created in the factory. This factory can be placed on the construction site. Otherwise, it cannot be defined as prefabrication, and it should be called an "in situ product" or "industrial product".

For example, in the case of a brick or a sink, there is no such choice, but there is in a façade panel or a slab-to-ceiling interior partition system (Feldmann, 2022).

1.3.1.3 Digitalization

Digitalization is the process of converting analogue information into a digital format. Analogue information is sometimes represented in a physical format which might have a higher likelihood of including errors. The digital data format is generally thought to be more stable and manageable.

Digitalization entails the integration of digital technologies into a process, organization, or system. Digitalization enables knowledge workers to perform at their highest level, and consequently become an integral part of business growth, not just unnecessary operational overhead. Digitalization offers profound improvements in pre-construction, including significant efficiency gains in bid team performance (Xie et al., 2023).

1.3.1.4 Renovation

Renovation involves restoring a building to an improved condition. This means replacing and upgrading present components to meet the required standards without altering the original design (Beetz et al., 2016).

Usually, renovation projects are done to increase the value of buildings on sale and are often shorter with a lower budget compared to other projects. They have little effect on the layout and structure of the building.

*Figure 2***.** Example of a renovation, before (left) and after (right), by Baumerk, 2022, https://www.baumerk.com/en/blog/what-is-renovation. Copyright 2022 by Baumerk.

1.3.1.5 Refurbishment

Refurbishment involves improving building decor, cleaning, re-equipping, and retrofitting. Its purpose is to improve the building's sustainability and energy efficiency.

Refurbishment is closely related to renovation and restoration as they all aim at restoring the building to its former state. Before the process, an expert should properly assess its structure and typology to determine a suitable refurbishment approach.

Figure 3. Example of a refurbishment, before (left) and after (right), by Renovalium, 2021, https://www.renovalium.com/antes-y-despues. Copyright 2021 by Grupo Renovalium sl.

The main difference between the two is that renovation typically refers to restoring something to a good condition or state of repair (which in our niche is to do with restoring a building, window, or door to its former condition) and refurbishment implies the process of improvement by cleaning, equipping, or decorating.

1.3.1.6 Restoration, conservation

Restoration involves returning a building to its former state. It's done to historical buildings to maintain their heritage and rich culture. The features of a building are recreated to match its appearance and function (Beetz et al., 2016).

Restoration aims to achieve the highest level of authenticity and replication. If there's a need to install new systems utilities such as ACs, furnaces, and fire alarms, they'll be done in a concealed manner, so they don't disrupt the building's original appearance.

Figure 4. Restoration of a historic building example, Toledo cathedral cluster, by Ministry of Culture and Sport - Government of Spain, 2015, https://www.culturaydeporte.gob.es/planes-nacionales/planes-nacionales/catedrales/actuaciones/claustro-catedral-toledo.html. Copyright 2015 by Ministry of Culture and Sport - Government of Spain.

1.3.1.7 Remodeling

Remodeling means completely transforming the layout and structure of a building – often, involving a change in the usage of space.

Figure 5. Remodeling example, Canadian Museum of Nature, by KPMB Architects,2019, https://www.kpmb.com/project/canadian-museum-of-nature/. Copyright 2019 by KPMB Architects.

1.3.1.8 Point cloud

A point cloud is a discrete set of data points in space. The points represent a 3D shape or object. Each point position has its set of Cartesian coordinates (X, Y, Z) (Dore & Murphy, 2017). Point clouds are generally produced by 3D scanners or by photogrammetry software, which measures many points on the external surfaces of objects around them.

1.3.1.9 Takt time
It is a manufacturing term to describe the required product assembly duration that is needed to match the demand. It is a tool used to design work and it measures the average time interval between the start of production of one unit and the start of production of the next unit when items are produced sequentially. The takt time is based on customer demand; if a process or a production line is unable to produce at takt time, it is required demand levelling, additional resources, or process re-engineering, to ensure on-time delivery.

1.3.1.10 Element
The building as a whole consists of modules and elements, in their assembled form. It is an essential or distinctive part of a building. It may be a panel, stick, glass, or any other part of a building.

1.3.1.11 *Module*
The individual elements are combined to form modules; facade modules, windows, doors, stairs, roof systems, etc.

1.3.1.12 System
The building can be divided into systems that perform differentiated functions. For example, the structural system or the façade system, which in turn are made up of modules.

1.3.1.13 Material
Material refers to a substance that an element or component is made of. Material can be used to describe something that is made of matter and exists in the physical world. It can be, for example, iron, wood, etc.

1.3.1.14 Offsite manufacturing
Offsite manufacturing refers to the manufacturing, planning, design, fabrication, and assembly of building elements at a location other than their final installed location. The aim is to support the rapid speed of efficient construction for a permanent structure. This approach contrasts with traditional onsite construction, where most building processes take place at the construction site.

1.3.1.15 Level of Development (LOD)
Level of development is the overall state of the information model at a particular point in its design process as shown by the BIM Forum (2022).

1.3.1.16 Laser scanning
It is a scan that involves illuminating an object with a laser and using sensors to measure the distance between the light source and the object's surface, either through timing or triangulation.

1.3.1.17 Structured light scanning
It is a scan that projects patterned lines of light onto the object and analyses how the lines deform on its surface to determine its shape.

1.3.1.18 Photogrammetry
It captures photographs of an object from multiple angles and merges them using software to create a 3D shape of the object.

1.3.2 Stakeholders
According to the Spanish Building Planning Law 38/1999, **Fehler! Verweisquelle konnte nicht gefunden werden.** presents the list of stakeholders involved in any construction process (BOE-A-1999-21567-Consolidado, 1999):

Table 1. Stakeholders involved in any construction process.

BUILDING STAKEHOLDERS	**Description**
DESIGNER, CIVIL ENGINEER, OR ARCHITECT	They design the project to fulfil the property developer's requirements. They ensure compliance with relevant technical and urban regulations.
BUILDER OR CONTRACTOR	The builder or contractor is the stakeholder that assumes, contractually bound to the property developer, the commitment to execute with human and material resources, own or third parties, the works or part of them subject to the project and the contract.
BUILDING QUALITY CONTROL ENTITIES AND LABORATORIES	Building quality control entities are qualified to provide technical assistance and ensure compliance with specifications and regulations in force for the project, the materials, and the execution of the work and its facilities following the project and the applicable regulations.
CONSTRUCTION MANAGER	It is the stakeholder who, as part of the facultative management, directs the development of the works in technical, aesthetic, urban planning, and environmental aspects, under the project that defines it, the building license, as well as the relevant authorisations and the terms of the contract, to ensure its suitability for the proposed purpose.
DIRECTOR OF THE EXECUTION OF THE WORKS	The director of the execution of the works is the stakeholder who, as part of the facultative management, assumes the technical function of directing the material execution of the works and of qualitatively and quantitatively controlling the construction and quality of the building.
PROPERTY OWNER / USER	The property owner is responsible for keeping the building in good condition through proper use and maintenance in accordance with the instructions for use and maintenance contained in the documentation of the works carried out. It is also duty-bound of receiving, preserving, and transmitting the documentation of the works carried out.

PRODUCT SUPPLIERS	Producer suppliers are considered manufacturers, stockists, importers, or sellers of construction products.
PROPERTY DEVELOPER	Any person, physical or legal, public or private, who individually or collectively decides, promotes, programs, and finances, with their own or third-party resources, the building works for themselves or their subsequent sale, delivery, or assignment to third parties under any title.
PUBLIC ADMINISTRATION	The entity in charge of legislating, guaranteeing the adequacy of the project, granting the relevant licenses, and providing incentives or stimuli. They can also be property developers or owners.
*SURVEYOR	A person who examines the condition of land and buildings
*LIDAR OPERATOR	A person who operates a laser to make high-resolution 3D representations of areas and/or buildings.
*BIM MANAGER	A person who knows the BIM methodology and is capable of coordinating and managing a BIM project.
*MANUFACTURER	A specific type of product supplier. They will create prefabricated and modular building elements.

*new stakeholders

1.3.3 Digitalization in the prefabrication process

1.3.3.1 The current process of prefabrication

Nowadays, prefabrication requires generally the following steps (see *Figure 6*).

- **Project design**. Usually performed by the architects. Ideally performed with BIM software.
- **Prefabrication design**. Usually performed by architects and engineers. Ideally performed with BIM software too.
- **Fabrication**. Carried out by the manufacturer. It has a different degree of automation depending on the element or part that is been prefabricating.
- **Transport.** Usually performed by a shipping company. It delivers the prefabricated product to the worksite. This step is key for life cycle assessment.
- **Assembly in the site**. It can be automated to various degrees depending on the company or part assembling (Feldmann, 2022). Usually carried out by the constructor's team or, sometimes, by the company that produced the product.

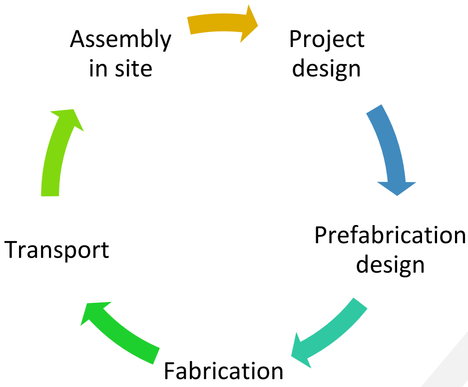


Figure 6. Simple lifecycle scheme of prefabrication process, by authors, 2023. Copyright 2023 by oPEN Lab.

1.3.3.2 Innovation in the prefabricated design

Scientific studies show that there is still a lot to investigate in the optimization of the prefabricated design (Feldmann, 2022). The most significant advances in the last year are related to the use of mathematical algorithms to optimize the possible exploded views of panels or frames.

Along the same line, another field of innovation is the simulation of exploded solutions with digital twins using mathematical algorithms. Exploded solutions are plane views of prefabricated modules or systems. Nevertheless, artificial intelligence can help to achieve and process data that can foresee the behaviour of certain simulations, contributing to the optimization of the design.

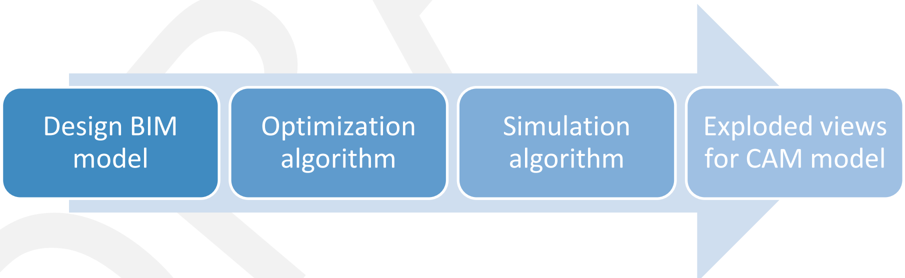


Figure 7. The innovative process within the prefabricated design, by authors, 2023. Copyright 2023 by oPEN Lab.

1.3.3.3 Innovation in the manufacturing

The use of robotics in the chain of fabrication of architectural pieces is still developing. Traditionally the flowchart to fabricate pieces was as shown in *Figure 8*:

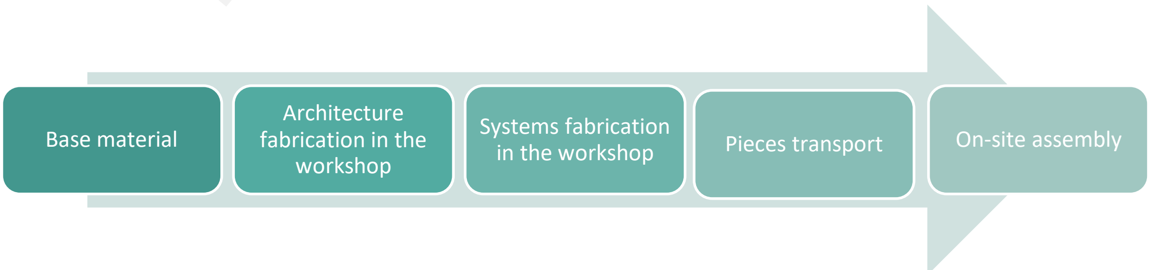


Figure 8. Innovative process within the fabrication and manufacturing process, by authors, 2023. Copyright 2023 by oPEN Lab.

The base material is needed to start the fabrication that is carried out in a workshop or factory (Liu et al., 2019). The analysis of the state of the art concludes that the automation in the robotics and systems within the factory or industrial building is still developing (Iloabuchi & Ocheoha, 2018). This is the step where more innovation is possible.

1.3.4 Integration of digital software tools

1.3.4.1 Point cloud

BIM has been defined as the recording and modelling of existing buildings, generating BIM geometry from point clouds (Dore & Murphy, 2017).

Volk et al. (2014) stated that BIM implementation in existing buildings is scarce, needing improvements in the conversion of point clouds to BIM models, updating data in BIM, and modelling items and relations in existing structures. This research, in contrast to other BIM sources, stated that detailed documentation of architectural projects, the last and most important point, is the ultimate aim of the BIM process (Volk et al., 2014).

Bosché et al. (2018) developed an algorithm that detects masonry surfaces from a point cloud. However, that system was not very successful. Also, Quattrini et al. (2015) supported the scanner laser technology to help BIM modelling to create high-quality BIM models (Mazzoli et al., 2021). Garagnani et al. (2021) proposed the parametric modelling of complex geometry over the point cloud using a Revit plug-in named GreenSpider. The relevance of these sources from the perspective of improving refurbishment projects resides in the incorporation of point clouds within BIM models.

These projects entailed very complex modelling thus, the Durable Architectural Knowledge (DURAARK) project (2016) suggested simplifying the current complex modelling process by making BIM semantic models much simpler and even generating them from the point cloud (Lindlar and Tamke, 2014).

During a workshop held in Luxor, Egypt, Counsell and Nagy (2017) proposed a cloud-based workflow for analysing best practices for 3D point clouds (Counsell & Nagy, 2017).

In conclusion, there is software that converts point clouds into solid BIM models, but they are still imperfect, especially in refurbishment projects where surfaces are sometimes not flat and there are irregularities (Bueno et al., 2018).

1.3.4.2 BIM and GIS

BIM and GIS are technologies that can be united through digital twins and databases. Smart cities need both computation and simulation algorithms. Communication nets and social media are used to extract data and teach computer machines through machine learning (Karimi & Iordanova, 2021).

The infrastructure of Spatial Data refers to the framework, technologies, policies, and standards that enable the collection, management, sharing, and use of geospatial data. It provides a systematic approach to organise and deliver spatial information to support decision-making processes in various domains, such as urban planning, environmental management, transportation, and emergency response.

The INSPIRE Directive (2007), establishing an infrastructure for spatial information in Europe to support Community environmental policies, and policies or activities which may have an impact on the environment entered into force in May 2007. It is based on the infrastructures for spatial information established and operated by the Member States of the European Union.

Some of the geospatial information tools and databases available that are worth highlighting are listed below.

1.3.4.2.1 Spanish Spatial Data Infrastructure (IDEE).

One GIS system is IDEE which is a specific Spanish Infrastructure Minister`s website.

This website provides geospatial files of different Spanish territories. These types of websites are databases used to obtain information, as seen in *Figure 9* and *Figure 10*:

- Web viewer with all the available GIS services.
- Services directory that allows downloading information (WMS/WMTS).
- Download websites to have geospatial information.

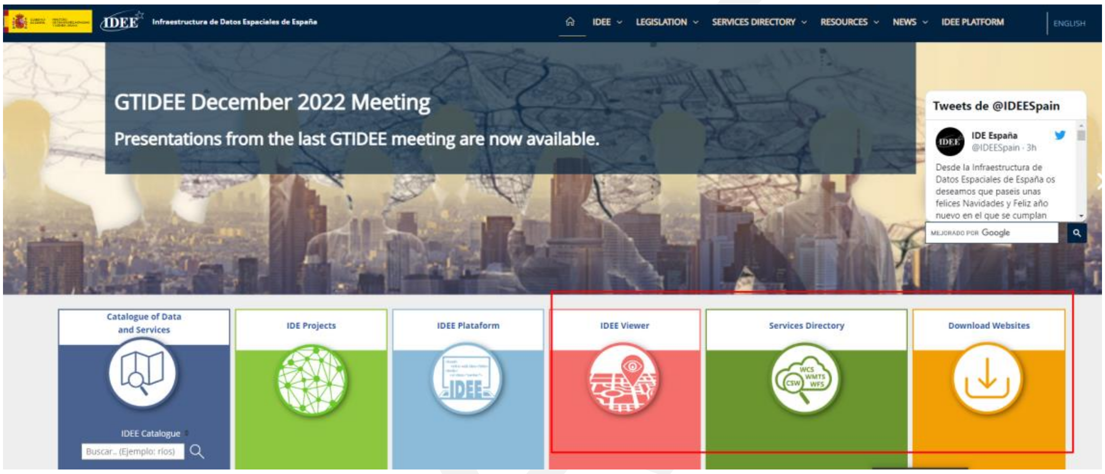


Figure 9. IDEE website, by Spatial Data Infrastructure of Spain, 2022, https://www.idee.es/en/. Copyright 2022 by Ministry of Transport, Mobility and Urban Diary - Government of Spain.

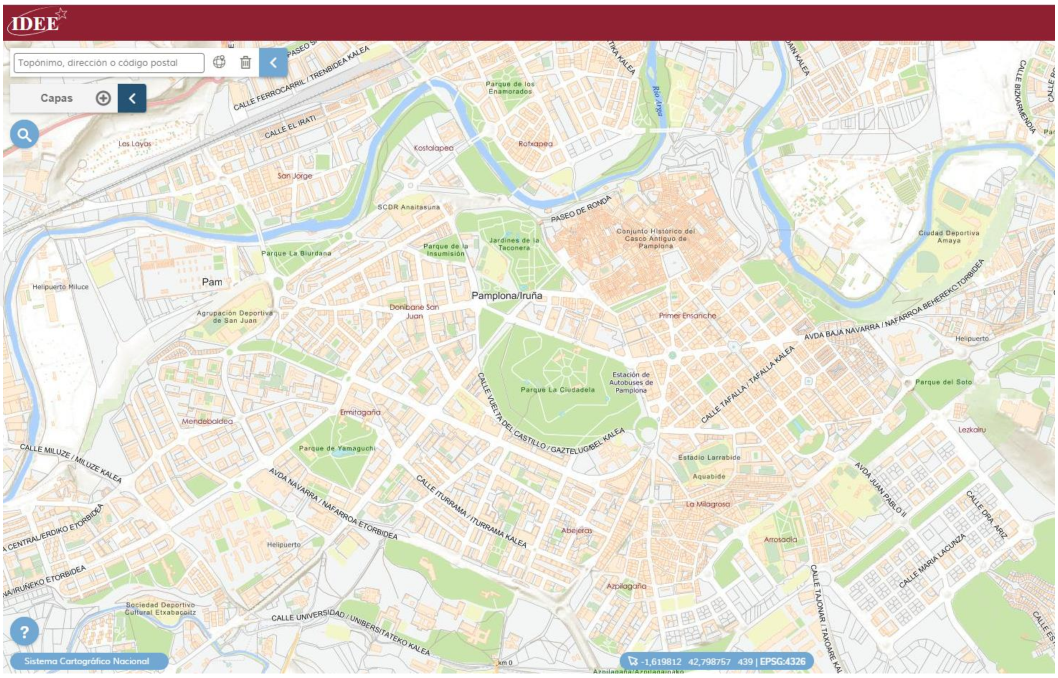


Figure 10. IDEE Gis software and maps, by Spatial Data Infrastructure of Spain, 2022, https://www.idee.es/visualizador/. Copyright 2022 by Ministry of Transport, Mobility and Urban Diary - Government of Spain.

1.3.4.2.2 Geopunt

This is the central access point to governmental geographical information, accessible publicly. It is the Flemish node in a European geographical data infrastructure, compliant with the INSPIRE framework.

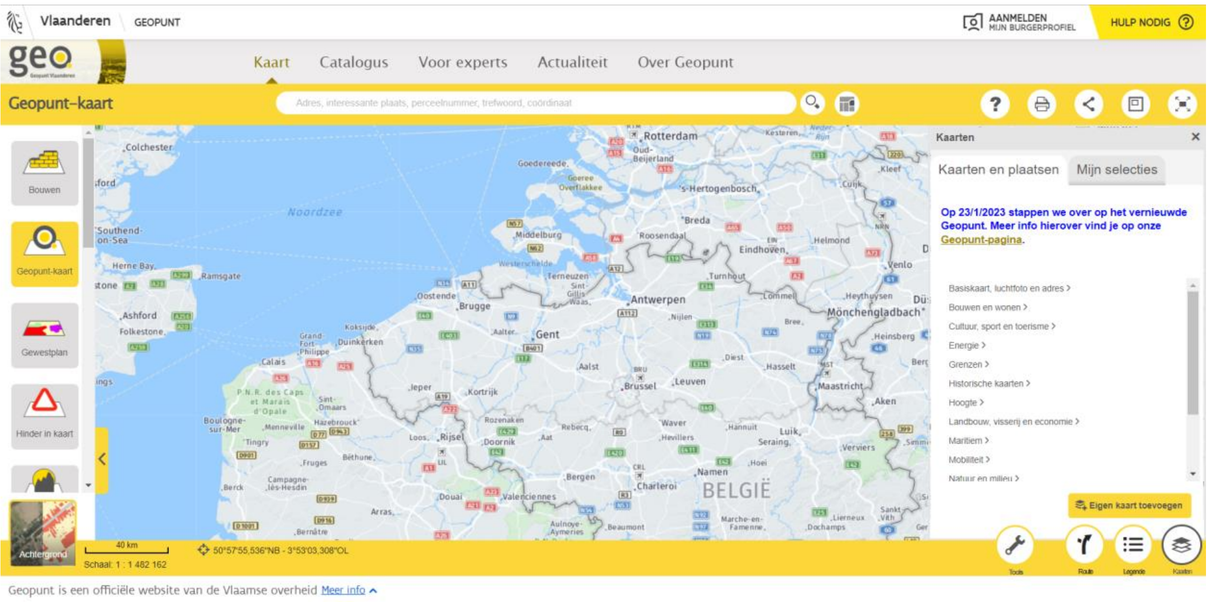


Figure 11. Starting page of geopunt, by Digital Flanders, https://www.geopunt.be/. Copyright by Flemish Government.

1.3.4.2.3 Estonian Building Register (EHR)

The Buildings Register is a national database from Estonia for submitting and processing documents related to construction, such as building permits, building permits, authorisations for use, etc.

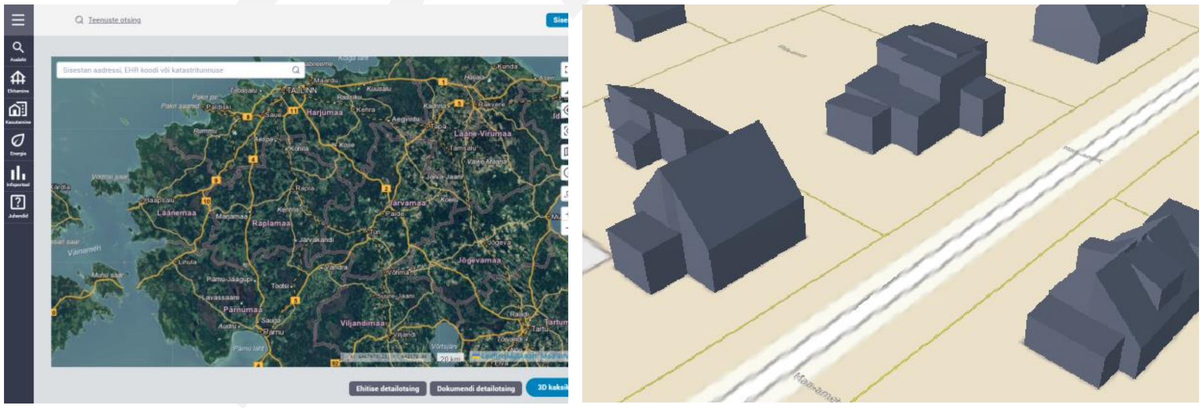


Figure 12. Geographical (left) and 3D information about building geometry (right) from an Estonian building register, www.ehr.ee. Copyright by Ministry of Economic Affairs and Communications – Republic of Estonia.

1.3.4.2.4 Infraworks of Autodesk

InfraWorks from Autodesk is a software package for creating, evaluating, and communicating infrastructure proposals. In addition to tools for creating roads, sewerage systems, buildings, and more, InfraWorks facilitates effective communication among team members and stakeholders. InfraWorks connects large amounts of data (such as GIS and CAD files) and supports linked BIM processes.

InfraWorks is considered a BIM software that unites BIM, GIS, and CAD files. It's from Autodesk and it is a conceptual design software that helps to model and understand design projects, in context. It can be used to:

- **Aggregate volumes of data** to generate information-rich context models.
- **Streamline processes** with conceptual design tools that incorporate engineering principles.
- **Use compelling visuals** to evaluate your designs and communicate intent to stakeholders.

1.3.4.3 *Preconstruction and BIM to CAM*

Several software developers companies have BIM products that allow the integration of prefabricated elements into the design process (Heigermoser et al., 2019). Some of them are described below:

1.3.4.3.1 Revit

1.3.4.3.1.1 Agacad precast concrete (plugin for Revit)

Agacad is a software that has developed a system to model precast concrete industrialized pieces. Precast Concrete software for Revit streamlines the 3D design process by automating the modelling, detailing, and documentation stages.

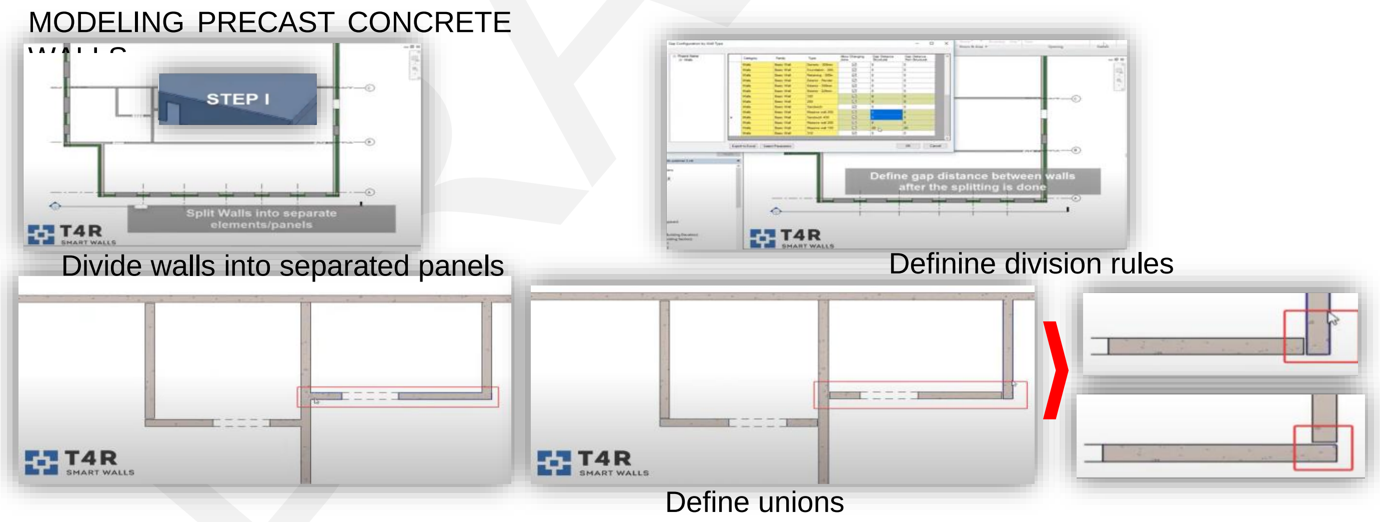


Figure 13. Process of modeling with Agacad precast concrete, by AGA CAD, https://agacad.com/. Copyright 2013-2023 by AGA CAD.

1.3.4.3.1.2 Agacad wood framing (plugin for Revit)

Similarly to the previous one, Agacad wood farming uses Revit as the main interface environment to develop specific precast wood construction such as:

- Create detailed multilayer timber wall framing for the Revit model, in a snap, using fully customizable rules and templates.
- Frame multi-story houses faster than using the standard Revit interface.

- Control stud, nogging, bridging, blocking, bracing placement, diverse openings, configure complex L or T connections, details, and service hole positions.
- Auto-distribute mailers, siding, and fastenings.
- Create all log house elements and group (pack)/number them automatically.
- Freely revise the Revit model, with a simple selection of the elements and properties to be modified.
- Find structural and engineering clashes; cut and frame openings according to predefined rules.

