8th edition of the European Congress on Energy Efficiency and Sustainability in Architecture and Urbanism (EESAP 8) and the 1st International Congress on Advanced Construction (CICA 1)

Universidad del País Vasco/Euskal Herriko Unibertsitatea
Donostia-San Sebastian, Spain
5-7 July 2017
www.eesap.eu

Prefabricated Solutions and Automated and Digital Tools for the optimisation of a Holistic Energy Refurbishment Process

Soluciones prefabricadas y Herramientas digitales y de automatización para la optimización del proceso integral de rehabilitación energética

Natalia Lasarte[1], Jose Antonio Chica[1], Ignacio Gomis[1], Josu Benito[1], **Kepa Iturralde**[2], Thomas Bock[2]

[1] *Tecnalia. Sustainable Construction Division. Parque Tecnológico de Bizkaia, c/ Geldo, 48160 Derio, SPAIN.*
[2] *Technische Universität München. Chair for Building Realisation and Robotics.*
Arcisstrasse 21 80333 München. GERMANY

+34 667 165 484 natalia.lasarte@tecnalia.com
+49–(0)89-289-22170 // +34 635 741 921 kepa.iturralde@br2.ar.tum.de

Key Words: Refurbishment, Timber, Energy Efficiency, Prefabricated, BIM, automation |

Abstract:

This document is a review paper of the ongoing BERTIM (Building Energy renovation through Timber Prefabricated Modules) research project, which scopes an automated procedure of prefabricated timber modules for the energetic refurbishment of buildings. The Energy Refurbishment is envisaged as key strategy to reduce the energy impact of the building sector. In addition, it is necessary to enhance the use of materials with low primary energy demand from cradle to grave and carbon-footprints, as timber based building materials, which performance is suitable in terms of global warming potential, carbon footprint, resource use, pollution, solid waste and embodied energy, when considered over a building's lifetime. In order to foster Energy Efficiency building retrofitting an urgent need for a holistic and integral building energy efficient renovation approach is required, from the data acquisition to the installation of the solutions in the building in order to reduce the renovation operations time. The adoption of prefabricated solutions for a deep building renovation, all together with the implementation of digital tools integrating the whole renovation process, will lead to reduce significantly the time in manufacturing and installation and consequently impact for users as well as get better quality in the process. In this context, BERTIM, a research and development collaborative project, develops a prefabricated solutions that provide the opportunity to renovate, improving energy performance, air quality, aesthetics, comfort, and property value at the same time, while ensuring low intrusiveness during renovation

works. The development is based on timber high-energy performance prefabricated modules for energy rehabilitation to ensure important building primary energy consumption reduction through high insulation properties. They also integrate windows, insulation materials, collective HVAC systems, renewable energy systems and energy supply systems. By means of the safeguarding of the existing buildings structure and envelope and integrating the services, the work load on-site is minimised attenuating the inconvenience for the tenants, producing less dust and noise and achieving higher work productivity for the whole process and especially reducing installation time. Prefabricated modules integrate in the factory all the building components (new windows, balconies, pipes and ducts). In order to enable the integration with enough accuracy and effectiveness, a computer tool based in BIM is also being developed to implement the mass manufacturing methodology from design to manufacturing and allow a digital data flow among the involved stakeholders. The platform includes a methodology and support tools to capture a real building data (using laser scanning techniques) transferring it to a BIM-based Web3D environment and a building renovation project definition and communication with CNC manufacturing system, by means of the usage of BIM, minimising the risk of any possible pre-fabrication mistake. As a last step of the procedure, the automated and even robotic installation procedures will be considered in order to reduce time and ensure safety during the on-site installation.

1. INTRODUCTION

The building sector has an enormous impact in sustainability and environment (representing 40% of the overall energy consumption) (DIRECTIVE 2002/91/EC Energy Performance of Buildings). Furthermore in Europe more than 70% of the building stock was built before the first energy crisis (70's) without consideration of Energy Efficiency criteria *(http://infohouse.p2ric.org/ref/17/16352).* Taking into account these data, by improving the Energy Efficiency of buildings, it may be estimated a reduction of EU energy consumption by 5-6% and CO2 emissions by about 5% Although currently the European Directives are mostly the drivers for Energy Retrofitting, it is foreseen that in a short future the drivers will be the energy savings for the building owners. Nowadays the main barriers for the rehabilitation are the price and the nuisances for the tenants due to the works. In this sense the efforts must be focused on overcoming the current barriers of the energy retrofitting sector by means of solutions which guarantee a fast and cheap application through the saving of lost times during the whole process.

Figure. 1: BERTIM project is based on the accurate data acquisition, digital design with the help of RenoBIM, CNC manufacturing, assembly and rapid installation.