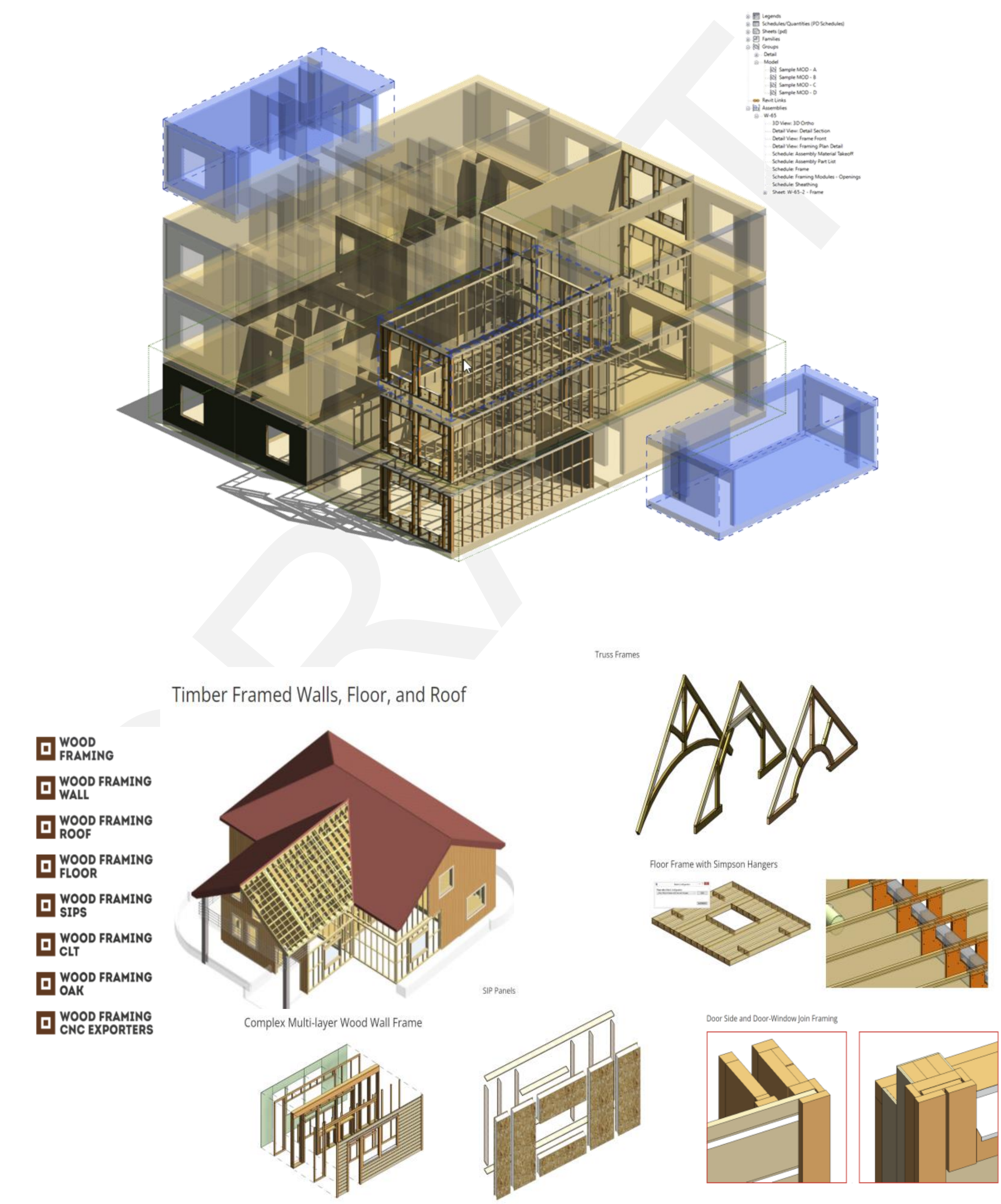


Figure 14. Revit with Agacad wood framing plug-in example of interface, by AGA CAD, https://agacad.com/. Copyright 2013-2023 by AGA CAD.

1.3.4.3.2 Tekla structures

Tekla Structures is a building information modeling software able to model structures that incorporate different kinds of building materials, including steel, concrete, timber, and glass (see *Figure 15* and *Figure 16***Fehler! Verweisquelle konnte nicht gefunden werden.**). Tekla allows structural drafters and engineers to design a building structure and its components using 3D modeling, generate 2D drawings, and access building information. Tekla is used in industrial offices of precast and steel construction.

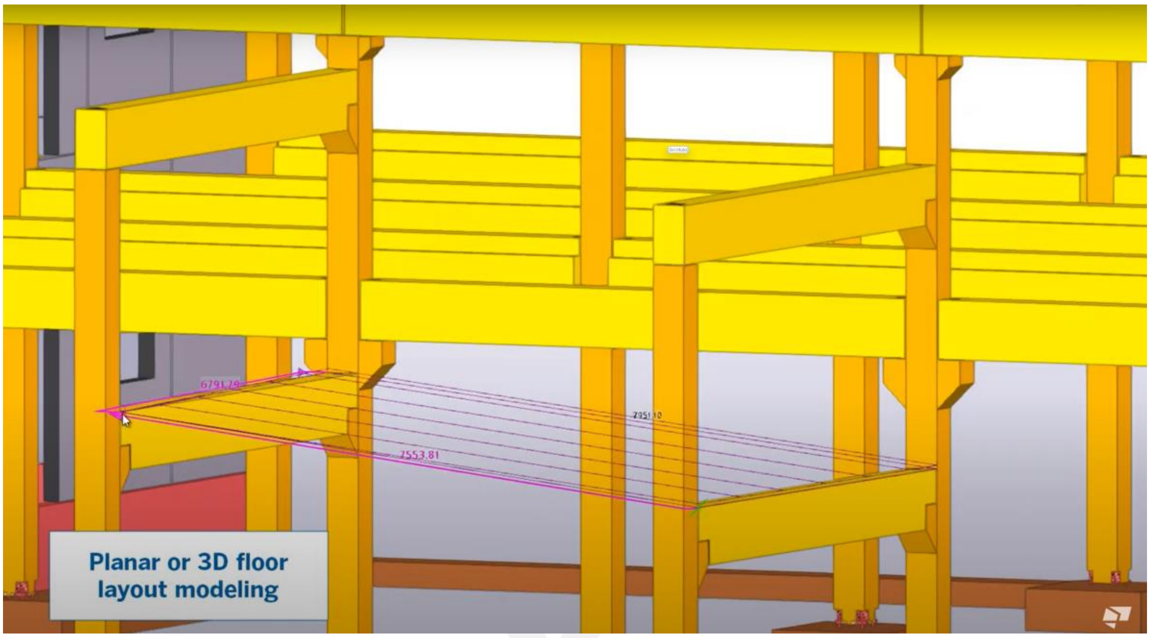


Figure 15. Tekla structures interface example, by Tekla, https://www.tekla.com/uk/products/tekla-structures. Copyright 2023 by Trimble Solutions Corporation.

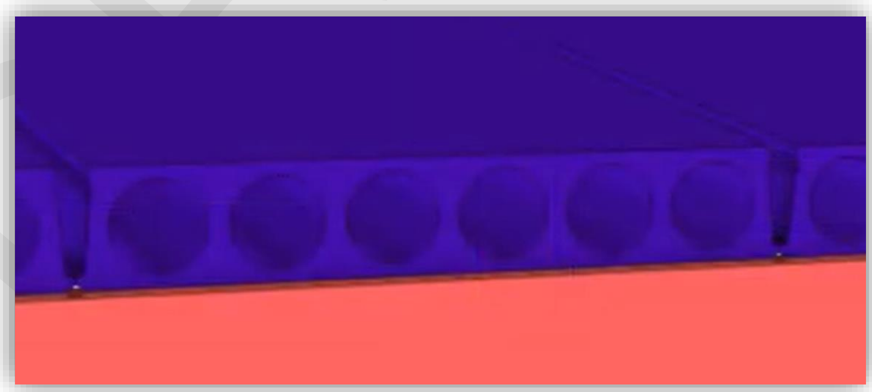


Figure 16. Tekla structures detail example, by Tekla, https://www.tekla.com/uk/products/tekla-structures. Copyright 2023 by Trimble Solutions Corporation.

The software allows personalized some of the pieces or unions as shown in *Figure 17* and *Figure 18*.

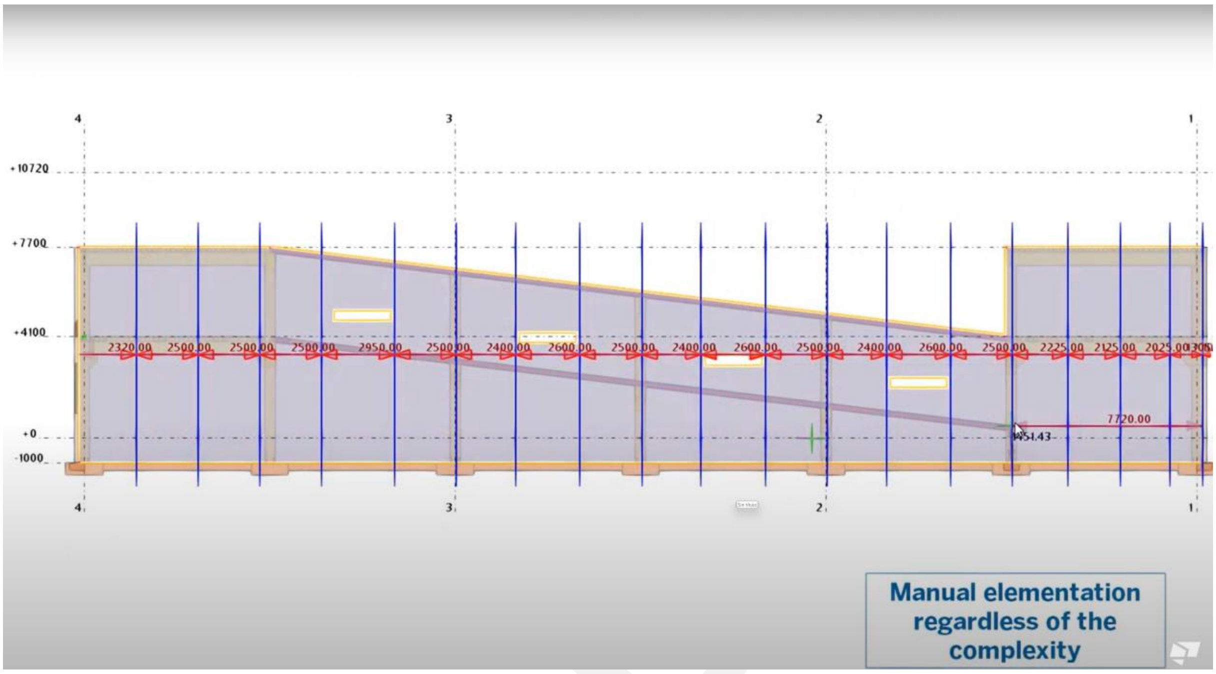


Figure 17. Pieces modulation within Tekla structures, by Tekla, https://www.tekla.com/uk/products/tekla-structures. Copyright 2023 by Trimble Solutions Corporation.

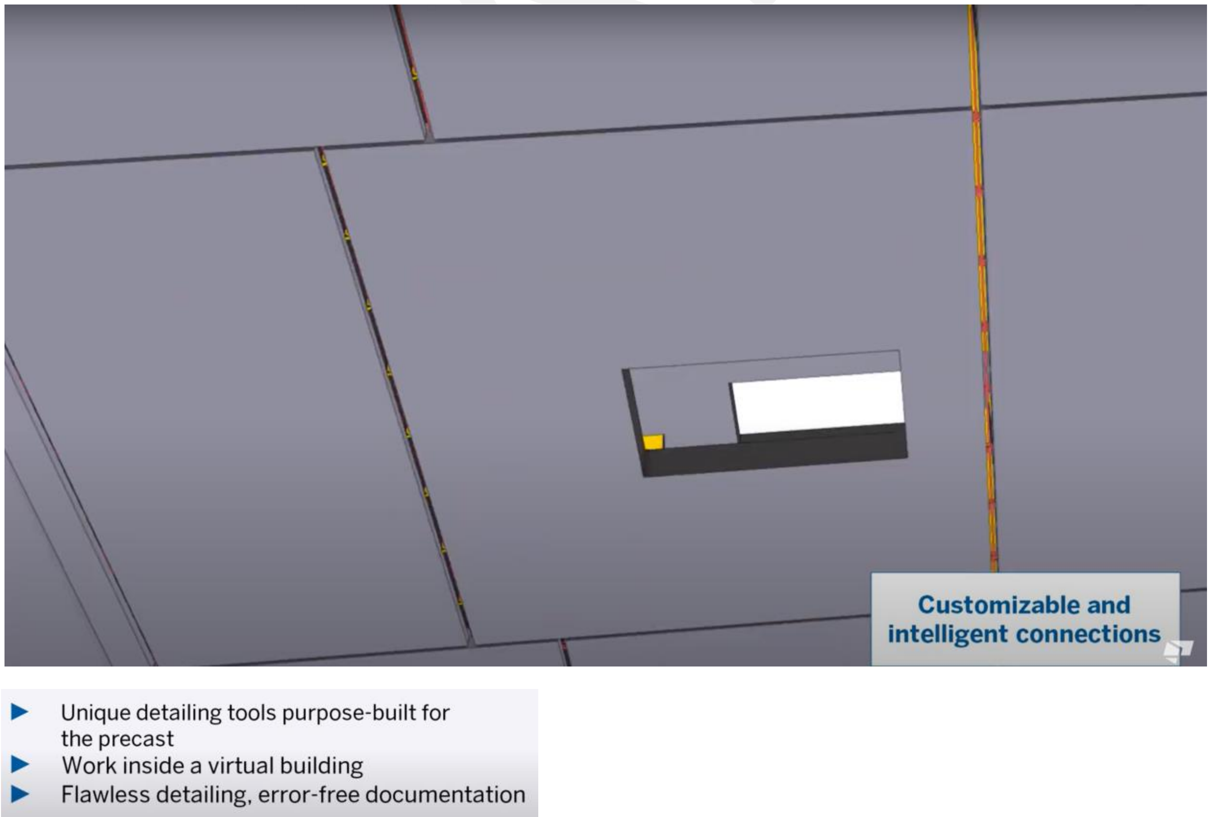


Figure 18. Tekla structures example of intelligent connections, by Tekla, https://www.tekla.com/uk/products/tekla-structures. Copyright 2023 by Trimble Solutions Corporation.

1.3.4.3.3 Vertex structures

Vertex is a BIM software for wood/timber and cold-formed steel framing that automates the design and manufacturing processes. It allows technical stakeholders to develop projects quickly and accurately while minimizing errors in production. It is possible to export the BIM design to CNC machines. See examples in *Figure 19* and *Figure 20*.

Figure 19. VertexBD example of Wood framing structure, by Vertex BD Building Desing Software, https://vertexcad.com/bd/. Copyright 1977-2023 by Vertex Systems.

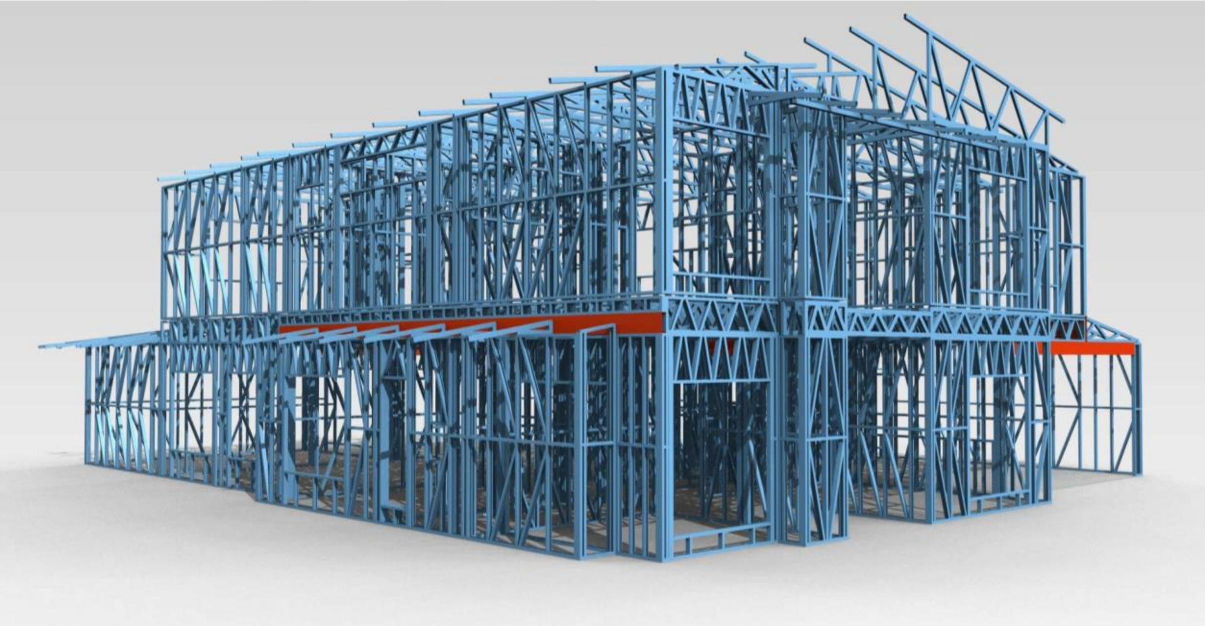


Figure 20. VertexBD example of Steel framing structure, by Vertex BD Building Desing Software, https://vertexcad.com/bd/. Copyright 1977-2023 by Vertex Systems.

1.3.4.3.4 Allplan Precast

Allplan Precast enables highly automated and precise design of structural precast elements, precast walls, and slabs. Allplan Precast Slabs automatically places the composite recesses and offers maximum flexibility for jointed systems. For filigree slabs, the software performs a shear force and bond check and installs any necessary lattice girders, if required. Rely on high precision in the provision of commercial and production-related data.

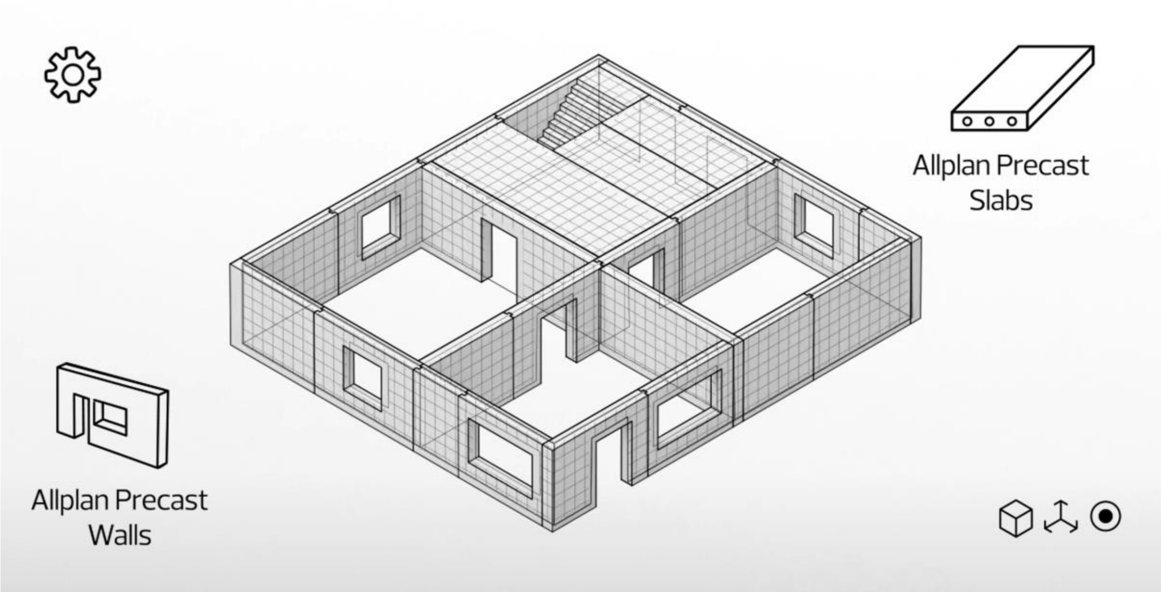


Figure 21. Allplan precast slabs, by Allplan, https://www.allplan.com/products/allplan-precast/. Copyright by ALLPLAN Deutschland GmbH ALLPLAN is part of the Nemetschek Group.

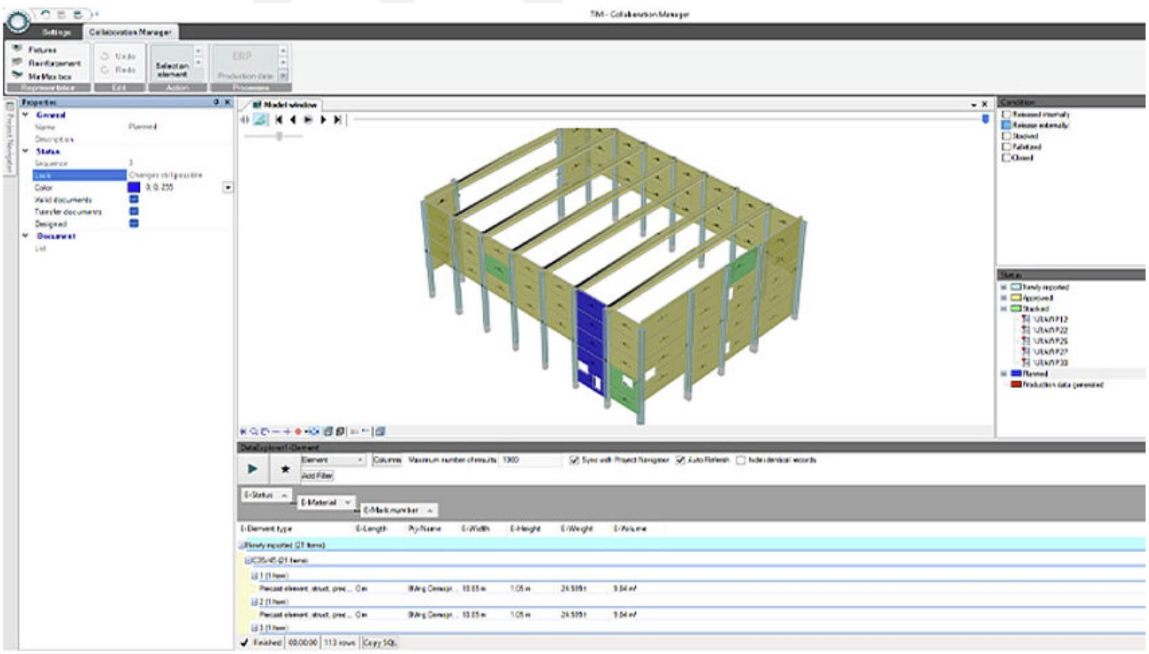


Figure 22. Configuration of the model in Allplan, by Allplan, https://www.allplan.com/products/allplan-precast/. Copyright by ALLPLAN Deutschland GmbH ALLPLAN is part of the Nemetschek Group.

1.3.4.4 Collaborative platforms

Several collaborative tools are available, among which the following can be highlighted:

1.3.4.4.1 BIM360

Autodesk® BIM 360™ is a cloud-based construction management platform that improves project delivery and outcomes. BIM 360 supports informed decision-making throughout the project lifecycle for project, design, and construction teams.

BIM 360 connects teams and data in real-time, empowering project members to anticipate, optimize, and manage all aspects of project performance.

1.3.4.4.2 Speckle

It is a collaboration platform for designers, engineers, hackers, and entire organizations. It is focused on interoperability, automation, and collaboration to deliver better results together.

1.3.4.5 Life cycle assessment (LCA)

LCA assesses the environmental impacts, such as global warming potential, over the life cycle (Wastiels & Decuypere, 2019). LCA is a methodology for assessing environmental impacts associated with all the stages of the life cycle of a commercial product, process, or service. For instance, in the case of a manufactured product, environmental impacts are assessed from raw material extraction and processing (cradle), through the product's manufacture, distribution, installation, and use, to the recycling or final disposal of the materials composing it (grave).

Among the software that develops LCA, it is worth mentioning the following:

1.3.4.5.1 Umberto

Umberto is an LCA software solution for professionals, and user experts from industry, consulting, research, and education.

1.3.4.5.2 Cocon

COCON is a software application for studying the environmental quality of materials and buildings and carrying out life-cycle analysis (LCA) based on digital models (BIMs) imported from the main drawing applications on the market. It is available in French, Spanish, and English. It includes regulations from different European countries to perform regular LCA checks.

1.3.4.5.3 Totem

To help the Belgian construction sector to objectify and reduce the environmental impact of buildings, the three Regions have developed the TOTEM tool (Tool to Optimise the Total Environmental Impact of Materials). The project partners are the Public Flemish Waste Agency (OVAM), Brussels Environment, and the Public Service of Wallonia.

Five years of research and development, in collaboration with universities and design offices, were necessary for the realisation of this scientific methodology, adapted to the specificities of the Belgian construction sector.

TOTEM's main values are objectivity and transparency, to enable the players in the Belgian construction sector (architects, design offices, contractors, owners, property developers, public authorities, etc.) to identify and limit the potential environmental impacts of buildings from the earliest stages of the design process.

1.3.4.6 Life Cycle Costing (LCC)

LCC calculates the costs of a product throughout its life cycle (which can include giving a monetary value to environmental externalities). It looks at the direct monetary costs involved with a product or service and not the environmental impact (Veselka et al., 2020).

Usually, the LCA software includes tools to calculate the monetary impact of the different LCA solutions (Carvalho et al., 2020).

1.3.4.7 Hydrothermal performance

The following are some of the software available to perform Hydrothermal performance studies:

1.3.4.7.1 Cypetherm

It is software from the company Cype that allows hydrothermal performance with IFC models. Ideally, the modelling may be performed in Cype, but it allows also external IFC (Horn et al., 2020).

It also calculates the government norms of different countries (for example Spain or Portugal) as shown in *Figure 23*.

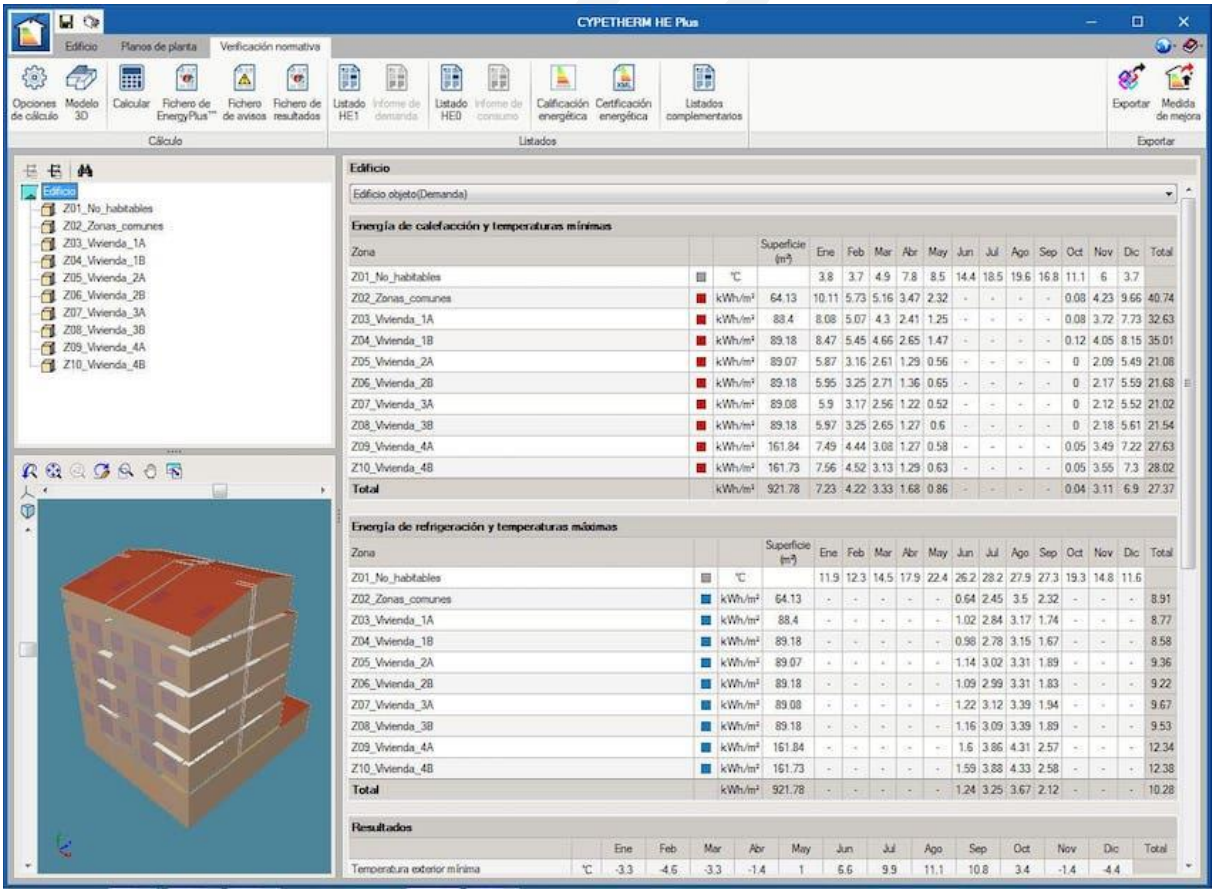


Figure 23. Interface of Cypetherm, by CYPE Ingenieros, S.A., https://info.cype.com/es/software/cypetherm-he-plus/. Copyright by CYPE Ingenieros, S.A.

1.3.4.7.2 Trisco

Software for steady-state thermal simulation of 2D and 3D orthogonal building components. Optimized for automated use according to EN ISO 6946 and EN ISO 10211.

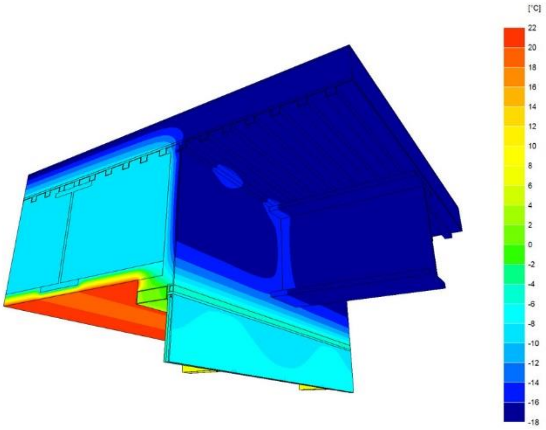


Figure 24. TRISCO visualized temperature gradient for construction detail, by TRISCO, https://www.physibel.be/en/products/trisco. Copyright by Physibel.

It has various application fields as shown in *Figure 24* and *Figure 25*:

- Thermal bridge analysis: heat loss calculation and surface condensation (EN ISO 10211)
- Thermal transmittance of building components and elements (EN ISO 6946)
- Thermal performance of windows, doors, and shutters (EN ISO 10077-2)
- Heat transfer via the ground (ISO 13370)
- Heat transfer in masonry and masonry products (EN ISO 1745)

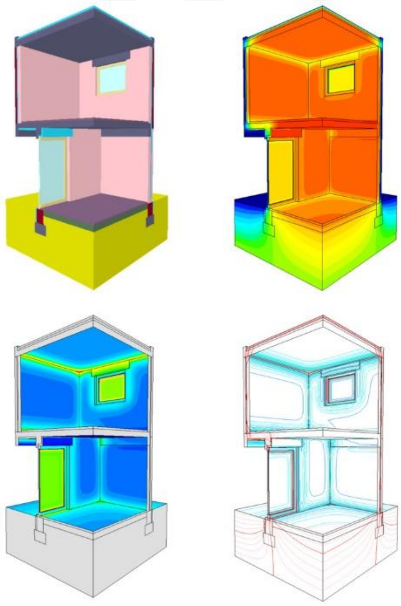


Figure 25. TRISCO visualizations of building materials, temperature gradients, surface temperatures, and heat flows, by TRISCO, https://www.physibel.be/en/products/trisco. Copyright by Physibel.

2 Objectives and methodology

2.1 Objective of the study

The main goal of this study is to generate a digitalized building renovation flowchart and test it in different building typologies (high-rise, single-family, row house, etc.) for its validation. This flowchart establishes seamless links between detailed laser scan data and computer-aided manufacturing (CAM).

This objective can be divided into three main sub-objectives:

2.1.1 Objective 1

To define a baseline scenario that represents the traditional renovation process and compare it with an improved scenario that includes an industrialization approach and with an optimized scenario that includes an integrated renovation process.

2.1.2 Objective 2

To digitalize the prefabrication process making seamless links between detailed laser scanning data to CAM. This includes improvements in the process of the connection of GIS, BIM, LCA, CAM, and LCC tools.

2.1.3 Objective 3

To test the optimized renovation process through: 1) testing the integrated renovation process in the three case studies and subsequent optimization; 2) recommending implementation suggestions for the renovation works of the three Living Labs and future developments.

2.2 Methodology/implementation

The hypothesis of this study is the inclusion of new processes, flowcharts, and tools in an integrated renovation process that will improve the quality of buildings and reduce time and cost. The hypothesis is related to specific improvements in the processes and the incorporation of relevant tools.

The methodological approach adopts the design science approach, which is a "lens" or set of synthetic and analytical techniques and perspectives (complementing positivist, interpretive, and critical perspectives) for performing research in Information Systems (IS) (Hevner and Chatterjee, 2010; Van Aken, 2004).

DSR has been an important paradigm of Information Systems research since the inception of the field. Its general acceptance as a legitimate approach to IS research is increasing (Hevner and Chatterjee, 2010; Kuechler and Vaishnavi, 2008).

DSR develops knowledge to create artefacts that improve processes (van Aken, 2004). This means that tries to create something that does not exist in nature (Kuechler and Vaishnavi, 2008).

The research design adopted (see *Figure 26*) was divided into five stages following the principles of DSR: identify the problem, define objectives, design the solution, implement the solution, and evaluate the solution (Peffers *et al.*, 2007).

Figure 26. Methodology flowchart carried out in the study), by authors, 2023. Copyright 2023 by oPEN Lab.

In the first stage, the state of the art was studied to identify optimization opportunities in digitalizing the prefabrication process and integrating digital tools. Later, the definition of the “baseline” and “improved” scenarios were carried out and improvement chances were identified.

In the second stage, the objectives were defined and in the third stage, the optimized scenario is defined. This was carried out considering improvement opportunities detected in the previous scenarios. Different flowcharts were created to accompany the written description.

In the fourth stage, the flowchart proposed has been tested in the three Living Labs in order to check the viability of the connections between the different software as well as the role and involvement of stakeholders in the process.

As the fifth and last stage, an analysis of the results obtained in the previous stage has been conducted, making the necessary adaptations and suggestions to improve the solution proposed. The optimized renovation process as well as the results have been examined by the different actors involved in the project.

Finally, as part of the evaluation phase, the stakeholders are working on the implementation of the flowchart and adapting it to the reality of every case study. The results of this process will be published in the next outcomes of the study.

3 Baseline scenario: traditional renovation process

This chapter analyses the baseline scenario of a traditional renovation process to identify procedures, flowcharts, and tools that have an opportunity for improvement. It describes the traditional renovation process, the involved stakeholders, common modelling tools, time and cost needed. It also defines problems and opportunities. In *Figure 27*, all the phases related to the renovation process through the lifecycle are visualized.

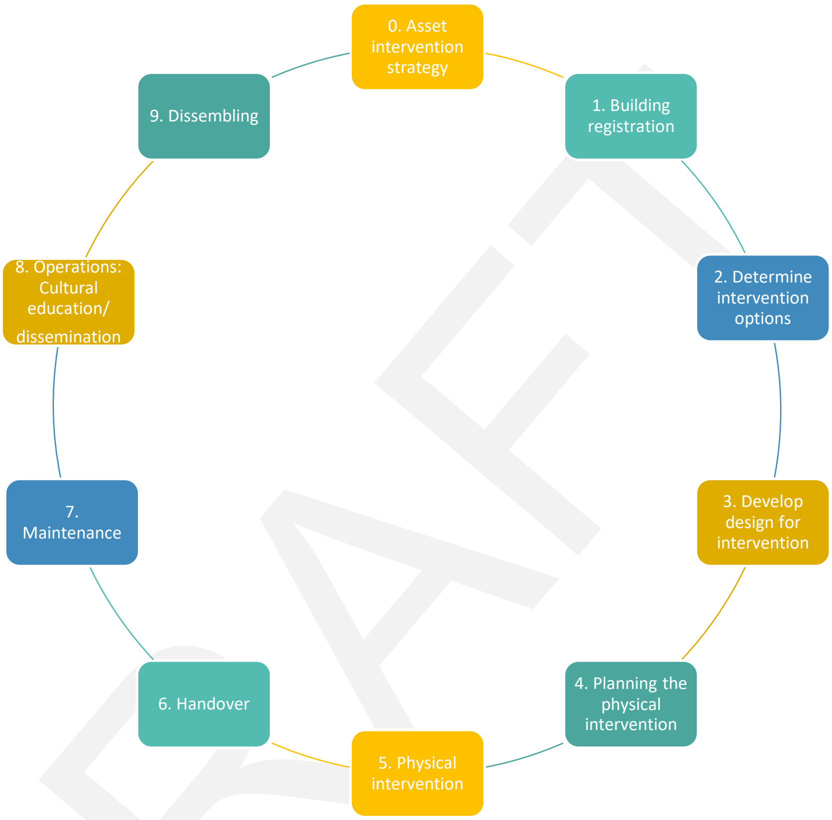


Figure 27. Phases of Lifecycle in a traditional renovation process), by authors, 2023. Copyright 2023 by oPEN Lab.

3.1 General description

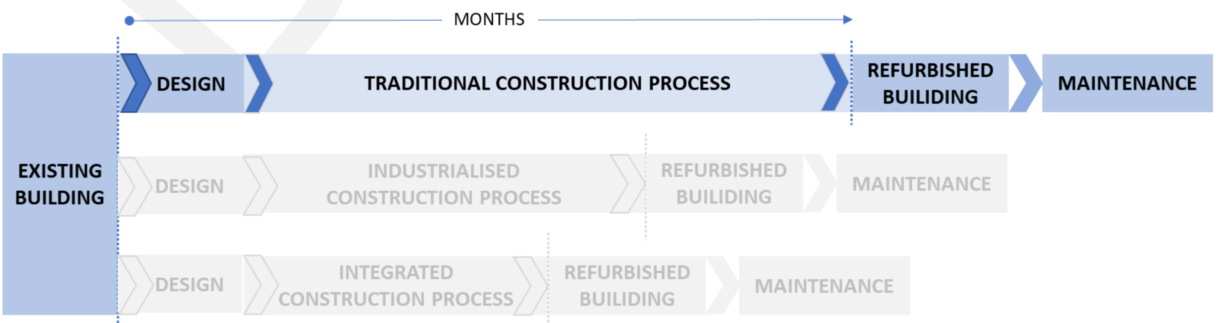


Figure 28. General scheme of the traditional construction process is in blue, the industrialized construction process, and the integrated construction process in grey (listed from top to bottom), by authors, 2023. Copyright 2023 by oPEN Lab.

In this scenario, the traditional renovation process takes longer than other scenarios, as seen in *Figure 28*. In this figure, the first row represents the traditional renovation process, the second row the industrialized renovation process, and the third row is the optimized scenario.

Most actors are only familiar with 2D BIM modelling in their specific fields of expertise. As is shown in *Figure 29*, the general design of the building is carried out by the architects/engineers in charge of the execution of the project. Nevertheless, the final construction design is carried out by improving the initial design with specific details of different elements to be executed, conducting collaborative work by the architects responsible for the construction management, the construction company, and the subcontracted companies.

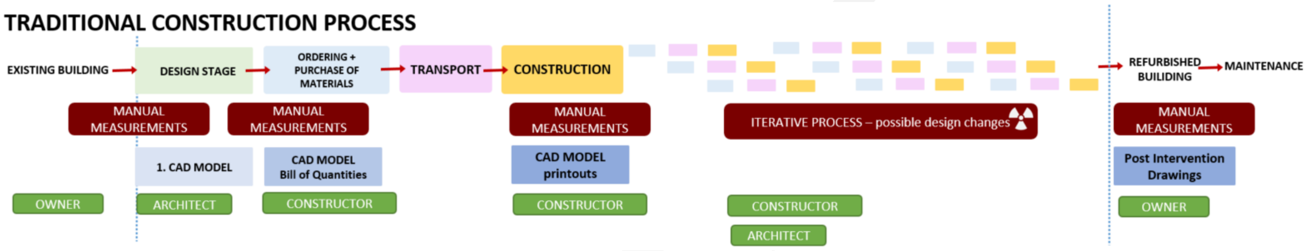


Figure 29. Specific flowchart of the baseline scenario), by authors, 2023. Copyright 2023 by oPEN Lab.

3.2 Existing building

The current situation of the building is documented and digitalized. The objective of this task is to have an accurate digital representation of the building as it is now. Gathering the necessary measurements by taking data on-site, as the existing documentation of the building may be not reliable.

Table 2. Tasks to be carried out in the collection of data on the current situation in a traditional renovation process.

STARTING POINT	END RESULT
EXISTING PAPER BLUEPRINTS	Validated paper blueprints
EXISTING DIGITAL 2D BLUEPRINTS	Validated digital 2d blueprints
MANUAL MEASUREMENTS ON-SITE	Validated digital 2d blueprints from measurements made

- Stakeholders involved and their role in the process:
  - Surveyor: takes measurements on-site.
  - Architect: validates measurements and establishes a new model.
  - Structural Engineer: from the data obtained at the site, analyses the load capacity of the existing structure.
- Common modelling tools:
  - Laser distance meter.
  - Total station.
  - 2D BIM software (VectorWorks, AutoCAD, BricsCAD…).
  - Total Station software.
- Time and cost:
  - Time depends on several characteristics such as project size, the extensiveness of the project, etc.

- Typical dimensional tolerance:
  - Laser distance meter: ±1,5mm/m.
  - Total station: 0,5” & 0,6mm+1ppm (1,6mm/km).
- Level of Detail:
  - LOD 100/200.
- Problems detected:
  - Carrying out reliable data collection requires a lot of time that is normally not conducted properly since during the execution it is common to find differences between the reality of the building and what is considered in the project.
  - Making a more precise model is economically challenging, as it increases the workload without adding value to the initial output objective.
- Opportunities:
  - No relevant opportunities to report.

3.3 Design stage

The goal of this stage is to have a digital representation of the building as it should be. Depending on the quality of the project, the representation can be very basic (the usual) or fully developed (very rarely).

- Stakeholders involved and their role in the process:
  - Architect: prepares the executive documentation of the building, and constructive design information for its construction.
  - Structural Engineer: is in charge of analysing the existing structure and the definition of the new structure ensuring that the final building meets the required regulations. In this scenario, the structural engineer usually uses a separate model.
- Common modelling tools:
  - 2D BIM software (VectorWorks, AutoCAD…).
- Time and cost:
  - Time depends on several characteristics such as project size, the extensiveness of the project, revisions needed, etc.
- Typical dimensional tolerance:
  - Depending on the quality of the initial data collection of the building, it can vary considerably.
    - Good quality data collection: +-1cm.
    - Bad quality +-10cm.
- Level of Detail:
  - LOD 200.
- Problems detected:
  - The developer's lack of conviction of the need to have a good design project. In addition, in some cases, the objective that the design cost must be low leads to low-quality projects that generate execution problems in the construction phase and unwanted delays and extra costs.
  - Making a more accurate model is economically challenging, as it increases the workload without adding value to the initial output target, but generally leads to savings in time and cost during renovation.
- Opportunities:
  - No relevant opportunities to report.

3.4 Manufacturing

During the execution of the building, the main constructor oversees its execution based on the initial approved design and the possible modifications that must be carried out as a result of:

- The design is not following the reality of the existing building, so the design must be modified during the renovation to adapt the project to the reality of the existing building.
- New requirements of the building developer not initially defined must be incorporated in the construction phase.
- Modifications are to be made to the design due to non-compliance of the initial design with regulations.

The construction director, the main constructor, and the subcontractors define the construction design to be executed. Depending on each case, one of them will prepare detailed designs with execution proposals based on the initial design project, and the construction director could require modifications until the final approval of the element design.

Many of the elements to be executed will be manufactured off-site but assembled on-site.

The definition of the execution details for each subcontractor is done independently. There are no common execution blueprints with all the details and elements included. For this reason, it is often necessary for further clarification of execution details or construction details between elements defined in different blueprints, being reviewed on-site during execution.

- Stakeholders involved and their role in the process:
    - General contractor: will be asked any questions that the subcontractors need to prepare their proposals.
    - Subcontractor: will define the constructive proposals to be executed.
    - Manufacturing company: will produce the constructive proposals to be executed based on what was discussed at the construction site.
    - Architect: will check the proposals submitted and will approve the final solutions.
- Common modelling tools:
    - Most manufacturing parties will use CAD and CNC-linked software. This allows them to export production files from the 3D drawing directly to the manufacturing line.
    - Some cases will have simpler manufacturing systems where the skills of the staff are of great importance.
- Time and cost:
    - The process of defining the elements to be manufactured extends from the preparation of the initial proposal, analysis by the construction management, and request for modifications and preparation of the final proposal.
    - The manufacturing cost is low, adjusted to the necessary personnel, low-profit margin, and material costs, since companies have been working in this way for many years, which has allowed them to keep their costs to a minimum.
- Typical dimensional tolerance:
    - Depending on the element to be manufactured and the tolerance needed it is from ± 0.2 cm to 0,5cm.
- Level of Detail:
    - LOD 200.
- Problems detected:

-
    - The process of defining each constructive element, although it is shorter than in an industrialized process, is proportionally longer as it is an iterative process and must consider other affected subcontractors.
    - Manufacturing measurements are taken on-site manually, so they are susceptible to human errors.
- Opportunities:
    - No relevant opportunities to report.

3.5 Transport

The material is delivered on-site, so only a list of materials delivered on-site is available.

Each material has manufacturing codes to follow the traceability of its manufacture but only in some cases it is coded to know where it must be installed.

The material is stored on site until the time when it must be installed. Therefore, each subcontractor must have space to store the materials.

- Stakeholders involved and their role in the process:
    - Logistics of the company: make deliveries according to material requests on site.
    - Manufacturing company: sends the material as it is available and requested.
    - General contractor: needs to know the arrival dates of the material to adapt the planning of the work to it.
- Time and cost:
    - Typically done just in time. If the main contractor does not have direct contact with the manufacturer, there may be problems with the delivery times of some components.
- Problems detected:
    - Often, materials are partially shipped (without all the necessary elements) and it is then necessary to wait for the back-ordered elements to arrive.
    - In some cases, there is no real information on delivery times due to problems in manufacturing or with the transport company.
- Opportunities:
    - No relevant opportunities to report.

3.6 Construction

The material is delivered to the site disassembled. From this material, the construction staff begins its assembly according to the planning in coordination with the rest of the subcontractors. The number of operations needed to install these units is far higher than the manipulations an off-site construction process would have needed.

- Stakeholders involved and their role in the process:
    - Subcontractor: has the greatest responsibility for the proper execution of the element.
    - Main contractor: must coordinate the different subcontractors in the execution of the different elements.

  - Construction manager: must coordinate the different subcontractors in the execution of the different elements. It will require the necessary modifications until the appropriate quality is achieved.
- Time and cost:
  - The terms of execution of the elements are longer.
  - If it is compared to industrialized processes, the elements that must be built by several subcontractors imply greater coordination at the site.
- Problems detected:
  - The quality of the finished product strongly depends on the training of the operators on site.
  - It is difficult to meet deadlines due to the coordination process of the different subcontractors, as it is highly unlikely that all of them will comply with the established schedule.
- Opportunities:
  - No relevant opportunities to report.

3.7 Renovated building

The building may have a quality similar to an industrialized building, but it depends on the quality of the subcontractors' work and the quality of the supervision work of the main contractor and construction management.

In contrast to industrialized solutions, in the case of elements manufactured on-site, the quality of the same is detected once it is already executed on-site. Therefore, solutions with a quality lower than expected are more common.

The execution terms of the building will have been longer, although the price will depend on more factors.

Currently, the costs of executions on-site are lower than in an industrialized execution because few companies can propose industrialized solutions, whereas for on-site construction there are a large number of them with many years of experience.

The final documentation of the renovation carried out consists of the project blueprints with the modifications made on-site during the execution process and manuals with technical characteristics of the installed materials. Like the initial documentation, it is of poor quality, as it represents schematically the situation of the installed elements, pipe routes, conduits, etc.

3.8 Maintenance

Only some companies have predictive or preventive maintenance plans. In most cases, maintenance is of a corrective nature, solving problems as they arise with the use of the building.

There is no perfectly defined as-built documentation. Only the schematic situation of the elements executed and the routes of the facilities. Normally there is no detailed documentation that defines the characteristics, assembly manuals, or maintenance of the installed elements.

- Stakeholders involved: their role in the process.

    - Owner: does not carry out a correct verification of the documentation received at the end of the works to facilitate the maintenance tasks of the building. He/she should be more involved in obtaining the final documentation.
    - Construction manager and subcontractors: the delivery of final documentation is not consistent with the original documentation of the project in terms of quality.
- Time and cost:
    - The transmission of knowledge of the installation between the different maintenance operators is more complicated because adequate documentation is usually not available.
    - It implies a greater dedication of time to know how the installation of each element has been done.
- Problems detected:
    - The degree of knowledge of the building from its final documentation is very low.
    - Over time, if the as-built documentation is not updated with the modifications that are made to the building over the years, the available documentation is no longer valid.
    - As the building documentation is of low quality, it is not possible to know exactly how an element has been executed until it is analysed on-site.
    - The available documentation is of significantly lower quality than in industrialized processes.
- Opportunities:
    - No relevant opportunities to report.

4 Improved scenario: Industrialized renovation process

This chapter analyses the improved scenario in the industrialized renovation process to identify procedures, flowcharts, and tools that have an opportunity for improvement.

4.1 General description

What if we would build houses the same way we build cars? In this improved scenario, it is considered the effects of industrialisation on the building sector. It is an evolution that has been accelerated with the introduction of automated production facilities. Hence, the role of CAD/CAM is discussed concerning the design and manufacturing of prefabricated modules.

The main objectives of the industrialized production process are related to optimising the construction phase. By introducing prefabrication, the amount of manual labour on-site can be reduced. This offers a solution for both reduction of building errors and the scarcity of skilled labour. The reduction of time needed to deliver a finished product is shown in *Figure 30*.

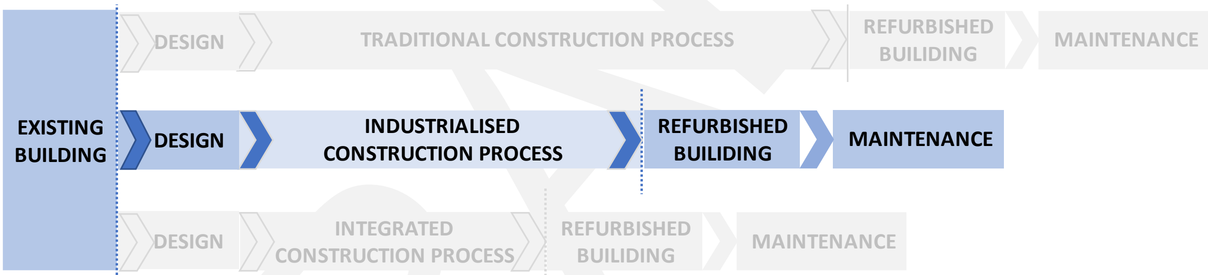


Figure 30. The general scheme of the traditional construction process is in grey, the industrialized construction process is in blue, and the integrated construction process is in grey (listed from top to bottom), by authors, 2023. Copyright 2023 by oPEN Lab.

The stakeholders in this scenario will take on slightly different roles from the traditional workflow. For various reasons, they include BIM to optimize their processes. It is revealed the challenge posed by the disconnection between the models that each stakeholder uses. This is indicated in *Figure 31* where the distinct BIM models are identified.

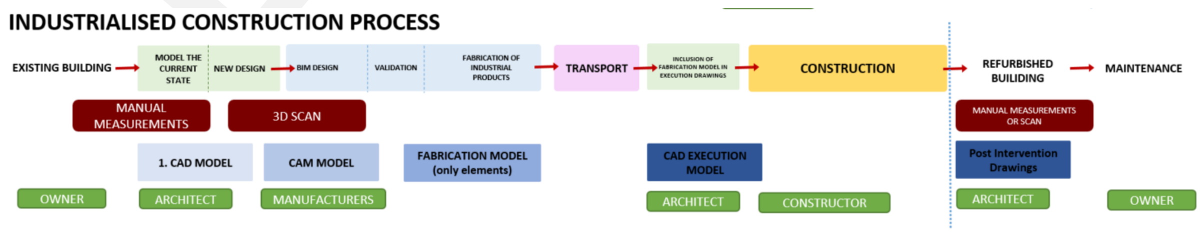


Figure 31. Flowchart of Industrialized construction process), by authors, 2023. Copyright 2023 by oPEN Lab.

In this scenario, most of the actors are familiar with BIM modelling in their specific fields of expertise (Feldmann, 2022). These models however are often heavily customised and built for a single purpose. This can be seen in *Figure 31*, where the various BIM models are disconnected. Content, as well as precision, vary depending on the intended use, making the interaction between the different models cumbersome or even impossible.

Additionally, the information exchange with other specialists is often done in a monodirectional manner. The architectural model is leading and is exported on several occasions to feed information to other studies. This can be the case for the static and/or dynamic structural study, the LCA, or the hygrothermal analysis. The conclusions of these studies result in modifications to the architectural model which must be carried out manually.

During each iteration, there is a risk of information distortion and loss. Because there is no bidirectional link between the architectural model and the analysis conducted, results may conflict with the architectural boundary conditions such as:

- The size of a beam can clash with the required free headspace over a staircase.
- The required layer of external insulation might be thicker than urban regulations allow.
- Changing the façade material to a more circular one might imply a change in supporting structure which can require a rethink of the element structure.

4.2 Existing building

4.2.1 Digitalizing the building survey

In this stage, the current situation of the building is documented and digitalized. The objective is to have an accurate digital representation of the building as it is now. Gathering the necessary measurements can be done in many ways, with varying degrees of trustworthiness.

The most basic way to do this is to convert existing paper blueprints into digital CAD drawings. The accuracy is heavily dependent on the precision of the blueprints and the conformity of the building to those blueprints.

Ideally, measurements are taken and validated on-site to create a model. These can be taken manually or automatically using handheld lasers, LiDaR, or photogrammetric tools. The output can be validated blueprints, a fully digital three-dimensional model, or a point cloud.

Table 3. Tasks to be carried out in the collection of data in the industrialized renovation process.

STARTING POINT	END RESULT
EXISTING PAPER BLUEPRINTS	Validated paper blueprints
EXISTING DIGITAL 2D BLUEPRINTS	Validated digital 2d blueprints
EXISTING DIGITAL 3D MODEL	Validated digital 3d model
MANUAL MEASUREMENTS ON SITE	Point clouds
LIDAR SCAN	

- Stakeholders involved and their role in the process:
    - Surveyor: takes measurements on-site, sometimes validates point cloud, and establishes a basic model.
    - LiDaR operator: takes measurements on-site.
    - Architect: validates measurements and establishes a new model.

  - Structural Engineer: validates the structural soundness of the current building, considering additional loads that might be added during the project.
- Common modelling tools:
  - LiDAR scan.
  - Manual laser.
  - Point cloud software may be used (Cyclone of Leica…).
  - 2D BIM software (VectorWorks, AutoCAD, BricsCAD…).
  - 3D BIM software (REVIT, ArchiCAD…).
- Time and cost:
  - Time depends on several characteristics such as project size, the extensiveness of the project, etc.
- Typical dimensional tolerance:
  - Laser distance meter: ±1,5mm/m.
  - Dimension ± 2 cm, due to simplification because of the varying flatness of the surfaces considered (e.g. a brick surface or an existing wooden beam) (Kosny et al., 2014).
- Level of Detail:
  - LOD 100/200.
- Problems detected:
  - A first full scan of the existing building is often ordered or executed by the stakeholder responsible for the new design. Its precision and accuracy will be in tune with its objective of presenting an appealing design for the client or obtaining a construction permit from the local authority. This is often not sufficiently precise for manufacturing parties to use in their CAD/CAM process.
  - Making a more precise model is economically challenging, as it increases the workload without adding value to the initial output objective.
- Diverging models:
  - An LCA study of the existing building will not be based on BIM-available data.
  - The structural check by the Structural Engineer will likely be carried out in a separate model.
  - Hygrothermal analysis of the existing building will be carried out in separate formats, such as the EPC (Engineering, Procurement, and Construction). More detailed calculations can be done but will typically but will normally be made on separate drawings.
- Opportunities:
  - Adding precision-based information at this early stage prevents future inconveniences such as measurement incoherencies.

4.3 Design stage

In many cases, the manufacturer is not defined at the design stage which, thus it is important to consider and document all assumptions and design options, so they can be validated at a later stage.

- Stakeholders involved: their role in the process.
  - Architect: translates the project brief into a representation of the project.
  - Structural Engineer: validates the structural soundness of the current building, considering additional loads that might be added during the project. In this scenario, the structural engineer usually uses a separate model.

- Common modelling tools:
  - 2D BIM software (VectorWorks, AutoCAD…).
  - 3D BIM software (REVIT, ArchiCAD…).
- Time and cost:
  - Time depends on many characteristics such as project size, the extensiveness of the project, revisions needed, etc.
- Typical dimensional tolerance:
  - Dimension ± 4 cm, depending on the precision of the current situation model.
- Level of Detail:
  - LOD 200.
- Problems detected:
  - The objective of presenting an appealing design for the client or obtaining a construction permit from the local authority does not require all details to be considered or known. Dimensions relative to neighbouring structures are generally leading.
  - Making a more precise model is economically challenging, as it increases the workload without adding value to the initial output objective.
  - Diverging models: most information exchange in this situation will be mono-directional. Information and geometrical data can be exported to accommodate supporting specialist studies. Oftentimes the importing of results cannot happen through a direct bidirectional link. It will require manual input and thus creates possible clashes and interpretation errors. This is the case of:
    - When a preliminary LCA study is requested, the architectural model or the BoQ (bill of quantities) can be exported for analysis. Modifications during the LCA study cannot be fed back into the main BIM model. Updates to the BIM model are not automatically reflected in the LCA study. It has to be done manually.
    - Structural analysis is typically done in separate software. Most allow importing .ifc or other files, and some also export them. Very few have a bi-directional link between architectural and structural models.
    - Hygrothermal studies could be carried out on building elements by uploading them into specialised software. A digital energy twin can be used to simulate the building. It is rare to have a real-time link where updates to one model are reflected in the other.
    - Piping systems for HVAC can also be added to the drawings for the execution phase. In most cases, this is done by specialists using distinct software. Since clash detection is key here, a bidirectional flow of information is essential, albeit not always available.
- Opportunities:
  - Adding a BIM model of LOD300 as one of the deliverables at this stage.
  - Providing an export of the BIM model that can be used to validate thermal studies of the building.

4.3.1 Digital survey to BIM

The process starts with the insertion of the digital output of the building survey into the BIM model (Revit, ArchiCAD, etc.). It is good practice for the BIM model to be georeferenced and oriented to the true north. An initial validation needs to be done to check its exportation to IFC or gbXml for future energy studies, solar studies, etc. Typically, it is the BIM Manager who performs this.

The use of a point cloud for the existing architecture survey facilitates the centralisation of all the measurements in the floor plan and elevations. The 360º planar images included in the point cloud survey help to complement the existing information: existing installations (HVAC and other building services such as fire extinguishers, etc.), the definition of windows, doors, etc. This stage requires a certain time, and it has notable costs. However, it is helpful to prevent problems in the beginning that could arise later on.

4.3.2 Design of current situation

The BIM model of the existing building is created. Items and operations that are relevant to the design are reflected in the model. Parts that are to be demolished or particular elements that need to be preserved are identified.

It is important to note that the information that is reflected in this BIM drawing depends, to a certain degree, on the stakeholders involved in this process.

- The position of a concrete column in a plasterboard wall might not have any impact on the architectural design but will be crucial information for the Structural Engineer.
- The position and size of radiators do not have an impact on the exterior façade design but will be important information for the HVAC Engineer.

4.3.3 Refurbished project design

The desired situation of the building is then projected and digitalized, based on the model of the existing building. The objective is to have an accurate digital representation of the building as it should become. Including the necessary building elements and layers can be done in several ways, with varying levels of detail. BIM models help the decision-making in the refurbishment design:

- Facilitating accurate budgets from the early stages of the project.
- Relating BIM models to energy calculation software (6D) and updating conditions.

4.3.4 Hygrothermal performance check

In this phase, a preliminary study is done to ascertain the hygrothermal performances. This can be done using specific software that can read or import IFC models. It includes internal condensation simulations, U-value calculations, and the determination of surface temperatures.

To do this type of simulation is very important to understand the behaviour of the materials used in the construction elements. If the information isn't available at this stage because the manufacturer is not being identified yet, it is important to document all assumptions, so they can be validated at a later stage.

4.3.5 LCA

Preliminary life cycle assessment simulations can be performed in this phase. The architectural BIM Models are exported, either through the Bill of Materials (BoM) or the Bill of Quantities (BoQ) or in IFC format.

4.4 Manufacturing

4.4.1 Execution design

After the general architectural design, construction details are developed. In many cases, the selected manufacturer will submit their (standardized) details to the other stakeholders

(General Contractor, Architect) for approval. Using standardized details and connections will allow for lower manufacturing costs and faster process flows.

After approval, the execution model can be set up by the Manufacturer in BIM drawings. This means the introduction of layers, modules, parts, and elements that can be traced back to physical counterparts. The assembly of these items will create the building.

It is often an iterative process using algorithms to improve material use by reducing cutting losses. When the entire CAM model is set up and approved by the various stakeholders, a complete BoQ and BoM can be exported. With these documents, a detailed budget, manufacturing, and execution planning can be outlined.

Figure 32. View of a production line for prefabricated building elements, by Arquima, https://www.arquima.net/. Copyright by Arquima.

4.4.2 Approved execution design for CAM

Each building element can be broken down into constituting materials. This is a necessary step in realizing and preparing an automated process during which these elements can be prefabricated, preassembled, and possibly mass-produced in an off-site workshop.

The objective is to have an accurate digital representation of all the needed elements and their connections. Including the necessary building elements and layers can be done in some ways, with varying levels of detail.

- Stakeholders involved: their role in the process.
    - General contractor: will be consulted as the integrator of the preassembled modules on-site for things such as technical quality of the standardized design, transport, installation rate, and maximum size/weight of modules that can be handled on-site.
    - Manufacturing company: will create a point cloud model of the current situation and translate the architectural design into an execution drawing, complete with assembly instructions. They do not usually carry out on-site assembly.

  - Architect: will try to adapt their design to manufacturer requirements which implies substantial changes on many occasions.
- Common modelling tools:
  - Most manufacturing parties will use CNC-linked software such as:
    - VertexCAD
    - REVIT plugins

This allows the export of production files from the 3D drawing directly to the machines on the manufacturing line. The process typically includes clash detection and quality checks.

- Time and cost:
  - Depends to a large extent on the level of parametrization of the design which enhances the automation. The initial setup time for these parameters is considerable, as all connections and links need to be designed. By selecting the correct parameters, manual design work can be drastically reduced during the rolling out over a large and repetitive building (stock). The result is a substantial increase in the efficiency that large-scale projects can achieve.
- Typical dimensional tolerance:
  - Dimension ± 0.5 cm, depending on the tolerance required for installation on site.
- Level of Detail:
  - LOD 300/350.
- Problems detected:
  - The manufacturer wants to use a validated model, as they are expected to guarantee the dimensions of their products. To this effect, they will often include a budget (time and labor) to make a LiDAR scan of the building to create their point cloud model. They will make their production drawings in this ‘trusted model’.
  - There is an important feedback loop back to both the designer and the responsible for the building quality. To meet both aesthetical and technical requirements, proposed standardised connections should be validated and approved by them.
  - Further details of the execution model are provided by the manufacturer. This more realistic representation of the building elements is not automatically fed back into the 3D model that was created by the Architect.
  - Each production line will have an intrinsic takt time to be considered for planning.
- Diverging models:
  - In case a preliminary LCA study is requested, an export from the architectural model or the BoQ can be imported for analysis. Modifications during the LCA study cannot be automatically fed back into the main BIM model. Likewise, updates to the BIM model are not automatically reflected in the LCA study.
  - Since manufacturing and structural soundness are intertwined, the producers of prefabricated modules will aim to use software that communicates in real time between CAM-model and the structural model.
  - The extent to which the composition of the prefabricated elements is standardized generally has an impact on the level of detail to which hygrothermal studies are available. In most cases, the calculations are done in standalone programs. A full export of the BIM model to create a digital energy twin is always possible. This link is not in real-time, so any changes after the export are not shown automatically in the other program.
- Opportunities:

- To allow parametrisation, the amount of freedom should be reduced. Standardized connections, a limited palette of material choices, and a consistent composition are important boundary conditions to ease the initial setup of the parameters.
- Prefabrication and modular construction created off-site offer many advantages:
    - Improved quality: working in a controlled environment reduces the impact of external factors on meeting project specifications.
    - Increased efficiency: repetitive processes require less time and allow for a lower chance of error. No mitigating circumstances, such as bad weather, are a risk for project timing.
    - Predictability: working in a controlled setting allows easier budgeting and planning.
    - Increased safety: automated processes on the production line require fewer crew members working with dangerous tools on-site.
    - Reduced waste: BIM automated cutting proposals reduce the amount of waste material. Cutting losses can even be inventoried for future use.
    - Less workforce needed: fewer workers are required because of the automated processes. Installation on-site will typically also be done by fewer workers.
- The use of a common cooperative data transfer platform greatly reduces the risk of incorrect version tracking.
- Including the technical installations and in particular the ducts and piping would increase the value of the BIM model, specifically for the maintenance phase.

Figure 33. Final steps of the production of prefabricated wall elements, by BuildUp Offsite Construction Company, https://www.buildupoffsite.com/nl_BE/blog/buildup-nieuws-1/how-does-offsite-construction-contribute-to-meeting-the-un-sustainable-development-goals-14. Copyright by BuildUp.

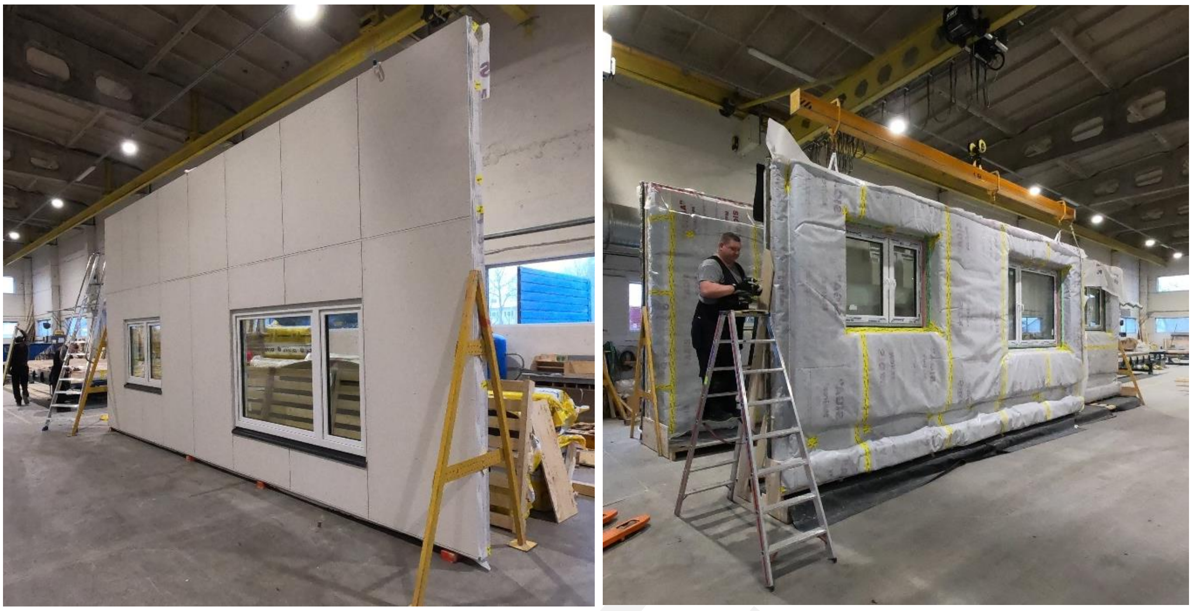


Figure 34. Example of production of prefabricated wall elements in Tartu Living Lab), by authors, 2023. Copyright 2023 by oPEN Lab.

4.5 Transport

Classic packing lists are not sufficient when prefabricated elements are transported. Keeping track of the order of assembly as well as size and weight restrictions become increasingly important with larger modules. Compared to a traditional building site, where material can be stored temporarily on-site, the prefabricated elements must arrive just in time.

- Stakeholders involved: their role in the process.
  - Logistics Company: needs to be aware of the importance of timely delivery.
  - Manufacturing company: needs to load transports in the correct order so unloading can be done safely.
  - General contractor: needs to communicate the rate of installation and order of delivery required to meet the objective.
- Common modeling tools: N/A
- Time and cost:
  - Typically done just in time, to limit the stocking of building components at manufacturers or on-site.
- Problems detected:
  - Size and weight limitations generally apply for any road freight, which should be considered when dividing the project into modular prefabricated elements.
- Opportunities:
  - Prefabricated modules and elements can be assigned to specific freights. This way the filling out of the CMR[1] can be automated.

[1] CMR: abbreviation of the “Convention relative au contract de transport international de Marchandises par Route”; it is a standardized waybill that accompanies road freight.

Figure 35. Finished wall elements loaded onto sleds for transport by truck, by BuildUp Offsite Company, https://www.buildupoffsite.com/nl_BE/offsite-construction/efficiency#. Copyright by BuildUp.

4.6 Construction

The preassembled components are brought to the building site in modular units. The number of operations needed to install these units is far lower than the manipulations an onsite construction process would have needed. Preparatory work is limited to installing the connection elements on the existing building. This can typically be done with limited disturbance for the inhabitants. Other than reducing building time and thus limiting nuisances to inhabitants, this also limits the chances for human error.

The installation of (larger) modular prefabricated elements on site implies the use of the appropriate lifting gear and machines. Hence the role of crane operators will typically increase when compared to a traditional construction site.

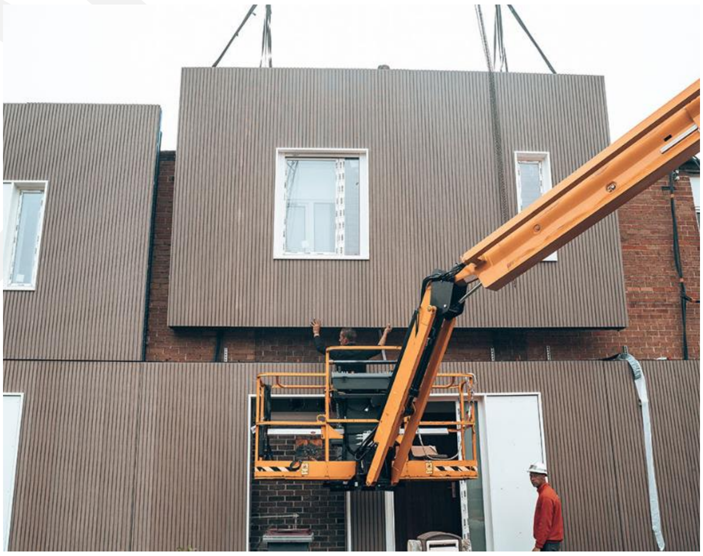


Figure 36. Installation of prefabricated wall elements on site, by BuildUp Offsite Company, https://www.buildupoffsite.com/nl_BE/about-us/our-story. Copyright by BuildUp.

The compliance with the building requirements of each modular prefabricated element should be checked at the manufacturing site and guaranteed. Therefore, the correct treatment of the joints and seams between the modular prefabricated elements is crucial to reach the project requirements.

Depending on the size of the modular elements and the difficulty of the connections to be made on-site, one crane operator with a crew of three workers can install between eight and 20 elements per day.

The overall quality of the result will depend on the quality of the assembly and joint treatment on site.

4.7 Renovated building

The joints and seams where multiple modular prefabricated elements meet require particular attention in the design process. When properly planned, these joints can be made almost invisible in the finished building.

Currently, the costs of an industrialized execution are higher compared to traditional on-site construction, mainly due to the limited number of companies that can propose industrialized solutions. The construction sector is somewhat of an exception in the manufacturing world, as most processes have adopted production-line-based processes and a varying degree of modular prefabrication.

The available final documentation of the works consists of the project BIM model with the modifications made on-site during the execution process and manuals with technical characteristics of the installed materials. Like the initial documentation, is of low quality as it represents the location of the installed elements and a schematic representation of the piping lines.

4.8 Maintenance

Currently, only a limited number of companies have predictive or preventive maintenance plans. For companies with a larger portfolio to look after, this trend is getting more traction. In most cases, maintenance is of a corrective kind, solving problems as they arise with the use of the building.

There isn't perfectly defined as-built documentation, but it is a little bit more defined than in the traditional scenario. Normally there is no BIM detailed documentation that defines the characteristics, assembly manuals, and maintenance of the installed elements.

- Stakeholders involved in the process:
    - Property owner: he/she does a general verification of the documentation received at the end of the work that facilitates the maintenance tasks of the building. He/she should be more involved in obtaining the correct final documentation of work.
    - Construction manager and subcontractors: has to guarantee that the delivery of final documentation is consistent with the original documentation of the project in terms of quality.
- Time and cost:

  - The transmission of knowledge of the installation between the different maintenance operators is more complicated than if a central BIM model was available.
  - The installation of each element is done by different industries and, sometimes, they are not coordinated, which implies more time and costs.
- Problems detected:
  - The degree of knowledge of the building from its final documentation is still low.
  - The as-built documentation can be not updated with the modifications that are made to the building over the years. Thus, the available documentation is no longer valid.
  - As the building documentation is of low quality, It is not possible to know exactly how an element has been executed until it is analysed on-site.
  - The available documentation is of significantly lower quality than the optimized one. In addition, it is not BIM centralized.
- Diverging models:
  - Unless the LCA model is updated after construction, it will remain unchanged and based on the initial design.
  - Unless the structural model is updated after construction, it will remain unchanged and based on the initial design.
  - Unless the hygrothermal (digital energy twin) model is updated after construction, it will remain unchanged and based on the initial design.
- Opportunities:
  - By having an accurate post-intervention BIM model, predictive and preventive maintenance becomes feasible. Faulty connections and/or appliances can be easily searched for in the entire building stock and subsequently reviewed before any damage occurs.

5 Optimized scenario: Integrated renovation process

In this chapter, the specific solution was designed, and it was named the optimized scenario: integrated renovation process.

5.1 General description

This section is the main outcome of this study and describes a renovation process, the involved stakeholders, common modelling tools, time and cost needed. The construction time is shorter in this scenario, as it is shown in *Figure 37*.

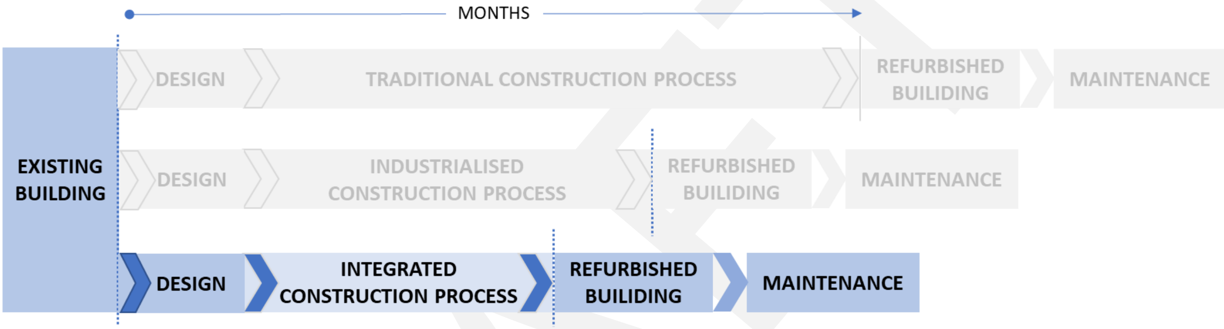


Figure 37. The general scheme of the traditional construction process and industrialized construction process is in grey and the integrated construction process is in blue (listed from top to bottom), by authors, 2023. Copyright 2023 by oPEN Lab.

This section also defines the problems and opportunities of this scenario. As is shown in *Figure 38,* this scenario includes different tools and processes that improve general production. BIM is the centralized source of information that integrates the different processes. It requires tools such as BIM and CAM software ad specific processes such as the exportation of the models from BIM to CAM. These tools and processes did not take place in previous scenarios.

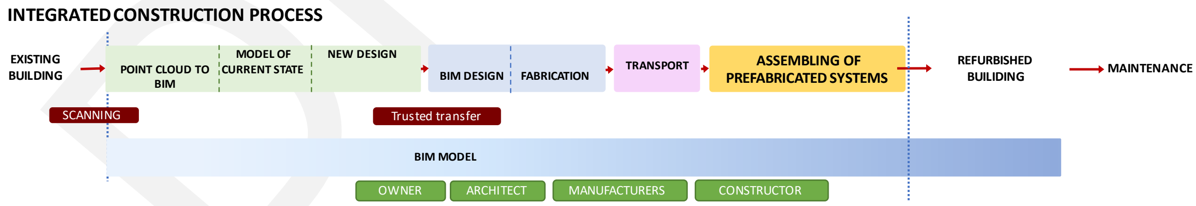


Figure 38. Tools and processes included in the optimized scenario: Integrated construction process**,** by authors, 2023. Copyright 2023 by oPEN Lab.

The flowchart below, *Figure 39*, shows the holistic process of “optimized scenario: integrated renovation process” from the data caption phase with the Point cloud until the maintenance phase. In the central column, this flowchart has a sequence of phases that links with processes (in dark red) and stakeholders (in green). Subprocesses, objectives, and client requirements are represented in boxes.

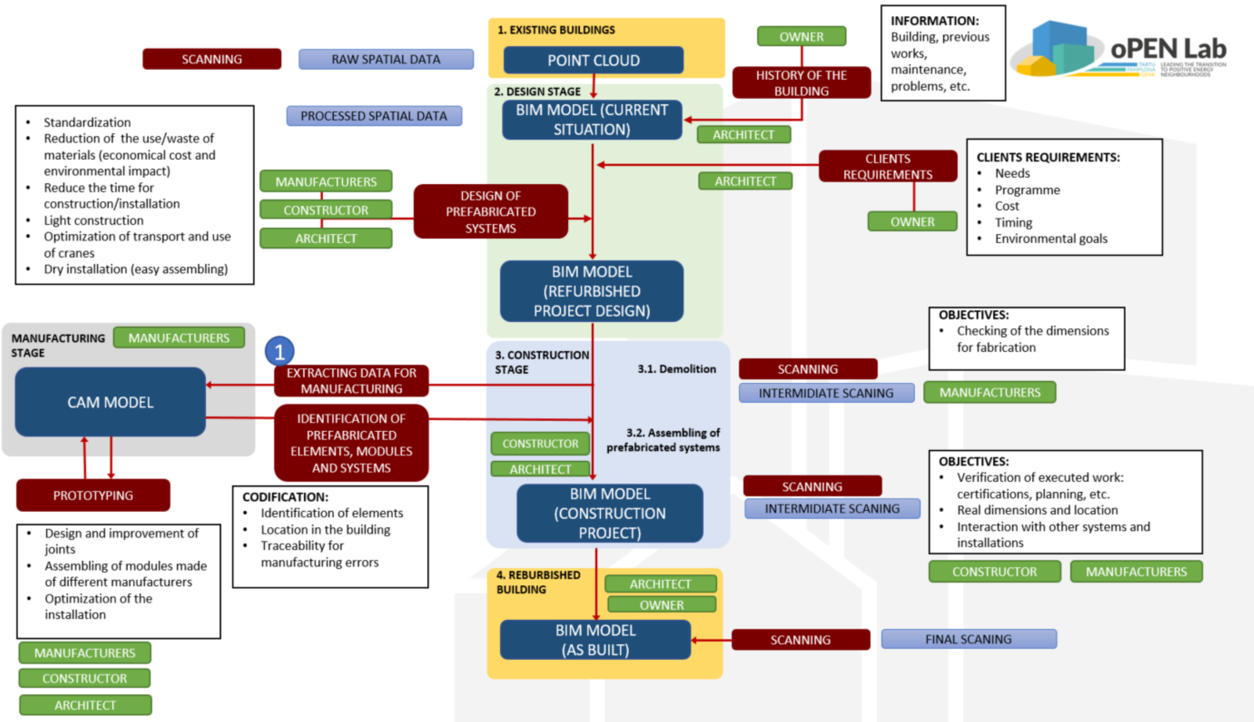


Figure 39. Processes of the different stakeholders during the different stages of the lifecycle in the optimized scenario, by authors, 2023. Copyright 2023 by oPEN Lab.

This flowchart is further explained in each of the following sections. This full section is the main outcome of this study.

5.2 Existing building

In this scenario, the building data collection is performed both with a laser scanner and photogrammetry before any demolition takes place. As a result, a 3D point cloud and a mesh model are obtained to start the BIM model. *Figure 40* represents the tools required to perform the data capture in this scenario.

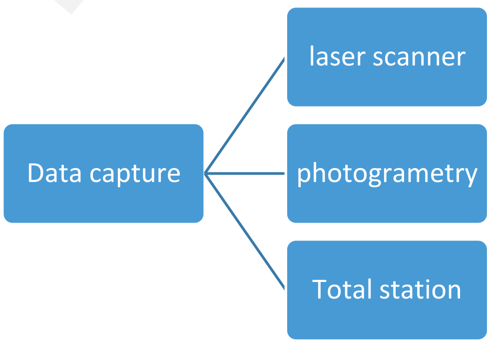


Figure 40. Flowchart of Data capture within the optimized scenario, by authors, 2023. Copyright 2023 by oPEN Lab.

The scope of the existing building stage in this scenario is:

- Stakeholders involved: their role in the process.
  - Surveyor: takes measurements with the scanner laser and photo camera.

  - LiDaR operator: takes measurements on-site if needed.
  - Architect: validates measurements and establishes the BIM model of the current state.
  - Structural Engineer: validates the structural soundness of the current building, considering additional loads that might be added during the project.
- Common modelling tools:
  - LiDAR scan.
  - Advanced laser scanner.
  - Point cloud software such as Leica.
  - 3D BIM software (REVIT, ArchiCAD…).
  - IFC Visors.
  - GIS software.
- Time and cost:
  - Time depends on several characteristics such as project size, the extensiveness of the project, etc.
- Typical dimensional tolerance:
  - Laser distance meter: ±1,5mm/m
  - Dimension ± 2 cm, due to simplification because of the varying flatness of the surfaces considered (e.g., a brick surface or an existing wooden beam)
- Level of Detail:
  - LOD 200.
- Opportunities:
  - Adding a precision-based objective at this stage.
  - A first full scan of the existing building is often ordered or executed by the stakeholder responsible for the property so it can be precise enough to be useful also for the fabrication phase.
  - Making a more precise data capture 3D model adds value to the initial output objective.

5.3 Design stage

If possible, the maintenance records provided by the owner of the building are taken into consideration in the design phase. Those maintenance records may point to problems in the use, installations, etc.

The owner (for example the Pamplona City Council of social housing, in the case study of oPEN Living Lab Pamplona) should define the project requirements: program of needs, maximum budget, deadlines, and environmental objectives so the architect can include them in the design.

- Stakeholders involved: their role in the process.
  - Architect: prepares the executive documentation to develop the architectonic project for the building construction.
  - Structural Engineer: analyses the existing structure and the definition of the new structure ensuring compliance with regulations. In this scenario, the structural engineer usually uses an integrated model.
  - BIM Manager: prepares the current state BIM models from the point cloud.
- Common modelling tools:
  - 3D BIM software.

  - LCA software. In this scenario, LCA takes the information from the BIM model.
  - Hygrothermal software. Data is obtained from the BIM model.
  - Mesh software works with triangles and polygons (Rhino, Blender, etc.)
- Time and cost:
  - Time and cost are considered at early stages so there is less insecurity for the property.
  - Time depends on many characteristics such as project size, the extensiveness of the project, revisions needed, etc.
- Typical dimensional tolerance:
  - Depending on the quality of the initial data collection of the building, it can vary considerably.
    - Good quality data collection: +-1cm.
    - Bad quality +-3cm.
- Level of Detail:
  - LOD 300.
- Opportunities:
  - The property wants to have a good design project to avoid execution problems in the construction phase and unwanted delays and extra costs.
  - The property understands that making a more accurate model adds value to the output target and leads to saving time and cost during the works.

The design stage has some subprocesses explained below:

5.3.1 Point cloud to BIM

The design stage starts with the importation of the point cloud into the BIM modelling software (Revit, ArchiCAD, etc.). The point cloud needs to be georeferenced and oriented to the real north. Once the point cloud has been imported to the BIM model, an initial validation of the BIM model needs to be done to check its exportation to IFC or gbXml for future energy studies, solar studies, etc. The BIM Manager is the stakeholder responsible for it.

The use of a point cloud for the existing architecture survey facilitates the centralisation of all the measurements in the floor plans and elevations. The 360º planar images included in the point cloud survey help to complement the existing information: existing installations (mechanisms, fire extinguishers, etc.), the definition of windows, doors, etc. This stage requires a certain time, and it has notable economic costs.

Additionally, a photogrammetry survey of the existing building could be necessary because it may be needed during the manufacturing phase.

5.3.2 Design of current situation

The BIM model of the existing building is created based on the point cloud. Demolitions and elements to be preserved must be reflected within the BIM model.

In this phase also a mesh 3D model can be generated based on the point cloud or based on the photogrammetry survey if needed for future manufacture. This mesh has to be a fully enclosed surface that contains the same information as the point cloud. Additionally, intersections and Boolean operations are required.

5.3.3 Refurbished project design

The refurbishment BIM models must be based on the existing building model. BIM models help the decision-making in the refurbishment design thanks to:

- Obtaining accurate budgets from the early stages of the project.

- Updating construction programming modifications within BIM models, what is called BIM 4D.
- Getting construction costs directly related to graphical representation in the BIM model, which is named BIM 5D.
- Relating BIM models to energy calculation software, which is named BIM 6D, and updating conditions.

5.3.4 Detailed project design and optimization

After the general architectural design or the refurbishment design, construction details are developed. After the approval of the planning applications from different stakeholders (property, city hall, local council, etc.) or the tender concession, the BIM model is delivered to the construction company. The contractor must adjust the model to the budgeting and planning, and the approved technical alternatives.

5.3.4.1 Simulation and optimization algorithms to improve the design

During this detailed project design, simulation algorithms, and optimized algorithms are performed to improve the material waste of the prefabricated pieces. These simulations use

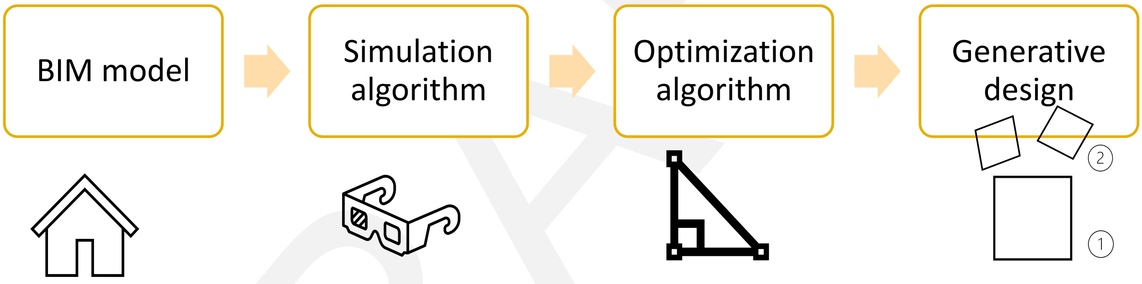


Figure 41. Detailed project design flowchart for the optimized scenario, by authors, 2023. Copyright 2023 by oPEN Lab**.**

BIM information to be performed, as shown in *Figure 42* and *Figure 42*. These optimizations will reduce material waste and improve constructive design. The design of the prefabricated pieces is optimized by using simulation and heuristic algorithms, giving as a result the generative design that will be used in the manufacturing phase.

Algorithms are a series of operations used to optimize a set of variables or properties. These algorithms provide optimized information on certain variables. The results of optimized information are shown to the stakeholder who is the one that decides improvements for the generative design. The algorithms do not optimize the process itself just help the decision-making.

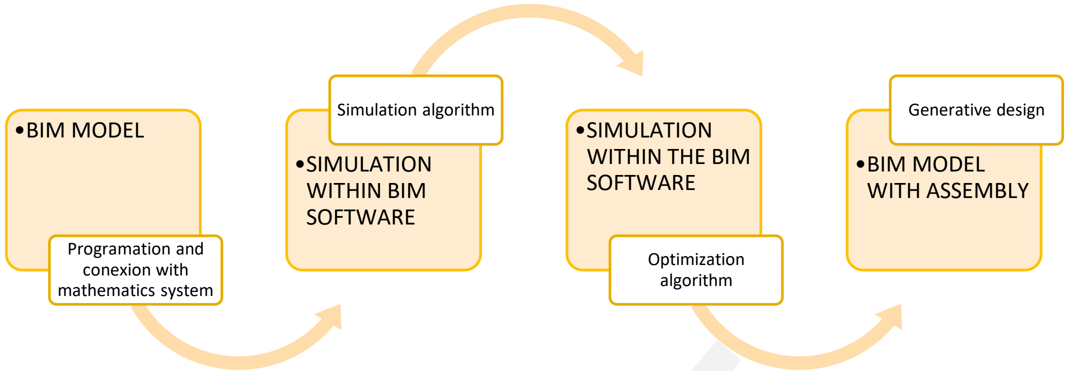


Figure 42. Detailed project design process of the optimized scenario, by authors, 2023. Copyright 2023 by oPEN Lab.

The objective of heuristic algorithms is to produce a solution in a reasonable time frame that is good enough for solving the problem at hand. BIM data is extracted from the model and optimized with these mathematic formulas through algorithms.

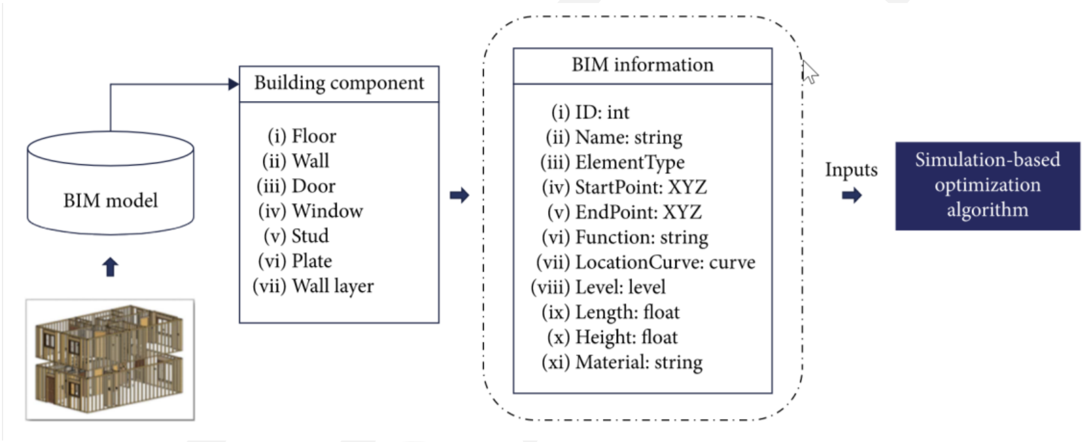


Figure 43. Extraction of information from the BIM model, by Lobo J. et al. (2021)

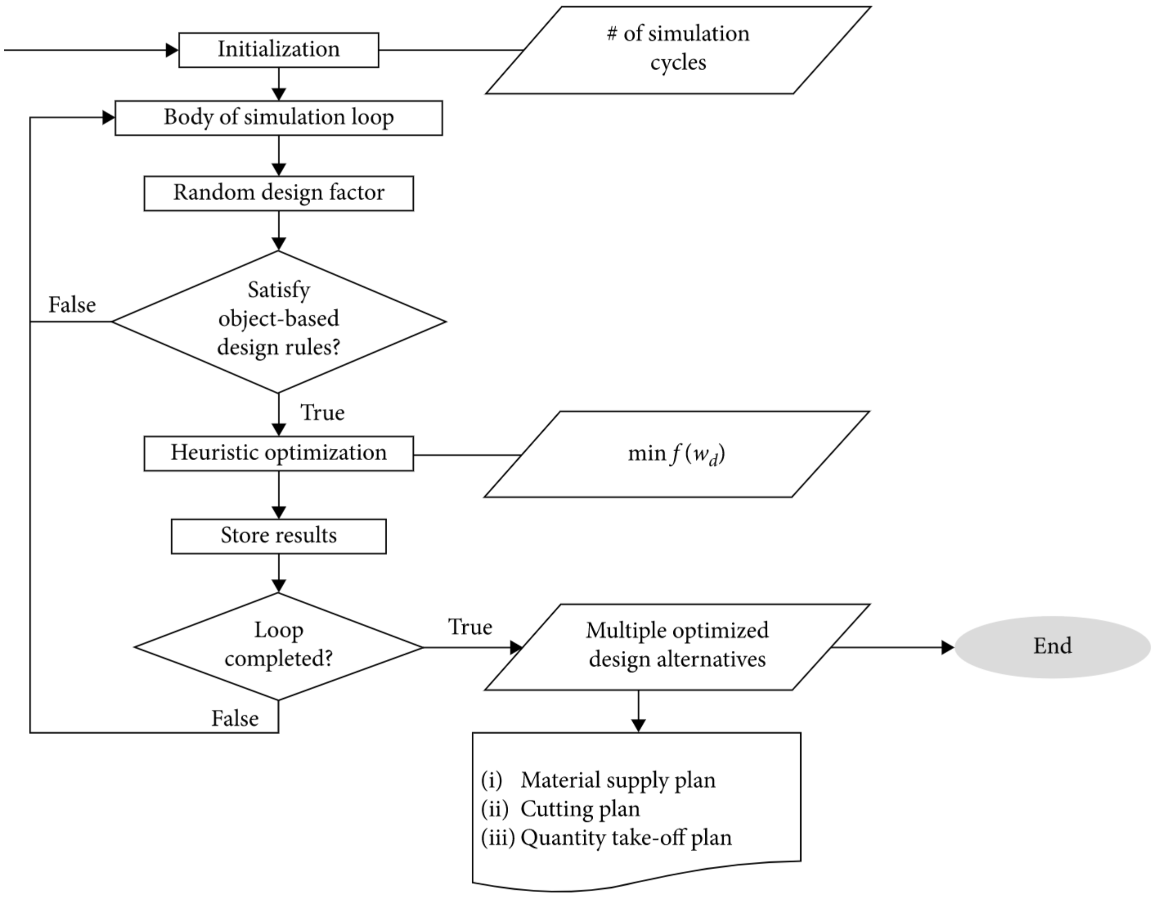


Figure 44. Algorithms: Simulation-Based Design and Heuristic Optimization, by Lobo J. et al. (2021).

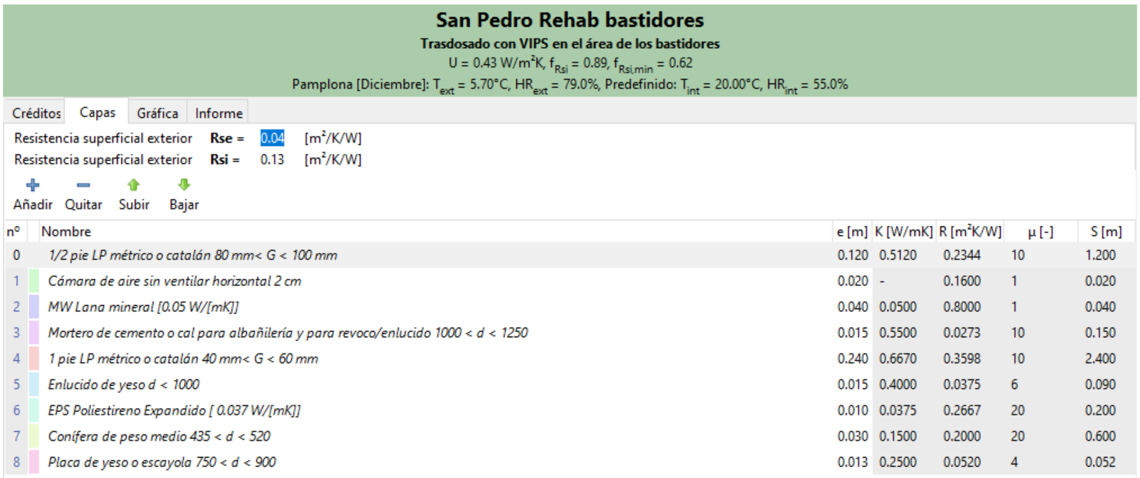
5.3.4.2 Coding BIM elements

In another hand, it is necessary to code each part of the BIM model. Coding is a critical part that is performed after the generative design of the pieces. Each piece needs to have a unique code that identifies it unequivocally. The BIM model needs to be exported to IFC format, which is the open BIM format that will facilitate the communication between BIM and CAM machines. Each element of the IFC models has this unique code that is named IFCGuid. This parameter needs to be transferred to the manufacturing phase.

5.3.5 Hygrothermal performance

In this phase, the hygrothermal performance analyses are done using specific software that can read or import IFC models. Those performances include enclosures condensation simulations and calculations of surface temperature.

This type of simulation is very important to know the hygrothermal characteristics of the different layers of the walls and construction elements as shown in *Figure 45*.



San Pedro Rehab bastidores

Trasdosado con VIPS en el área de los bastidores

U = 0.43 W/m²K, f_{Rsi} = 0.89, $f_{Rsi,min}$ = 0.62

Pamplona [Diciembre]: T_{ext} = 5.70°C, HR_{ext} = 79.0%, Predefinido: T_{int} = 20.00°C, HR_{int} = 55.0%

Créditos | Capas | Gráfica | Informe

Resistencia superficial exterior **Rse =** 0.04 [m²/K/W]

Resistencia superficial exterior **Rsi =** 0.13 [m²/K/W]

Añadir Quitar Subir Bajar

nº	Nombre	e [m]	K [W/mK]	R [m²K/W]	μ [-]	S [m]
0	*1/2 pie LP métrico o catalán 80 mm< G < 100 mm*	0.120	0.5120	0.2344	10	1.200
1	*Cámara de aire sin ventilar horizontal 2 cm*	0.020	-	0.1600	1	0.020
2	*MW Lana mineral [0.05 W/[mK]]*	0.040	0.0500	0.8000	1	0.040
3	*Mortero de cemento o cal para albañilería y para revoco/enlucido 1000 < d < 1250*	0.015	0.5500	0.0273	10	0.150
4	*1 pie LP métrico o catalán 40 mm< G < 60 mm*	0.240	0.6670	0.3598	10	2.400
5	*Enlucido de yeso d < 1000*	0.015	0.4000	0.0375	6	0.090
6	*EPS Poliestireno Expandido [0.037 W/[mK]]*	0.010	0.0375	0.2667	20	0.200
7	*Conífera de peso medio 435 < d < 520*	0.030	0.1500	0.2000	20	0.600
8	*Placa de yeso o escayola 750 < d < 900*	0.013	0.2500	0.0520	4	0.052

Figure 45. Example of layers of a wall inserted in the hygrothermal software, by authors, 2023. Copyright 2023 by oPEN Lab.

Values of vapor pressure and temperature between the inside and outside are the result of the calculations. An example of these calculations is shown in *Figure 46*.

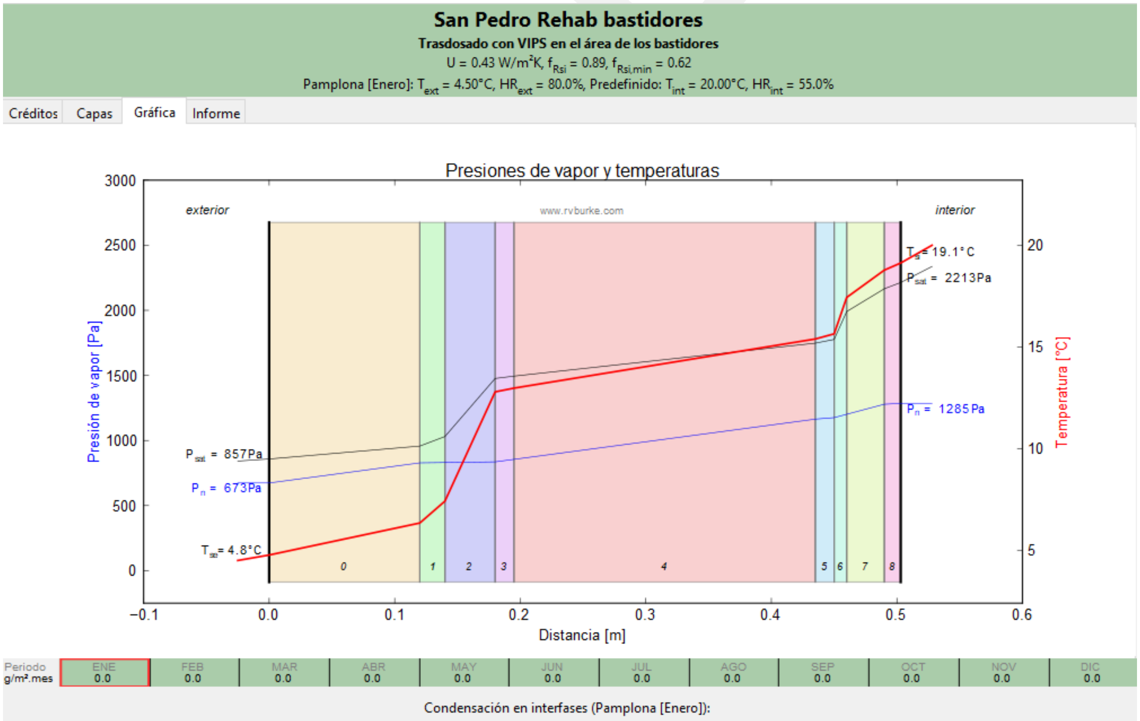


Figure 46. Vapor pressure and temperature difference between inside and outside, by authors, 2023. Copyright 2023 by oPEN Lab.

5.3.6 LCA

In this scenario, life cycle simulations are performed during this phase. The BIM models are imported, ideally in IFC format in the life cycle software, and the required data to define spaces is specified in this kind of software. The more information the IFC can provide, the more automated the LCA calculations will be.

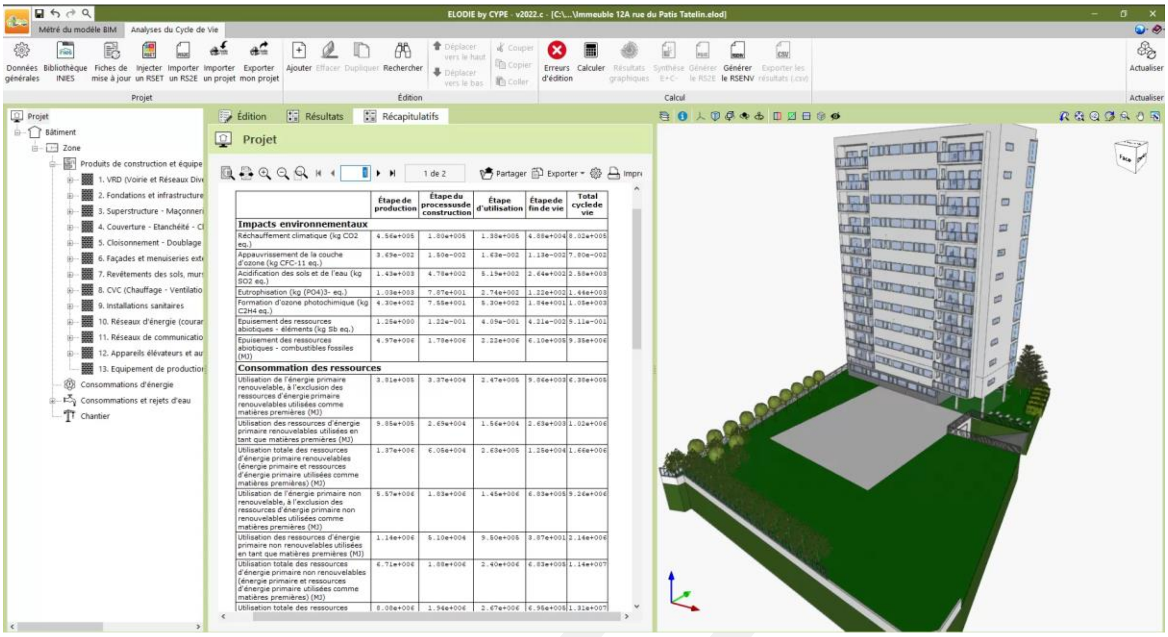


Figure 47. Example of LCA software used in the design phase to know LCA performance, by CYPE Ingenieros, https://info.cype.com/fr/software/elodie-by-cype/. Copyright by CYPE Ingenieros.

5.4 Manufacturing

In this scenario, manufacturing is key to improving the general cost and time savings. The manufacturing companies must be digitalized. In general terms, the manufacturing phase in this scenario includes the sub-phases described in the figure *Figure 48*. The sub-phases are explained below.

- Base material or raw material arrives at the workshop, and it needs to be classified and arranged.
- Architecture fabrication in the workshop implies off-site production of construction and architectural systems, such as walls, floors, etc.
- Systems fabrication in the workshop implies off-site construction of mechanical, electrical, and plumbing construction systems.
- Pieces transport consists of moving the pieces or systems from the workshop to the final location of the building.
- Assembly on site implies unpacking, organising, and assembling on site the pieces or systems.

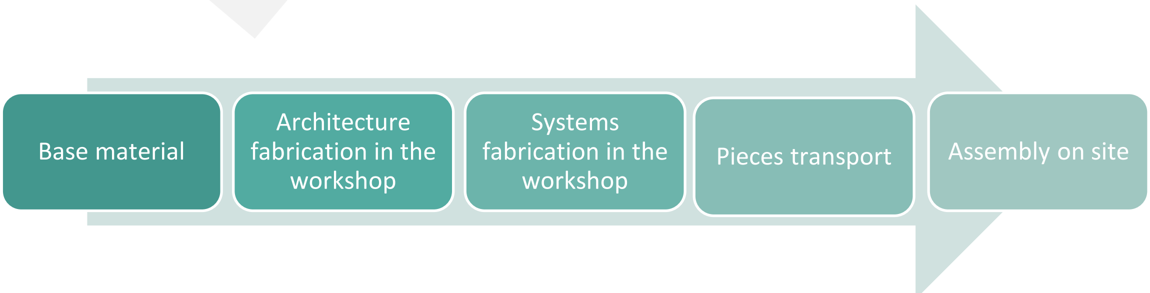


Figure 48. Manufacturing process from receiving material to assembly on-site, by authors, 2023. Copyright 2023 by oPEN Lab.

The characteristics of manufacturing are:

- Agents involved in the process:
  - General contractor: will be asked any questions that the subcontractor needs to prepare their proposals.
  - Subcontractor: will define the constructive proposals to be executed.
  - Manufacturing company: will prepare the constructive proposals to be executed based on what was discussed at the construction site.
  - Architect: will check the proposals submitted and will approve the final solutions.
- Common modelling tools:
  - Manufacturing parties use BIM software. This allows them to export production files from the 3D drawing directly to the manufacturing line.
  - CAM software.
  - Mesh editing software (such as Rhino Inside).
- Time and cost:
  - The process of defining the elements to be manufactured extends from the preparation of the initial proposal, analysis by the construction management, request for modifications, and preparation of the final construction design.
  - The manufacturing cost is high, adjusted to the necessary personnel, medium profit margin, and material costs of prefabricated manufacturing.
- Typical dimensional tolerance:
  - Depending on the element to be manufactured and the tolerance needed from ± 0.2 cm to 0.5 cm.
- Level of Detail:
  - LOD 400.
- Opportunities:
  - The process of defining each constructive element is collaborative and must consider other affected subcontractors.
  - Manufacturing measurements are taken from the BIM model, so human errors are reduced.

The digitalization of the process to obtain data from BIM to CAM models is the key to manufacturing optimization. The manufacturer must obtain the data from the BIM model as is represented in *Figure 49*. The BIM models are exported into intermediate software if needed, such as Rhino. From the intermediate software, the files can be exported to CAM machines to be produced. This process is the main purpose of the document, and it is further explained in the next sections.

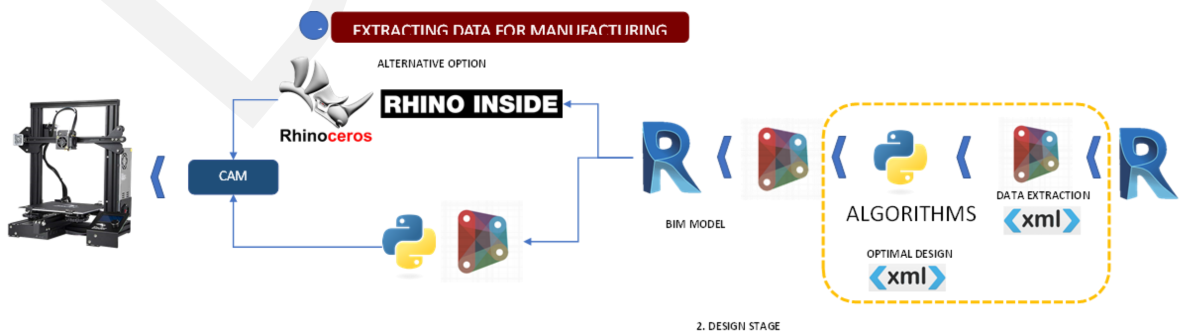


Figure 49. Optimized scenario: integrated renovation design process flowchart, by authors, 2023. Copyright 2023 by oPEN Lab.

The error range may be no more than 5mm between the point cloud and the CAM machine. The fabrication model that reads the CAM machine does not need to have a high level of detail. The goal is that the CAM machine can recognise as much data from the BIM model as possible. The level of detail is linked to the precision level of the CAM machine depending on the machine engines.

In industrial engineering, 3D printing machines are sometimes used to generate a full specific product. The specification of the type of CAM machine is very important to reduce cost and time and to improve manufacturing quality.

5.5 Transport and Construction

The material is delivered on-site, so only a list of materials delivered on-site is available.

Each material has manufacturing codes coming from the BIM model to follow the traceability of its manufacture. These codes also include information on where the piece or material must be installed. These codes arise from the IFC BIM model and the information should remain both in the BIM model and in the CAM model. The characteristics of this phase are:

- Agents involved: their role in the process.
  - Logistics Company: makes deliveries according to material requests on site.
  - Manufacturing company: sends the material as it is available and requested.
  - General contractor: needs to know the arrival dates of the material to adapt the planning of the work to the arrival of the material.
- Time and cost:
  - The main contractor has direct contact with the manufacturer. Hence, there may be fewer problems with the delivery schedule.
- Opportunities:
  - Every element necessary is sent to the construction site. So, delays of the material pending delivery would be reduced.
  - BIM 4D information is available on delivery times so manufacturing issues or problems with the transport company would be reduced.

In this scenario, the construction planning predetermines the following:

- The rhythm elements fabrication in the factory does not have unsupplied processes on the construction site.
- The number of trips to the construction site. This can be optimized through a previous simulation with the BIM models.
- The size of the truck transporting pieces according to the storage possibilities on-site.
- The transportation emissions. The goal is to reduce the number of trips and the truckload.

The construction phase begins normally with the interior demolition works, in case of refurbishments. Once it is completed, it is recommended to carry out a laser scanning of the interior. It is not necessary to run it again on the outside if there were no demolitions outside.

Adjustments to the existing BIM building model should be done after checking the interior point cloud measurements. If something in the BIM model changes it must be updated and sent again to the manufacturing company.

For invoicing purposes of the construction works carried out during the construction works, it is desirable to run a laser scanner survey of the affected areas to reflect the advances in each work certification. The point cloud of the certification is compared with the BIM model to check possible deviations and corrections. Also, point clouds in each certification are useful to record future hidden Mechanical, Electric, or Plumbing (MEP) installations before covering them.

5.6 Assembling of prefabricated systems and GIS

The optimized scenario includes this development related to the use of the BIM model for site management. Once the pieces or materials arrive at the construction site, the BIM Coding of the IFC model should be considered to assemble them on-site. BIM models are related to GIS software to locate the pieces. BIM IFC models also support the on-site storage of elements as fixings for example.

If assembling in the factory is not possible, the typified and numbered pieces (uprights, crosspieces, and panels) can be packaged for their assembly on-site. This option provides improvements compared to the traditional method since cuts and material waste are reduced because the assembly needs have already been studied.

5.7 Maintenance

The maintenance phase occurs after the construction is finished. In this phase, the BIM model is as-built. In general, it is a simpler BIM model than in the construction phase. For example, if the object of maintenance is the fire systems, the other construction systems would be modeled in a very simple way.

Figure 39 (presented in section 5.1) shows the holistic process from the data caption phase with the Point cloud until the maintenance phase of the optimized scenario. *Figure 50* is an extract from this flowchart that shows the maintenance part.

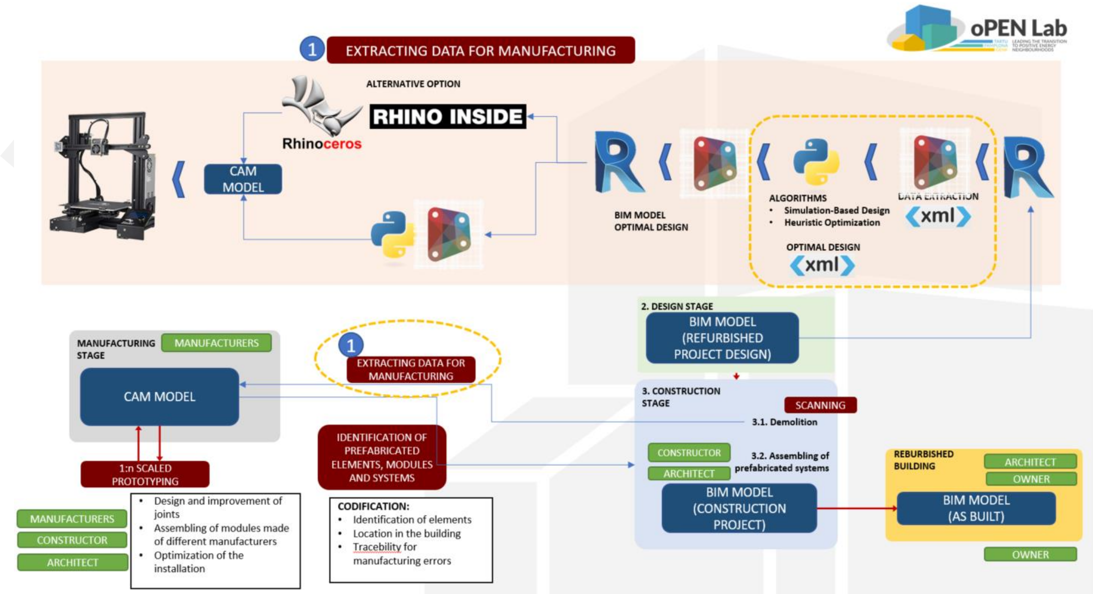


Figure 50. Life cycle process until as-built model of the refurbished building in the optimized scenario, by authors, 2023. Copyright 2023 by oPEN Lab.

The BIM model of the maintenance phase is generated from the construction BIM model, and it requires a final scanning. The maintenance BIM model must have the location parameters of each room or element as a general criterion.

Maintenance is linked through parameters in the BIM model. This allows linking any BIM parameter with external maintenance software.

5.7.1 LCA

During the maintenance phase, it is important to take LCA into account. LCA indicators need to be carried out as well as integrated with the IFC BIM models. The proposal is to include LCA parameters in the BIM models that could be used during the whole operations phase. These parameters could be filtered depending on the system that is needed to manage within the BIM model.

5.8 Conclusion of optimized scenario: Integrated renovation process

The graphic below shows the improvement in time between the different scenarios.

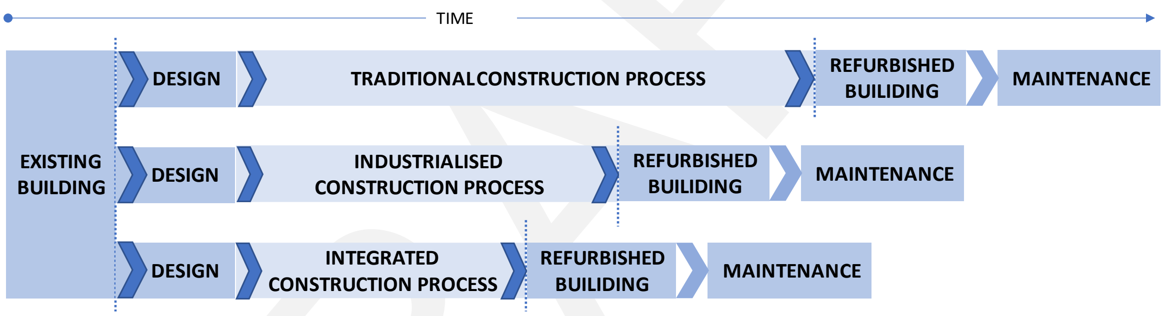


Figure 51. Comparison of time improvement between the different scenarios: traditional construction process, industrialized construction process, and the integrated construction process (listed from top to bottom). This figure was already presented before in the introduction, by authors, 2023. Copyright 2023 by oPEN Lab.

In this scenario, the time of the integrated construction process is shorter than in the other scenarios presented. It means that the final cost of the construction is lower, and the quality of the construction is higher.

6 Testing the optimized scenario flowchart

In this chapter, it is presented the testing of the digital flowchart in the three oPEN Living Labs. The current report is limited to this stage of testing. However, the implementation of the flowchart and its adaptation to the reality in the case studies is ongoing, and the results of this process will be published in the next outcomes of the study.

6.1 Testing procedure

The objective of this chapter is to explain the grounds on which the testing stands, and why the proposed actions constitute a valid procedure. The digital flowchart of the optimized scenario has been tested in the three living labs. Nevertheless, the implementation and validation in real cases study is ongoing due to the speed of development of the construction works of the three case studies.

6.1.1 Selection of case studies

Three case studies were selected to test the optimized scenario, one in each Living Lab: Tartu, Pamplona, and Genk. The case studies consist of characteristic and innovative prefabricated solutions that best represent oPEN Lab renovation works. The testing in various building typologies located in different countries and contexts provides a wider perspective of the proposal and enables replicability ad applicability to other case studies.

- In Pamplona Living Lab, the prefabricated system to study is the interior high-performance insulation panel in San Pedro dwellings (Pamplona Living Lab)

-In Tartu Living Lab, the prefabricated system to study is an exterior façade system in the Annelinn building.

-In Genk Living Lab, a prefabricated façade system in Nieuw Texas homes.

6.1.2 Application of the flowchart to case studies

Firstly, the scope, processes, tasks, and tools used in each case study were analysed to determine how the proposed flowchart can be implemented. After that, two differentiated stages have been defined:

1. **Testing of the digital flowchart**: in this stage, the digital workflow has been tested in the three Living Labs to check the feasibility of the software´s links (exports and imports), stakeholder roles and relationships and stages of the process, breaches in the flow and possible problems, etc. Each living lab has undertaken this with a different approach and level of definition, as it will be described below. The results of this phase will be analyzed and discussed in the current report.
2. **Implementation and validation of the process in real case studies**: this stage, which is currently ongoing, is focused on the implementation and adaptation of the flowchart in three real case studies (one per oPEN Living Lab): Pamplona, Tartu, and Genk. The results will be compared to the baseline scenario in order to quantify the benefits of the proposal in terms of reduction of cost, time, and environmental impact improvements achieved. Key Performance Indicators will be defined for this purpose. The results and conclusion of this process will be published in the next outcomes of the study.

6.1.2.1 Pamplona oPEN Living Lab case study

In the Pamplona case study, the full digital flowchart has been tested in San Pedro with the fabrication of a 1:10 scale model of the prefabricated wall system in the Fablab of the University of the Basque Country (UPV/EHU). The building was fully scanned and a BIM model was built. Due to the development of the renovations, it was decided to first validate it in a lab environment, recreating all the stages of the process. Thus, the manufacturing actions could have experimented with a 3D printer and a milling machine in a lab environment (development of a 1:10 scale model as a prototype) but not in real CAD/CAM industrial machines yet. As some industrial manufacturers use 3D printers and/or milling machines in their production chain, this testing and validation with the model will help to further translate CAD/CAM processes to a real production chain.

At present, since the renovation works in San Pedro have started (interior demolition works), the stakeholders (including the construction company) are working on the implementation and adaptation of the flowchart to the case study. The results of this process will be published in the next outcomes of the study.

6.1.2.2 Tartu oPEN Living Lab case study

In the Tartu case study, the flowchart has been tested in Annelin with the fabrication of a prefabricated wall system as a prototype. The building was fully scanned and a BIM model was built. The renovation process has been digitalized, making seamless links between detailed laser scanning data to computer-aided manufacturing (from scan to CAM). It conducted the study of the continuity of digital information and the guts of the link from BIM to CAM.

At present, the stakeholders are working on the implementation and adaptation of the flowchart to the case study. The results of this process will be published in the next outcomes of the study.

6.1.2.3 Genk oPEN Living Lab case study

In the Genk case study, the optimized flowchart was analyzed and partially tested in the design stage of Nieuw Texas homes. The BIM model was built from blueprints and not from scanning.

The BIM model of the architect has been exported to .ifc and shared with project partners to identify and improve workflows and stakeholders` relationships.

At present, the stakeholders are working on the implementation of the flowchart and adapting it to the reality of the case study. The results of this process will be published in the next outcomes of the study.

6.2 Pamplona oPEN Living Lab Case Study

In oPEN Living Lab Pamplona, one of the case studies is San Pedro, a residential building composed of 12 dwellings. In this building, the prefabricated system to study is the interior wall insulation panel. The intervention in this case study includes:

- A renovation of the interior layouts and facilities is proposed, adapting them to current needs.
- It is also proposed to improve the energy efficiency of the building by installing an interior insulating façade system. Maintaining the exterior aesthetics of the building was a requirement. In addition, the building has already a thin layer of external insulation,

so there are no large thermal bridges to mitigate. Doing so allows the reduction of scaffolding and associated inconveniences to the users.

As mentioned before, the full digital flowchart has been tested with the fabrication of a 1:10 scale model of the prefabricated wall system in the Fablab of the University of the Basque Country (UPV/EHU).

As first approach, it has been carried out the adaptation of the general flowchart to the specific machines available in the Fablab as shown in *Figure 52*. For clarity, the figure includes the icons of the specific software used during the testing: Revit, Grasshopper, and a 3D printer machine.

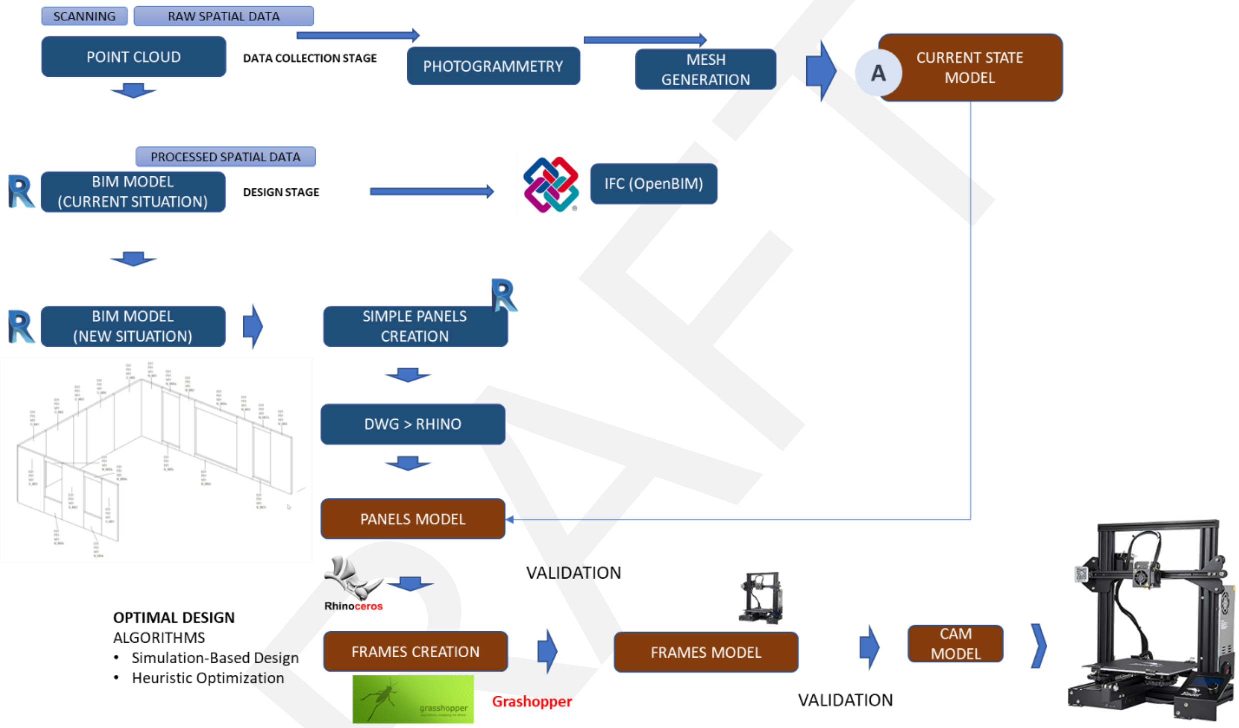


Figure 52. Digital flowchart from point cloud to CAM model used in Pamplona oPEN Living LAB, by authors, 2023. Copyright 2023 by oPEN Lab.

6.2.1 Existing building

Full data collection of the San Pedro building was performed with an RCP Leica laser scanner following all the recommendations of the optimized scenario. As a result, a point cloud of the building was created.

It was necessary to do a photogrammetry data caption at the beginning of the process because it was required to produce a specific CAM mesh model. Ideally, this step would not have been necessary because the mesh would have been generated directly from the point cloud. In practice, in this specific case, the laser scanning for the creation of the point cloud was done before the definition of this workflow and the requirement for the CAM mesh model was not covered. It should have included the corners of windows and façade entrances, the roof, and mirror and glass reflections.

The photogrammetry model has been done with 207 photographs with a Sony Alpha 7 Mark II (ILCE-7M2) and compiled with the commercial software Agisoft Metashape Standard©, Versión 2.0.0. The resultant models are a massive point cloud that contains 145,545,317 points and a mesh. The mesh model has been used to fabricate the exterior facade prototype of the San Pedro building, as seen in *Figure 53***.** The photogrammetry model has been compared with the LIDAR model to validate the data. Even though the data of the point cloud was incomplete, the quality of the information was good enough to validate the information.

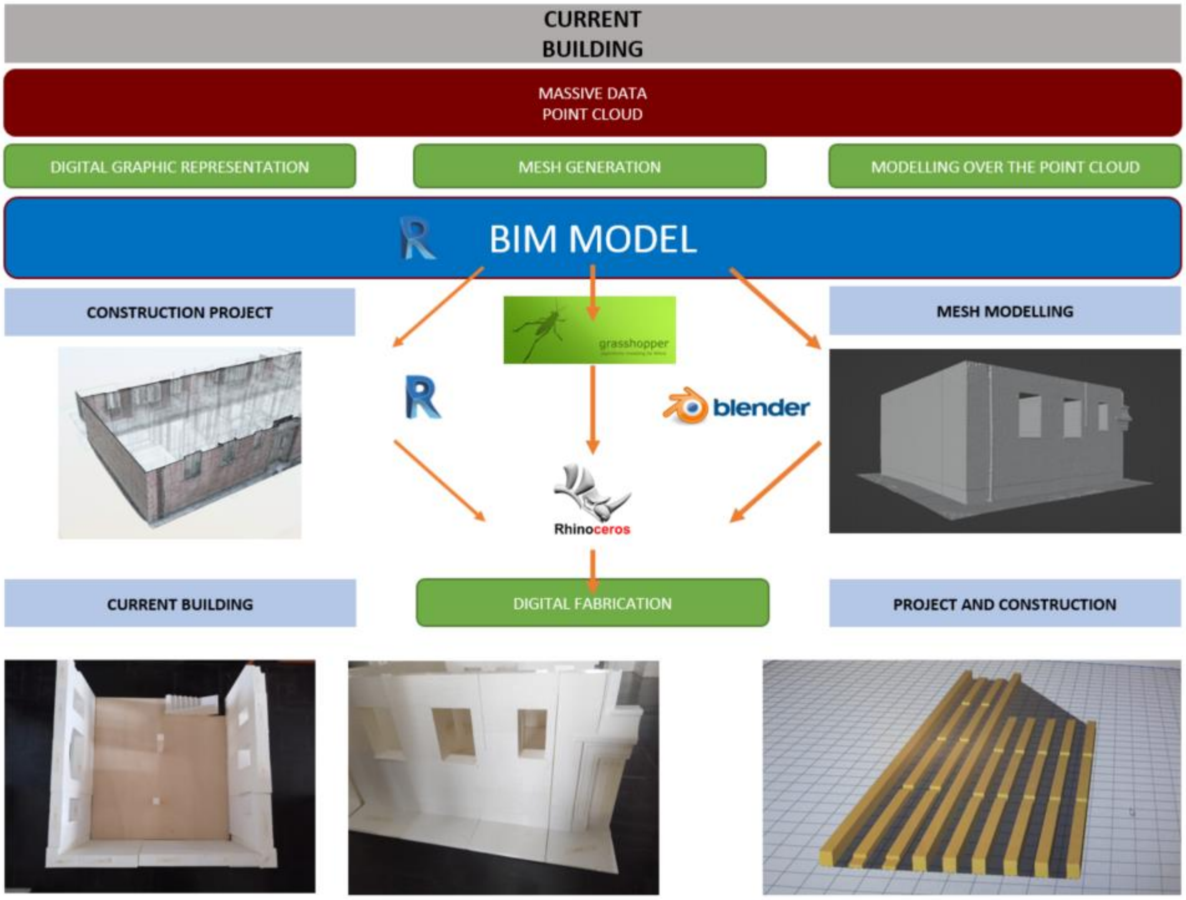


Figure 53. Adaptation of the flowchart to the San Pedro case study, by authors, 2023. Copyright 2023 by oPEN Lab.

6.2.2 Design stage

6.2.2.1 Point cloud to BIM

The building point cloud was used as a skeleton to build a BIM model of the existing façade, as is represented in *Figure 54*, *Figure 55*, *Figure 56*, *Figure* 57, and *Figure 58*.

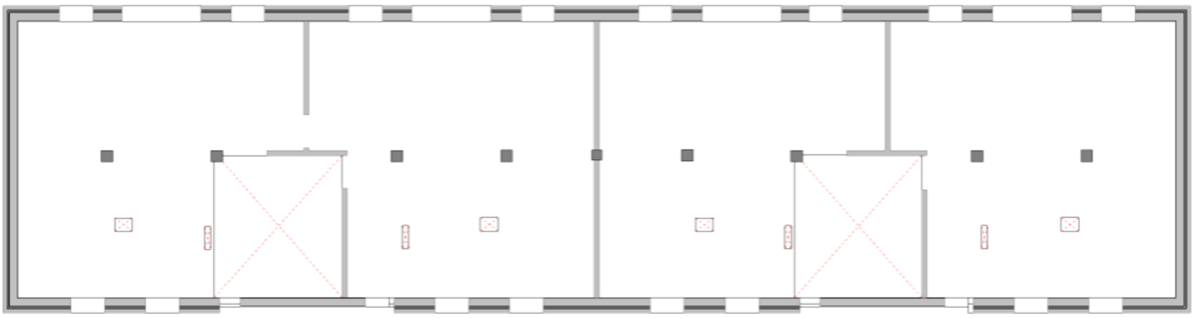
6.2.2.2 Design of current situation

The irregularities, conflict points, and existing elements such as structural systems were represented in the existing BIM model.

6.2.2.3 Refurbished project design

The building is divided into zones, blocks, floors, dwellings, etc. A code comprising different parameters allows the location of each room in the building. Each type of building requires its coding system according to its characteristics.

As an example, the following coding system was proposed for the Pamplona living lab. Specifically, *Figure 54* shows the “San Pedro” building. A coding system is proposed to know the specific position of each prefabricated element in the building. This system contemplates a tool to locate this element in a GIS environment.



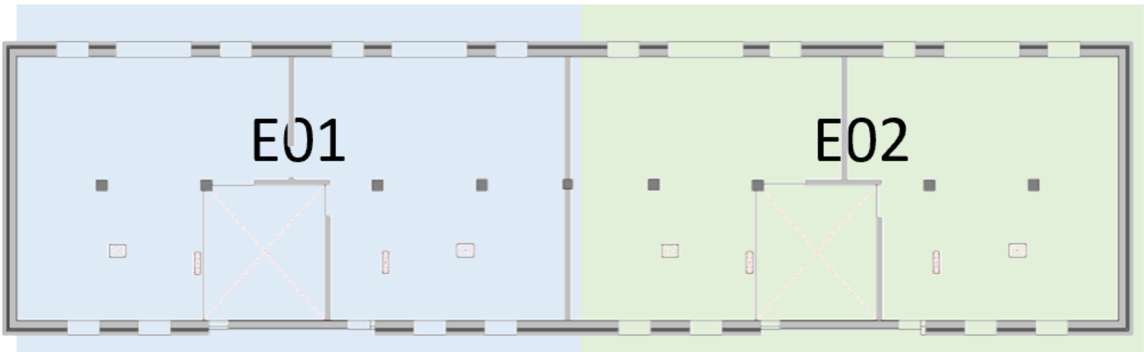
NEW SITUATION. OPEN FLOOR. COMPLETED DEMOLITIONS

Datos	
LOC_Ubicacion1	E01
LOC_Ubicacion2	P00
LOC_Ubicacion3	V1
LOC_Ubicacion4	N_PA1
LOC_Ubicacion5	03

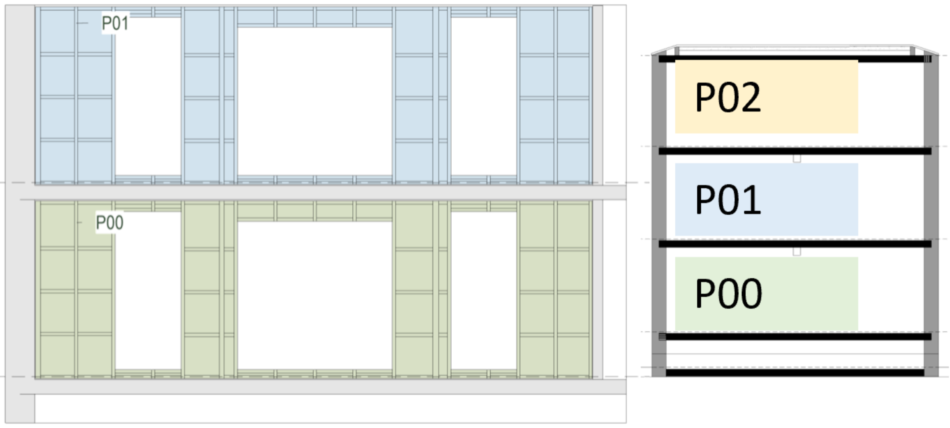
Parameters to include in model objects.

Figure 54. Pamplona oPEN Living Lab, San Pedro. Example of the floor plan in Revit with the corresponding coding, by authors, 2023. Copyright 2023 by oPEN Lab.

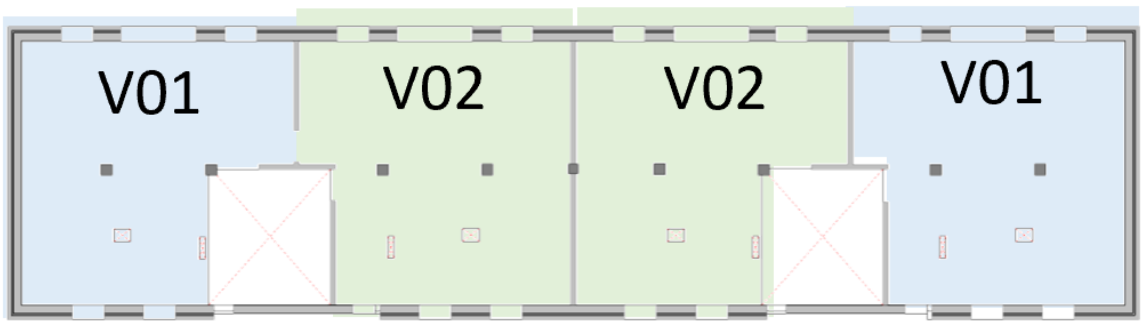
Each building is coded with the letter “E” before and with two sequential numbers afterward. Likewise, the floors are coded with the letter “P” plus two numbers. The same logic is used for dwellings (V + two numbers). The BIM visor used was Periscoope and it allows to use of colors to differentiate sectors as shown in *Figure 55*.



Plan view. LOC_Ubicacion01 >> STAIR, PORTAL, BLOCK



Section view. LOC_Ubicacion02 >> FLOOR SILVER



Plan view. LOC_Ubicacion03 >> HOUSE NUMBER

Figure 55. Pamplona oPEN Living Lab, San Pedro building. Periscoope plans and section views, by authors, 2023. Copyright 2023 by oPEN Lab.

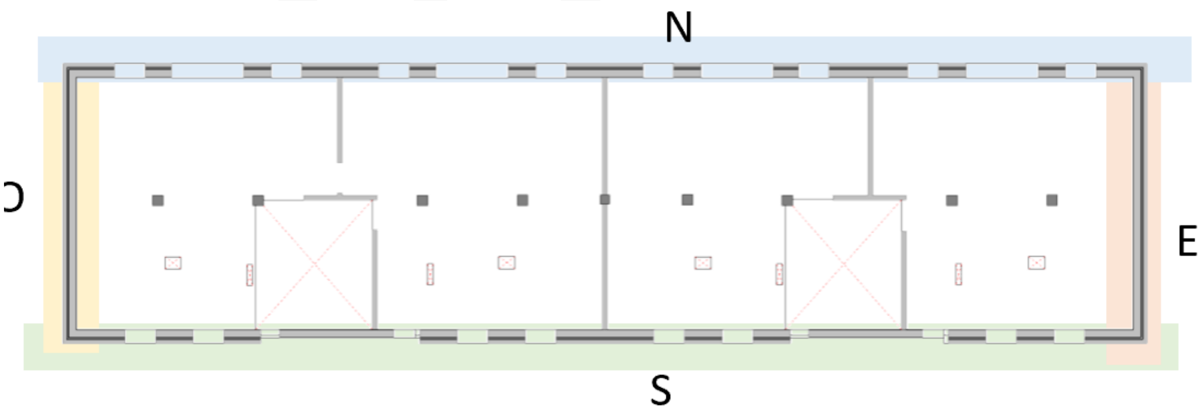


Figure 56. Pamplona oPEN Living Lab, San Pedro. Plan view. LOC_Ubicacion04 >> ORIENTATION, by authors, 2023. Copyright 2023 by oPEN Lab.

In each dwelling, the location of the prefabricated panels has been defined. For example, in the V01 dwelling, of the E01 Block, on the ground floor (P00).

To prefabricate the interior insulation panels, it is recommended to define the division of the panels within the BIM design model. The model provides the raw panel's division showing up the critical points: holes in the façade, passages of installations, and berthing of perpendicular partitions.

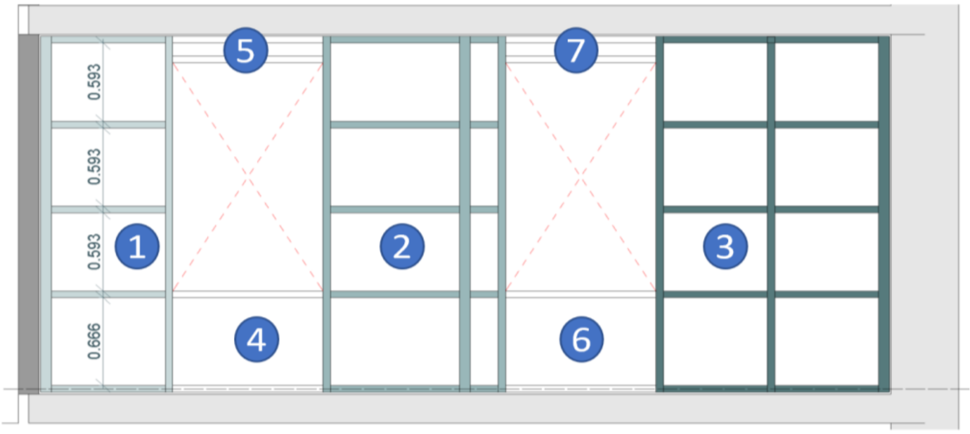


Figure 57. Pamplona oPEN Living Lab, San Pedro. South façade view from the inside, by authors, 2023. Copyright 2023 by oPEN Lab.

The combination of parameters defines a single element in the entire building, facilitating its identification.

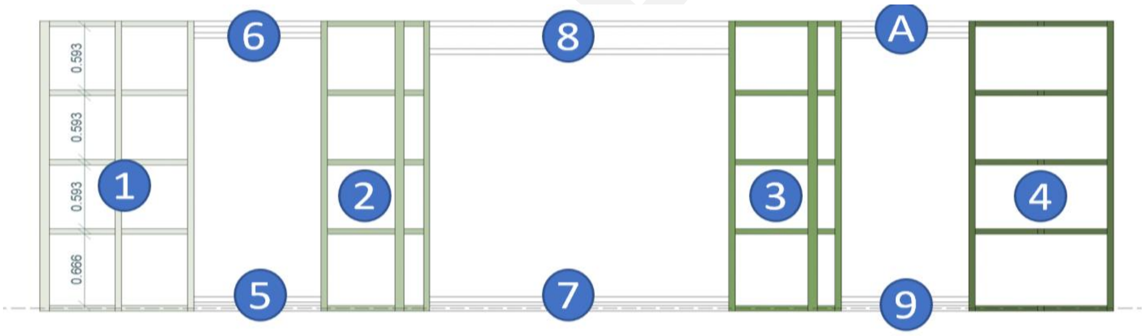


Figure 58. Pamplona oPEN Living Lab, San Pedro. North façade view from the inside, by authors, 2023. Copyright 2023 by oPEN Lab.

In *Figure 57*, the name of panel "1" is E01-P00-V01-1S. In the case of *Figure 58*, the name of panel "1" is E01-P00-V01-1N. Likewise, in the west façade, see *Figure 59,* the name of the panel is E01-P00-V01-1W.

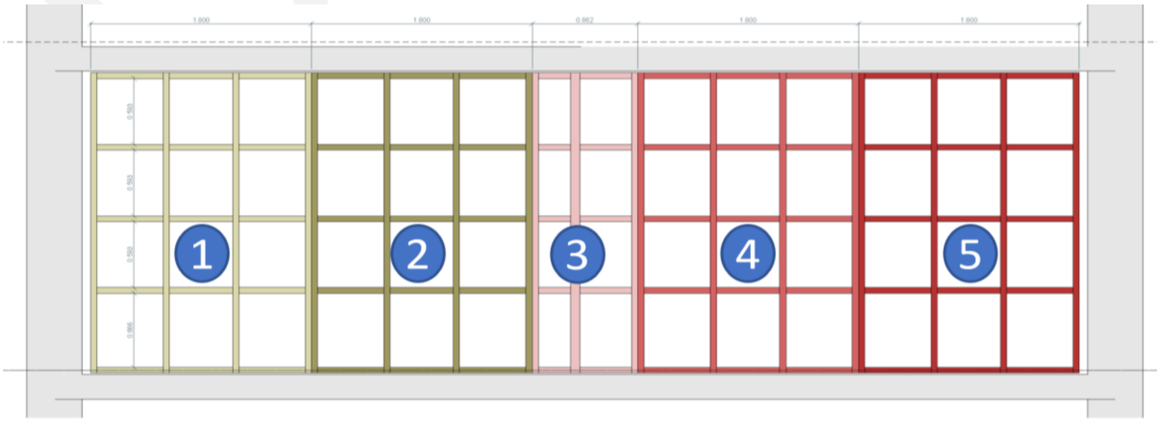


Figure 59. Pamplona oPEN Living Lab, San Pedro. West facade view from the inside, by authors, 2023. Copyright 2023 by oPEN Lab.

The coding of elements could be supported by QR codes generated directly in the BIM modeling software or added to the IFC model.

6.2.3 Detailed project and optimization

The BIM model may be simplified by eliminating the demolished elements or possible representation of construction aids, such as scaffolders. Then the characterization of beams, studs, and insulation panels is needed. The resulting BIM simplified model is the basis for the CAM model data extraction. This model can be created by the design team, the construction company, or the manufacturer itself depending on the level of maturity of each of them, responsibilities, and contract clauses.

It has designed the prefabricated systems using the best automation tools. For the prototype construction, the irregularities of the façade and joints were resolved. The designing tool was REVIT from Autodesk. The Revit file was connected to Rhino, from where the data to send to the laser cutter was extracted. This data was also sent to the milling machine and laser printer to manufacture the different elements of the façade system.

In the San Pedro building, as different solutions are studied to resolve insulation of the façade from the inside, both the builder and the manufacturer of the façade panels must be in contact with the architect (designer) to define the prefabricated modules.

The Revit models have been exported to Rhino inside using Grasshopper as shown in *Figure 60*. This process allows bi-directionality between the design and the fabrication model. Both the frames and the panels are fabricated in a milling machine, so using CUT 3D. The elements maintain the BIM coding during the digital fabrication.

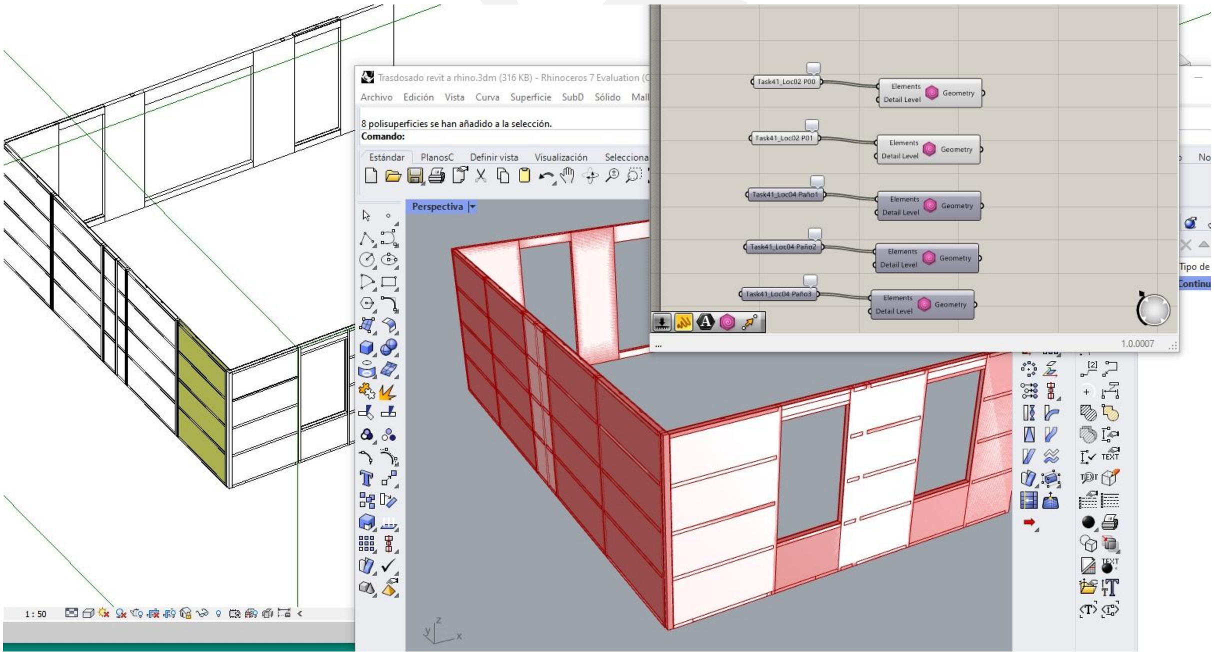


Figure 60. The connection between Revit and Rhino inside through Grasshopper, by authors, 2023. Copyright 2023 by oPEN Lab.

6.2.4 Manufacturing

In this section, it has been tested the proposed flowchart in the manufacturing phase by the fabrication of a prototype using digital tools, as seen in *Figure 61.*

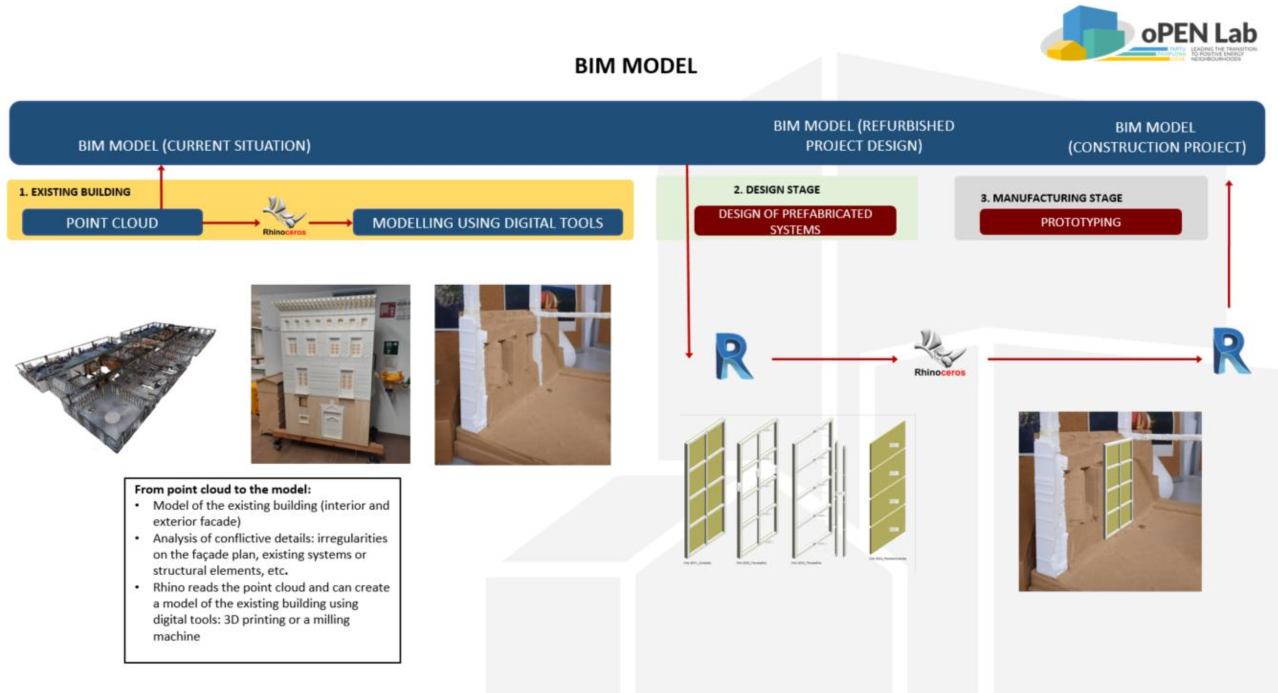


Figure 61. Description of the prototyping using digital tools, by authors, 2023. Copyright 2023 by oPEN Lab.

This prototype was a 1:10 scale model of one of the San Pedro block dwellings as indicated in *Figure 62*.

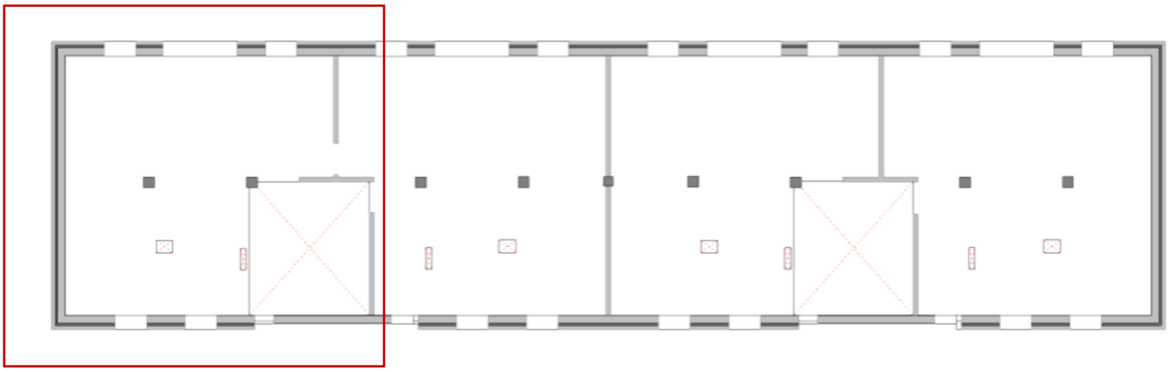


Figure 62. Pamplona oPEN Living Lab, San Pedro Building. Chosen dwelling to develop the 1:10 model, by authors, 2023. Copyright 2023 by oPEN Lab.

6.2.4.1 The process to create 3D printing machine code

In order to create the model of the manufacturing phase, massive data meshes have been used to generate the current state and the interior panels (see *Figure 63*).

The digital fabrication machine requires 2D closed polylines (.dxf). In 3D, closed mesh solids are required (.stl). Once the geometry data is defined, other information such as speed, temperature, language machine-machine, or specific material parameters is defined.

The 3D printing machine used to generate the model is Ultimaker 2+ Extend. The interior of the wall was modeled with flat faces, as in the Revit model in the new construction phase. The print volume is the intersection between the exterior mesh and the interior flat faces. 3D solid meshes were created to be printed in the CAM machine.

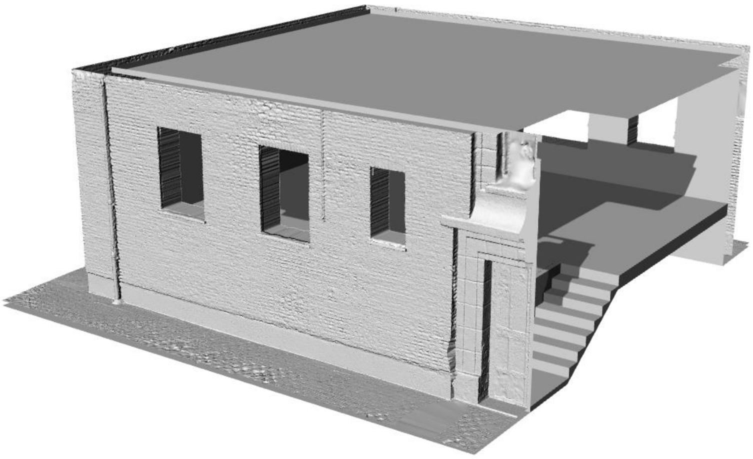


Figure 63. Pamplona oPEN Living Lab, San Pedro. Mesh model with the surfaces, by authors, 2023. Copyright 2023 by oPEN Lab.

The mesh model is a massive data model because it has 4.381.683 faces. Due to the large size of the model, it is better to use specific software to manage meshes. Grasshopper and Rhinoceros have been used to section and model the interior. Blender has been used to edit the meshes.

An MDF 3D model has been sent to print out. The software associated with the machine is Ultimaker Cura. It has 40 pieces with a medium fabrication time of 7.5 hours per piece (see *Figure 64*). The printing using various machines has been 15 labor days. The material used is a specific kind of thermoplastic named PLA (Polylactic Acid). Each piece has been sent to the machine in (.stl).

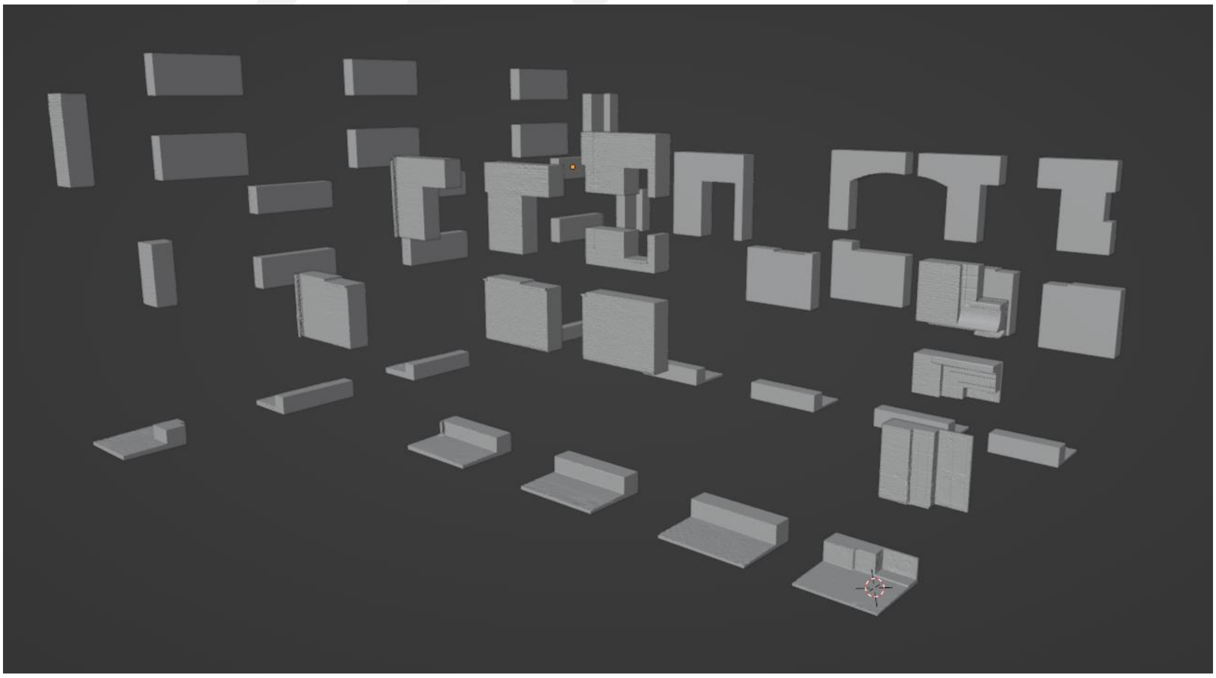


Figure 64. CAM prototyping of the current situation, by authors, 2023. Copyright 2023 by oPEN Lab.

The floors have been milled in 2D from a 25mm thickness board. The geometry was extracted in (.dxf) and sent to the commercial software CUT 2D. The machine used was 3 axes milling machine.

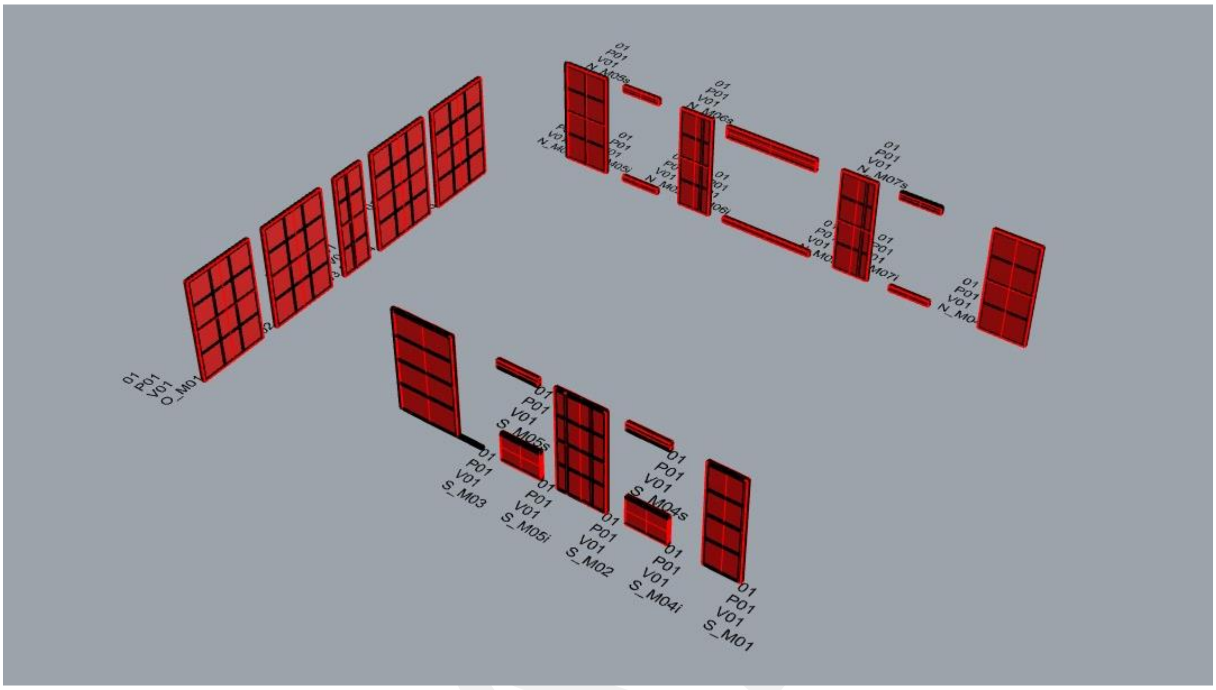


Figure 65. Panels and frames are divided with the coding of each piece, by authors, 2023. Copyright 2023 by oPEN Lab.

The interior paneling wall in 1:10 scale was done with a milling machine. The fabrication process was:

- To define the printing volume in Rhino in (.stl).
- To define the material information and machine speed.
- To validate the model just before producing the physical model.
- To validate the level of detail.

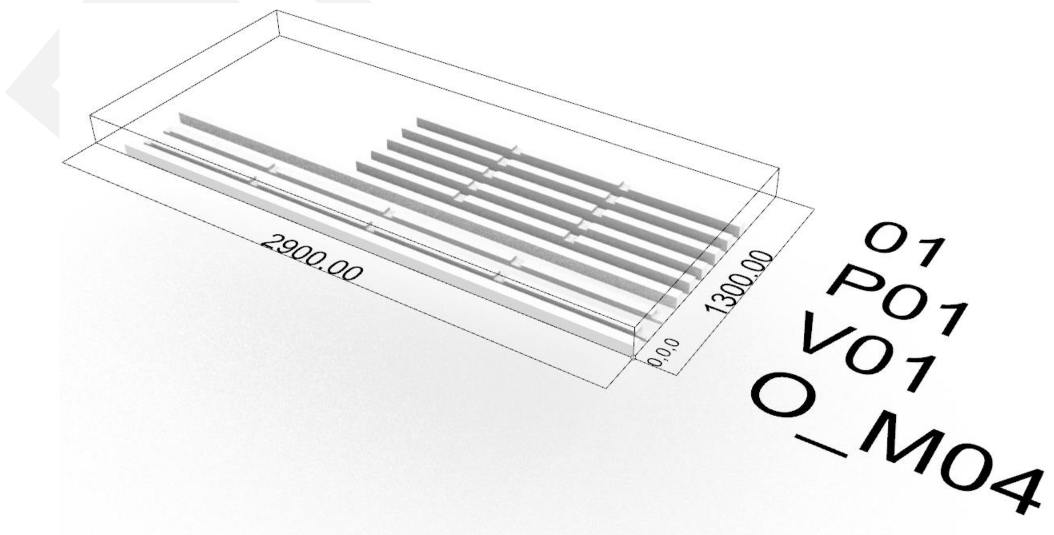


Figure 66. Ordered curving up (cutting pieces) of a fabrication series, by authors, 2023. Copyright 2023 by oPEN Lab.

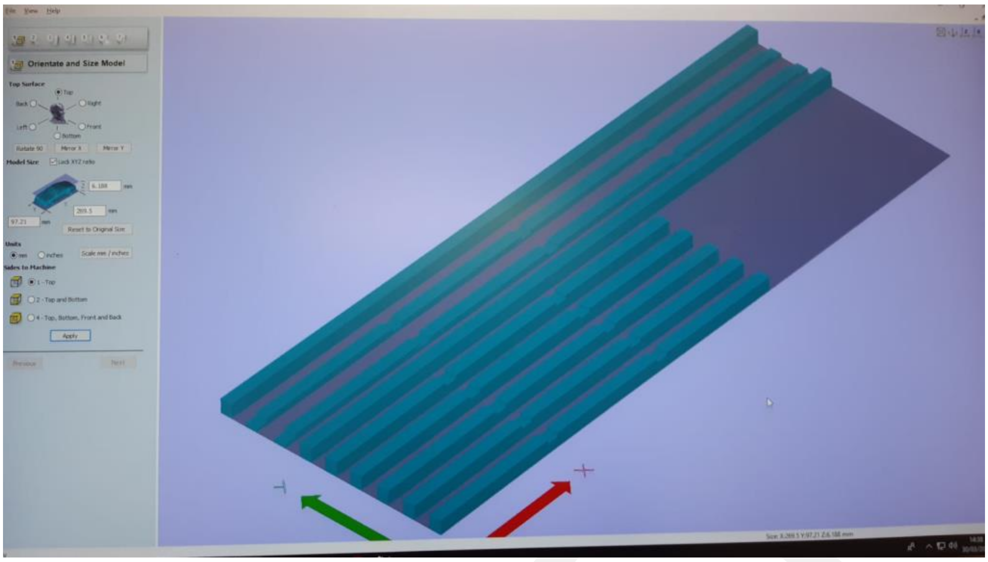


Figure 67. Parameters definition of the milling machine and visual inspection before fabrication, by authors, 2023. Copyright 2023 by oPEN Lab.

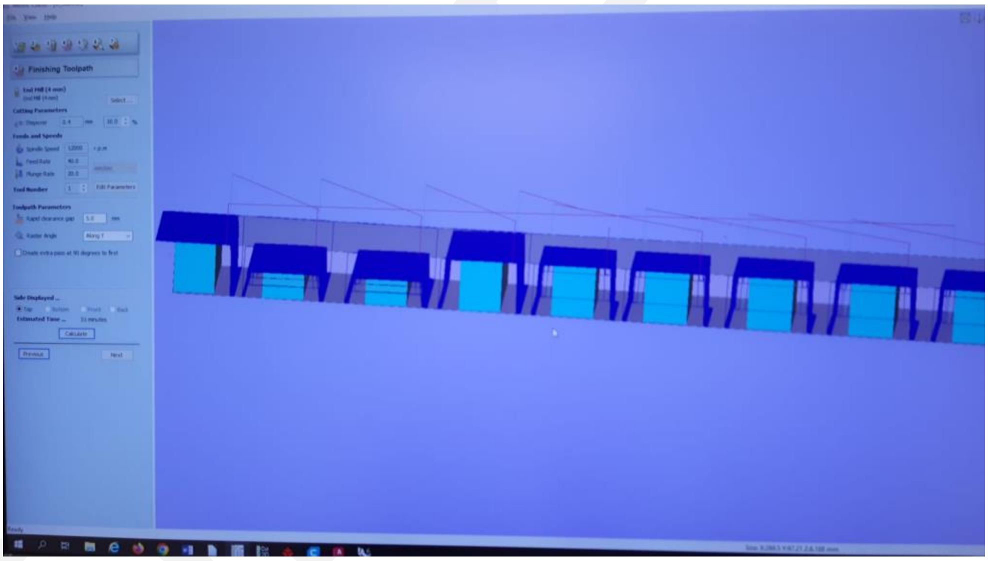


Figure 68. Validation of the trajectory of the CAM machine and penetration of the milling machine, by authors, 2023. Copyright 2023 by oPEN Lab.

There are multiple workflows and complementary programs for point cloud treatment, mesh creation, optimization, fixing possible gaps, and obtaining the solid. The goal of this process is to obtain the code that the 3D printing machine understands. The main software used were CloudCompare, MeshLab, Blender, Rhinoceros, Grasshopper, 3D Slicer, and Ultimate Cura. One of the main processes to generate fine 3D printing code is described below:

- CloudCompare program:
    - Import the point cloud (e57 format) at maximum resolution, and with the parking lots attached. Trim and isolate the dwelling.
    - Manual cleaning of not necessary points, what is named as “noise”: furniture, flashing, and existing partitions.
    - Clear floating points outside the range: with the color properties bar in “Scalar Field” and with the “SF display params” graphic, these points are removed.

- Clean repeated or overlapping points with the “SOR filter” tool (Static Outlier Removal)
- Orientation of normals. Step 1: Edit >> normals >> Compute (Quadratic)
- Orientation of normals. Step 2: Edit >> normals >> Orient normals << With minimum spanning tree.
- Mesh creation. Plugins >> poissonRecon (Poisson surface Reconstruction). In this step, the resolution of the mesh is defined according to the scale and definition of the prototype that is desired. Some bulbs that will be generated can be cleaned by adjusting the edges of the mesh and with “Filter points by value” they are eliminated. Sometimes it is necessary to reverse the normals so that they are on the correct face.
- The mesh obtained is exported to "STL" format.

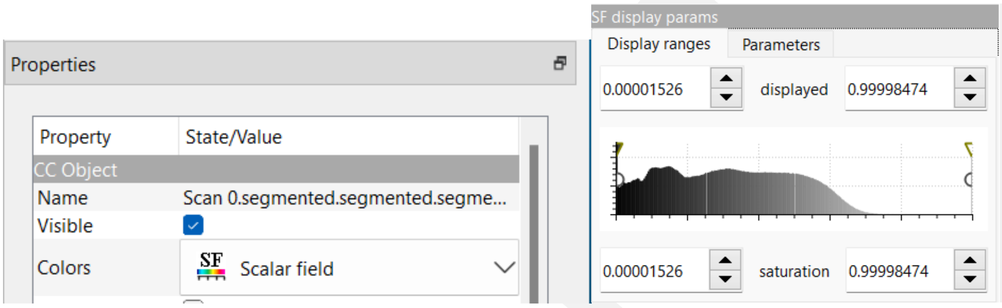


Figure 69. CloudCompare. Clear floating points “Out of range”, by authors, 2023. Copyright 2023 by oPEN Lab.

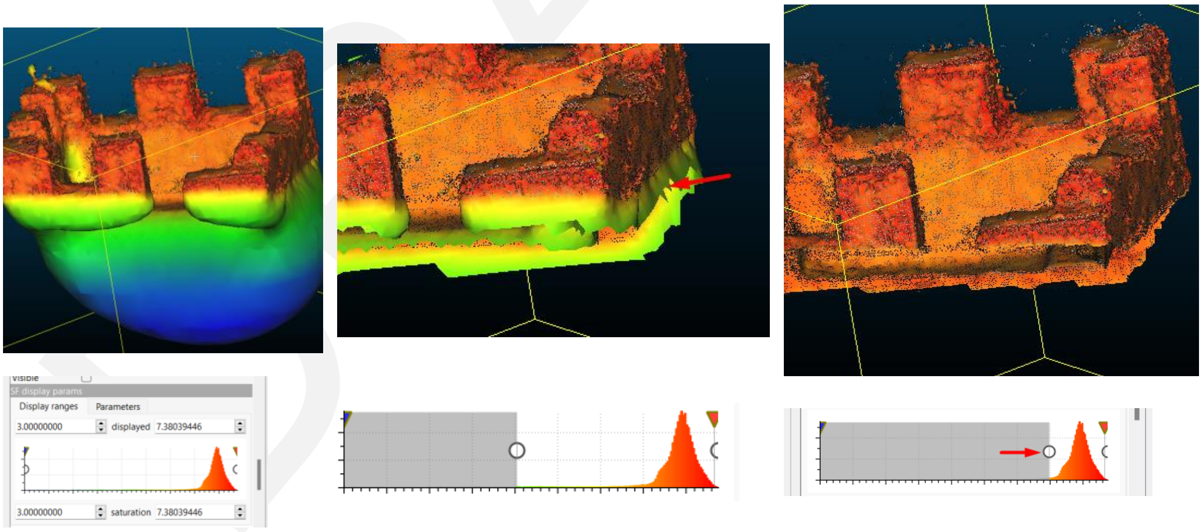


Figure 70. Adjusting the edges of the mesh, by authors, 2023. Copyright 2023 by oPEN Lab.

- Blender program
  - The mesh is imported in STL format.
  - Meshes are trimmed.
  - They are passed to solid.
- Ultimaker Cure
  - Import a 3D model in STL or OBJ format.

- Adjust the printing options according to the specifications of the 3D printer and the material to be used. This can include settings such as resolution, media type, print speed, cutting height when printing, temperature, etc.
- Preview the model in the software to make sure it will print correctly.
- Export the prepared print file in GCODE format, which is the format that 3D printers use to read the model and know which parts to print.
- Send the GCODE file to the 3D printer and start printing.

6.2.4.2 From manufacturing to BIM model

Once the prefabricated systems are manufactured, the information would return to Revit software, with its coding to facilitate, for example, assembly and subsequent maintenance.

Each panel is identified and its position in the construction site is defined.

Clearances must be considered to absorb irregularities of the existing walls, floors, or openings in the façade.

6.2.4.3 Real manufacturing

The manufacturer, within each panel, will manufacture the vertical studs, horizontal crosspieces, and insulating panels, which compose it according to the premises principles for its elaboration:

- Dimensions (width and height).
- Maximum separations between uprights or crosspieces.
- Installation passages and crosses.
- Heuristic optimization and simulation-based algorithms for material optimization by reducing blunting.

The fabrication machines are diverse depending on the specific task: cutting of strips, machining of notches, and cutting of panels. Panels assembled in the workshop are preferred since they allow:

- Work in a controlled environment with tools, and specialized workbenches for this purpose. It improves workers' comfort and health and safety measures.
- Standardization.
- Reduce material waste which decreases costs and environmental impact.
- Reduce construction and assembling in site times because some tasks can be carried out in the workshop/factory.
- Minimize the weight of the building.
- Optimize transportation and use of construction cranes.
- Facilitate dry installation assembly.

6.3 Tartu Living Lab Case Study

Tartu case study is a large residential building. A typical building in Tartu that needs to be renovated is a nine-story apartment building constructed in the 80-s by using prefabricated concrete panel elements. The optimized scenario: industrialized renovation process is used to renovate the external perimeter of these buildings (e.g., roofs and facades) to increase energy efficiency. An example of one of the buildings in Tartu, Annelinn, that needed to be renovated and was used as a reference object for testing the digital flowchart is shown in *Figure 71*.

Figure 71. A typical apartment building in Tartu, Annelinn, (picture on the left and point cloud on the right) that needs to be renovated**,** by authors, 2023. Copyright 2023 by oPEN Lab.

At the final stage of this report, it was possible to analyze and test in depth the existing building and the design stage. Further analysis is needed in the manufacturing, transport, and assembling stages following the precepts of the optimized scenario. However, the implementation and adaptation of the flowchart to the case study is still ongoing. The results of this process will be published in the next outcomes of the study.

Based on research and practical applications made in this task, it has been digitalized the process, making seamless links between detailed laser scanning data to computer-aided manufacturing. The steps followed were (see *Figure 72*):

1. During the process of 3D scanning, data was gathered about the surfaces of buildings. Laser scanning, structured light scanning, and photogrammetry are some of the more commonly used technologies in 3D scanning.
2. The point cloud of the facade surfaces was exported from the 3D point cloud. The vertical and perpendicular planes are assigned to them, which will be the basis for the building envelope surfaces.
3. The flatness of the original building façade was determined from vertical and perpendicular planes. It provided information on whether and how thick a buffer layer was needed between the original facade and the additional prefabricated thermal insulation element.
4. It was determined the locations of joints of additional insulation elements (for example, window/external wall, external wall corners, external wall-ceiling, external wall, roof, etc.). These locations served as anchor points/lines for the junctions of the additional prefabricated thermal insulation elements.
5. The 1D BIM models for the prefabricated additional thermal insulation elements were designed based on the needs of the building and the neighborhood: the building's load-bearing capacity, moisture safety and hygrothermal performance of building envelope, energy performance, acoustic, etc. A surface was defined on the additional thermal insulation element BIM model, which determines the location of the 1D element.
6. The 2D BIM models for the joints of the building envelope components were designed based on the needs of the building and the neighborhood: the building's load-bearing

capacity, moisture safety and hygrothermal performance of the building envelope, energy performance, acoustic, etc. A location was defined on the joint, which determines the location of the 2D joint element.

7. BIM models of building envelope structures and 2D joints and the geometry of the existing building were combined, and product drawings of additional thermal insulation elements were produced using parametric design.
8. Information to CAM and Product drawings (for commissioning and inspection) will be bases to produce additional thermal insulation elements.

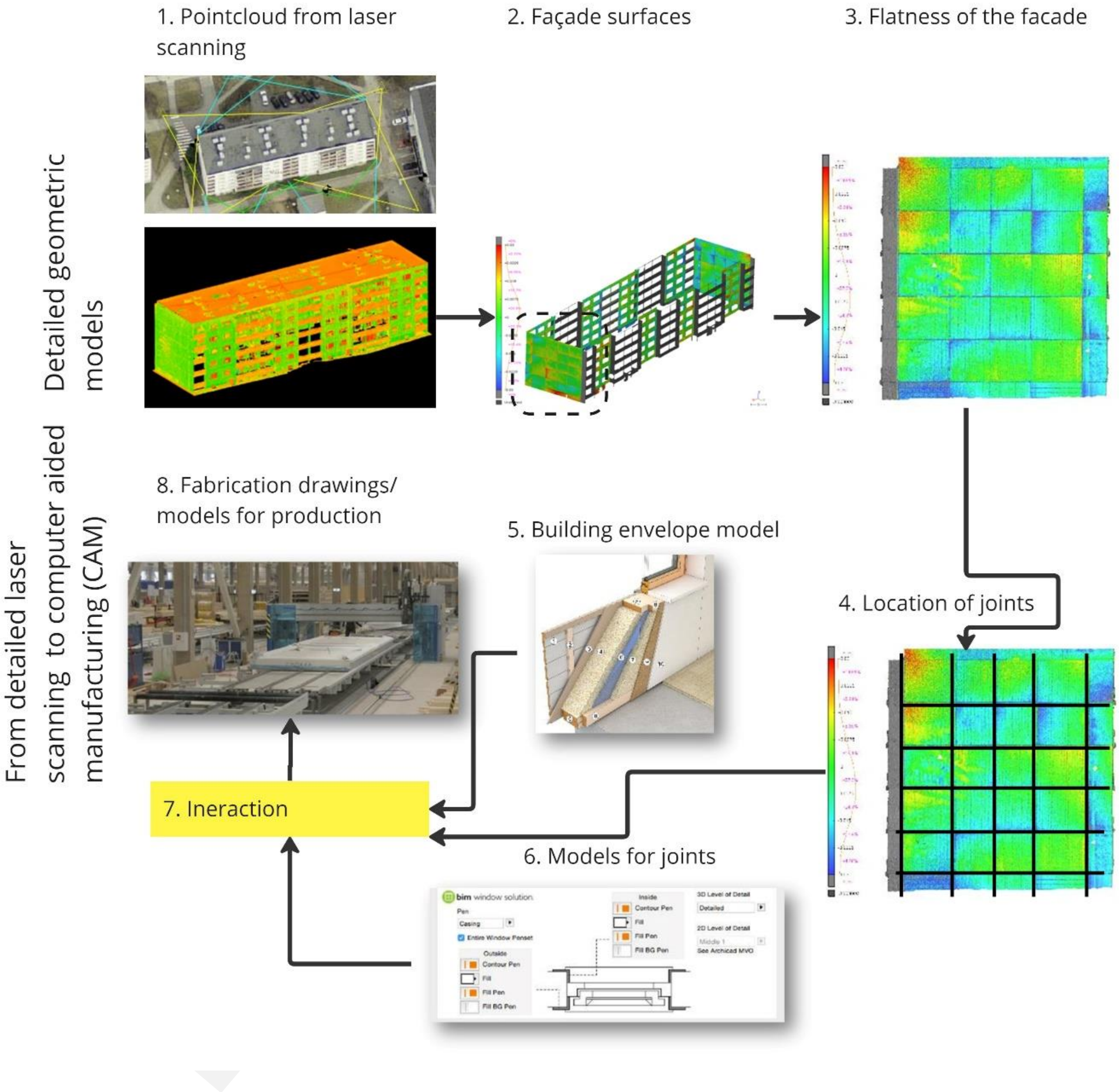


Figure 72. Suggestions for a seamless digital flow of the renovation process, by authors, 2023. Copyright 2023 by oPEN Lab.

6.3.1 Existing building and design stage

Autodesk Revit was used to model the digital twin model of the existing building and models of prefabricated elements. Technical drawings were generated from created BIM models of prefabricated elements. A manufacturer used a laser-scanned point cloud as a reference object to model the digital twin model of the existing building by using tools available in used Autodesk Revit software. Relevant structural elements were selected and fitted based on the point cloud of the existing building. Based on the geometrical digital twin model of the existing building, prefabricated elements were generated. The manufacturer's designer created prefabricated element models using Autodesk Revit-integrated tools developed by the manufacturer. Algorithms in developed tools generated the layout of prefabricated elements, all components of each element, and technical drawings for element assembly. The structural elements available in Autodesk Revit software were used to build a prefabrication model.

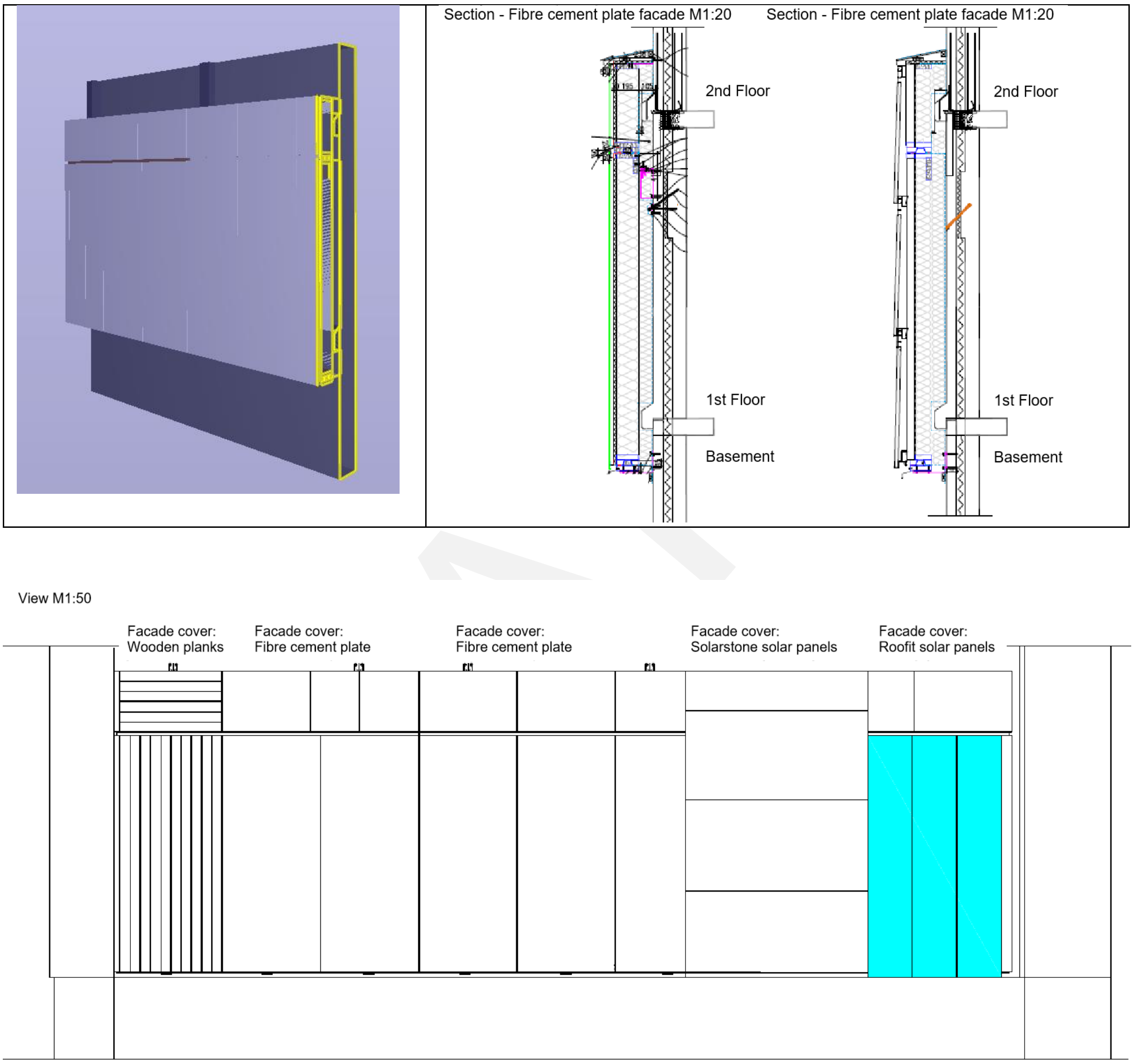


Figure 73. oPEN Living lab Tartu. Design solution of insulation elements, by authors, 2023. Copyright 2023 by oPEN Lab.

6.3.2 Manufacturing

Prefabricated elements were manually assembled in the factory. The work was carried out on the table layer by layer. The fabrication was based on the technical drawings generated in the design phase. A drawing layout for each layer of the prefabricated element was available. Visual supervision was carried out simultaneously with the assembling work. The existence, placement tolerances, and the number of components were checked. Received supervision results were entered into the checklist, and corrections in work were made if needed before assembling the next layer of components. Assembling and supervision work is shown in *Figure 74.*

Figure 74. oPEN Living lab Tartu. Production of insulation panels, by authors, 2023. Copyright 2023 by oPEN Lab.

6.3.3 Transport and construction

In this case study construction works were developing. The main outcomes of this phase were:

- The number of trips to the construction site. This can be optimized through a simulation with the BIM models.
- The size of the truck transporting pieces according to the storage possibilities on-site.
- The transportation emissions. The goal is to reduce the number of trips and the truckload.

Figure 75. oPEN Living Lab Tartu. Transport of the material, by authors, 2023. Copyright 2023 by oPEN Lab.

Figure 76. oPEN Living Lab Tartu. Delivery of the material on-site, by authors, 2023. Copyright 2023 by oPEN Lab.

6.4 Genk Living Lab Case Study

6.4.1 Existing building

The process flow in Genk follows the logic of the improved scenario. Some parts of the workflow are attributed to public tender, which challenges the flow of BIM and other information in the research project. The consortium partners initially investigated the possible technical solutions. During this process, a photogrammetric scan of the interior of two buildings was carried out.

The building permit has been granted and the public tendering process is ongoing. Hence, what follows next are expectations based on the partners' experience and market research.

Since the number of different typologies is limited, repetition is a key factor in the mass production of building elements. This makes the neighborhood a good candidate for prefabricated modules.

The conclusions and proposals were drafted into a concept note. Standard procedures of Nieuw Dak and social housing companies meant that the design assignment had to be tendered to an external party. This is why the concept note was made available for the external design team charged with making the tender documents.

Figure 77. Aerial view of the Nieuw Texas neighborhood; the repetition of housing types is visible, by authors, 2023. Copyright 2023 by oPEN Lab.

Design stage

The administrative cuts in the project prompted the architects to create their own BIM model. This model is based on the existing paper blueprints of the building. This means there is a possible disjoint between the model and reality, due to changes and inaccuracies in the original building process. For design purposes and the environmental building permit, this does not pose any immediate problem.

Figure 78. Architectural Render of refurbished homes in Nieuw Texas, Genk. by dbv architecten, https://dbv-architecten.be. Copyright by dbv architecten

6.4.2 Manufacturing

The commercial party that will create the prefabricated façade elements will need to start their production from precise representation. They will most likely include a full LiDaR scan of the exterior of all buildings. The resulting point cloud will then serve as a geometrical digital twin, on top of which the prefabricated modules can be designed and fitted. This model should include every material used, down to the tapes and screws.

A detailed bill of quantities (BoQ), bill of materials (BoM), and a CAM production plan are the main exports of this model. They allow the manufacturer to purchase the correct amount of material and optimize cutting losses. This model will be custom-built for production purposes.

The production model will need to be incorporated into the execution plans of the general contractor. They will need to identify every prefabricated element, the position it must be installed in, and how to do this correctly.

In an ideal setting, this model which was custom-built for production purposes, will ultimately flow back into the general BIM model. That way it can serve as a truthful digital representation of the building.

The tender process to find a Manufacturer and General Contractor is currently ongoing. The requirement of working in BIM and sharing the models with the design team will likely be included in the brief. The extent to which the information flow works bi-directionally will have to be followed up later.

6.4.2.1 Model sharing

The BIM model of the architect has been exported to .ifc and shared with project partners. They are using it now to create a digital energy twin for each building. By linking these models, they will also set up a digital energy twin of the wider neighborhood. It is expected that small inaccuracies in the model do not impact the precision of the energy modeling.

7 Conclusions & Recommendations

This report describes the optimization of the renovation process of buildings by digitalization and industrialization, linking laser-scanning data to computer-aided manufacturing.

Starting from the analysis of a traditional renovation process (baseline scenario), an optimized scenario is proposed, where industrialization of the renovation process is the main characteristic. Furthermore, an optimized scenario based on the integrated renovation process and digitalization is elaborated and represented in a flowchart.

The digitalization of the prefabrication process for deep energy renovation of the building was accomplished through industrialization and the use of relevant digital tools (GIS, BIM, CAM, LCA, and LCC). The main aim of this research was to define in detail the process of linking laser-scanning data with computer-aided manufacturing. The main outcome is an integrated renovation process that has been tested in three case studies (one in each Living Lab). Finally, a set of recommendations for applying the flowchart will enable replicability in other case studies and renovation works.

To attain high-quality renovation outcomes, it is vital the transition to renovating buildings on a district/neighborhood scale. By doing so, larger renovation volumes are achievable, and resources can be invested in the efficiency of the design and production process through digitalization. Moving towards an integrated and industrialized renovation process also allows for a shorter renovation time.

7.1 Overview table of the three scenarios

The following table compares three renovation scenarios; the traditional renovation process (baseline scenario), the industrialized renovation process (improved scenario), and the optimized scenario (Integrated renovation process) in the whole Life Cycle (from the Existing building to Maintenance). When needed, the project stages are divided into more detailed subcategories.

Each cross means that the Project Stage and/or the subcategory is contemplated in the corresponding scenario. If not it does not have a cross.

This overview is resulting from Chapters 4, 5, and 6 of this Deliverable.

Table 4. Comparison of three scenarios: baseline, improved, and optimized.

Project stage	Subcategory	Baseline	Improved	Optimized
Existing building		x	x	x
	Digitalizing the building survey	x	x	x
Design		x	x	x
	Point cloud to BIM			x
	Digital survey to BIM		x	x
	Design of current situation		x	x
	Refurbished project design		x	x
	Detailed project design			x
	Hygrothermal performance check		x	x
	LCA		x	x

Manufacturing		x	x	x
	BIM design			x
	Execution design		x	x
	Fabrication			x
	Hygrothermal performance check		x	x
	LCA		x	x
	Approved execution design for CAM			x
Transport and Construction		x	x	x
Assembling of prefabricated systems and GIS				x
Renovated building		x	x	x
Maintenance		x	x	x
	LCA			x

7.2 Problems detected in the baseline and improved scenarios

The main problems of the baseline and improved scenario detected within this study are:

- Stakeholders tend to work separately so the information is spread.
- Re-work is common and sometimes, in the construction stage, certain tasks must be done again (taking measurements, drawing plans, etc.)
- The design does not coincide with the existing building (non-precise dimensions, lack of details, etc.), thus the design must be modified during its execution to adapt the project to the reality of the existing building.
- New requirements of the building developer not initially defined must be incorporated in the construction stage.
- Modifications are to be made to the design due to non-compliance with the initial design or with the regulations.
- Fabrication is often done manually and without automation.

7.3 Benefits of the optimized scenario

The main benefits of the optimized scenario (the integrated renovation process) detected in this study are:

- All the stakeholders are involved in the project from the early design stages.
- BIM is the centralized source of information: updated information and data of the project is accessible to all the stakeholders reducing duplicities and errors.
- The BIM model is created using detailed data and information of the existing building obtained by laser scanning, reducing errors and time (manufacturers do not have to take dimensions for production plans, etc.)
- More accurate cost estimation and optimization from early project stages.
- Optimization in the use of materials and reduction of waste.
- Hygrothermal performance is studied using data extracted from the BIM model (updated and accurate data and no re-modeling is needed).

- LCA is calculated using the data extracted from the BIM model (updated and accurate data and no re-modeling is needed).
- The BIM model is exported to CAM machines (if needed using intermediate software).
- Higher quality of the construction and management of the building.
- Following the optimized scenario facilitates cheaper and faster projects related to the general objectives of the oPEN Lab project.

The proposed Integrated Renovation Process (Optimized scenario) was implemented in three living labs: Pamplona, Genk, and Tartu in order to test the effectiveness and gain knowledge. The results of these tests were successful and helped the stakeholders involved. However, this ongoing study must use objective key performance indicators to measure these improvements.

7.4 Conclusions of testing in oPEN Lab living labs

The knowledge and experience gained in this process were as follows:

7.4.1 oPEN Living Lab Pamplona

In oPEN Living Lab Pamplona the building's point cloud was used as a skeleton to build a BIM model of the existing façade. Several complementary workflows were generated for each stage of the process: point cloud treatment, mesh creation, optimization, fixing possible gaps, obtaining the solid, and prototype construction. The Revit file was connected to Rhino, where the data to be sent to the laser CAM machine was extracted. This data was also sent to a milling machine and 3D printer to manufacture the different elements of the façade system.

A prototype with a 3D printer machine was done to test the theoretical workflow proposed.

What is still needed to be done is to test the workflow proposed in real prefabrication CAM machines used for real manufacturers.

7.4.2 oPEN Living Lab Genk

Social housing companies in Flanders are locally organized while being regionally funded. For this reason, the design and tendering process is structured along a **pre-existing standardized process flow**. This is also the case for the social housing company in oPEN Living Lab Genk. For instance, no specific expectations were formulated regarding 3D scans.

For the Nieuw Texas neighborhood, the design was tendered through the typical flow. Therefore, there was no inclusion of a structured BIM flow based on a 3D scan. The architects used the **existing paper blueprints as a starting point**. This was digitized to be the base for a renovation concept that was developed in BIM.

The paper blueprints were not adapted after the construction phase. Inaccuracies and modifications during the building process are not properly reflected. A disjoint between model and reality is therefore possible. For the architectural design and the permit, this does not pose any immediate problem. In other words, there is no incentive for the architects to go through the additional work of setting up a 3D scan, reworking and interpreting the model, and using this as the base for their work.

Sharing the rendered images from the BIM drawing allowed all stakeholders to get a good grasp of the project. The BIM model of the architect was exported to IFC and shared with project partners. They are using it now to create a digital energy twin for each building.

The current BIM model will not be sufficiently accurate for the manufacturer of the building elements. This commercial party will need to start its production from a more precise representation. They will likely include a full LiDaR or photogrammetric scan of the exterior of all buildings. This means they will have to add several costs to their flow:

- Executing the 3D scan
- Analyzing the resulting data
- Setting up an initial 'as is' model
- Converting the architects' design into the parametric design which applies the constructive logic of the manufacturer.

The effort of creating a more accurate model could have been an unnecessary step if the architects had started their design from a 3D scan. **The architects will likely only include a 3D scan when it is explicitly mentioned in their assignment.** In this way, they would have been able to provide the manufacturer with an updated and more importantly, validated BIM model.

In an ideal setting, the custom-built model for production purposes would flow back into the general BIM model after manufacturing and construction. That way, it can serve as a truthful digital representation of the building.

7.4.3 oPEN Living Lab Tartu

Simultaneously by prototyping prefabricated wall elements for high-rise apartment buildings in the oPEN Living Lab Tartu, the digital workflow in the production process was under review. Although digital tools were not yet applied in each production phase due to the manufacturers' architecture of the workflow, and the full seamless link between the laser-scanned point cloud and CAM will be presented, during the real renovation process, digital tools used in the BIM design phase in the oPEN Living Lab Tartu Case Study, illustrate the feasibility of digital workflow and demonstrate the potential of using digital tools such as BIM software and software-integrated tools in the production process.

7.5 Recommendations for applying the oPEN Lab Integrated Renovation Process

Suggestions for optimization of the prefabrication process through digitalization are:

- Include executing an accurate 3D scan as part of the assignment of the Architect.
- Mesh models are required to generate some CAM models. It means that the BIM models need to be translated into mesh models before fabrication.
- 3D mesh models are needed for some CAM machines: laser + structured light + photogrammetry).
- Validate and guarantee the precision of the resulting BIM model of the existing situation.
- Make the BIM model correctly georeferenced and oriented; this will help additional studies, such as energy analysis.
- Design the desired renovated building on top of the BIM model of the current situation; clashes are easily detected in the models and are easier resolved digitally than physically during construction.

- The main problem is that at the beginning of the project, a lot of times we do not know the manufacturer, so we do not know the CAM software. Ideally, the CAM software would condition the design software.
- Communicate with the manufacturer on the type of input that is needed to run the production machines; some processes require meshes, and others require exports in .csv or text files. It is important to use software that allows these kinds of export.
- A 1:1 scale prototype of the prefabricated elements is needed to prove the correct link between BIM and CAM machines.
- Each manufactured element should have its code printed out. This will reduce residues. A QR code could be used.
- For avoiding modeling duplicities, it is necessary to model first in the design stage and to remodel again in the manufacturing stage.
- For calculating hygrothermal and LCA parameters do use directly the IFC BIM model.
- To avoid measuring duplicities, the point cloud must be consulted in a very easy way so all the stakeholders, technical and not technical can have easy access to the information.
- In-site operators should be able to understand a basic BIM model that will be accessible from a smartphone.

7.6 Expected follow-up actions

This is an ongoing study that requires further development, especially in testing and in adding key performance indicators to compare the results of the optimized scenario with the baseline scenario. This further development will be done in these results:

- A scientific publication, including results from the testing in real construction work and the application of key performance indicators comparing results of part of the construction stage following baseline scenario and optimized scenario. The real testing will allow us to perform a comparative analysis of the two scenarios and to evaluate the proposed improvements in terms of cost, time, and environmental impact.
- Guidance to the market regarding the digitalization of the process. It will require further refinement of the digital flowcharts generated within this study and clear examples to illustrate the guidance.

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