The use of prefabricated modules for the energy efficient building renovation allows the reduction of on-site works, minimising the consumption of raw materials, increasing the energy and resource efficiency in the construction sector (Iturralde et al, 2016). In this context, timber and timber based building materials gain added importance due to their low primary energy demand from cradle to grave and carbon-footprints (see Fig. 1).

2. OBJECTIVES

The following technical objectives are addressed in the project in order to reach the target of improving the rehabilitation rate by the enhancement of the whole process through the development of new products and efficient manufacturing and installation procedures supported by digital tools. First, regarding to the new **strategies** for buildings' holistic energy efficient renovation process, the next points can be highlighted:

- Define a methodology for a holistic building renovation process based on digital data workflow. The objective is to avoid the duplicity in the design tasks (currently each involved technicians must erect their own building model for their own analysis).
- Define a general methodology for the efficient mass manufacturing, transport and installation processes of prefabricated modules in the timber manufacturing industry.
- Develop a system of timber prefabricated modules for building energy efficient deep renovation of very for the different climatic zones in Europe.
- Prototype and validate the energy performance, quality standard and improvement of air quality due to the renovation with timber prefabricated modules in a real scale research infrastructure.

About the a **software platform** that supports the energy efficient renovation process methodology,

- Develop a software tool to implement the methodology for the holistic building energy efficient renovation process.
- Develop a repository of the developed prefabricated modules in BIM for building renovation.
- Develop a renovation project decision support tool that will allow the customization of the developed timber prefabricated modules requirements
- Assure the interoperability of the tool with sectorial software (energy efficiency calculation software, structural calculation software) and with CNC software used in timber industry for manufacturing

The **targeted building type** to be refurbished by the BERTIM module has been identified after a deep analysis among a wide range of buildings, taking into account the market that the BERTIM modules could cover and the most suitable typologies to be refurbished with prefabricated sytems,

In order to define the **settings of products to be developed,** there has been an analysis of the manufacturer companies that participate in the BERTIM project (EGOIN, POBI and SETRA). This has allowed to identify the most suitable products. The objective is that the BERTIM modules will be a natural evolution of their existing products. Four different products will be developed in the BERTIM project for the energy renovation of the targetable buildings typologies defined:

- 2D envelope module with insulation (=A)
- 2D envelope module with insulation + embedded installations (=B)
- 3D installations module (=C)
- 3D residential module (=D)


Figure 2: Images of the 2D envelope module and 3D residential

The BERTIM renovation concept not only includes the renovation of the envelope of the building, but also the **existing obsolete services**. The renovation of existing installation systems is a relevant point in the building energy efficiency renovation activities, resulting in considerable energy savings.

2. METHODOLOGY

How to reach the goals defined in the previous point? For achieving that goal, it is necessary an overall perspective. Three main sub-systems have been defined. Sub-system 1 defines the timber based prefabricated module configuration or design. Sub-system 2 deals with the off-site manufacturing process of the modules. Finally, Sub-system 3 is based on the on-site installation process. The development of all these subsystems is being accomplished thanks to an overarching research methodology (see Figure 3) that include the next steps:

- Review of Literature and State of the Art regarding the use of prefabricated modules for building renovation.
- Conceptual framework definition. At this point, the design of the modules, the manufacturing process and the installation process have been defined theoretically. Axiomatic Design (Suh, N.P., 2001) has been used for this purpose. Previous automated and robotic developments in construction have been considered (Bock, Linner 2016)
- Detailed development of solutions. The modules, the manufacturing process and the installation process were defined deeply.
- First Tests in relevant environment. This refers to the Demonstrator performed at the Kubik building in TECNALIA facilities.
- Development of supporting software, being in the case of BERTIM, the RenoBIM software.
- Validation of modules and software. The modules are being validated according to the results of the first demonstrator at the Kubik building.
- Implementation new robotic manufacturing and installation processes that should be developed further

in the project. .

- Demonstration in projects. There will be three different demonstrators: a virtual case in Madrid (Spain), and two real cases, in La Charité sur Lore (France) and Oslo (Norway).
-

As in every European Project, the research is based on Work Packages (WP) that are organized correlatively in a calendar. Within these WP there are tasks that focus on specific matters. On task 3.1, a generic and standard solution was defined. But when applying this solution to each specific building-case, some other steps must be considered. First there is a measurement of the building-case. The main purpose of the measurement is to accurately adapt to the existing building. After that, the re-design or adaptation of the BERTIM modules to the building-case using a CAD first and with RenoBIM must be achieved. With that information, the manufacturing of the modules according to CAD or BIM can be carried out. Before the installation of the modules on-site, the building must be prepared meaning the removal of unnecessary elements from the building. Finally, modules must be installed. In principle, the ideal scenario would be to carry out a fast and smooth installation process while avoiding re-work. This concepts and procedures are explained in Figure 4.

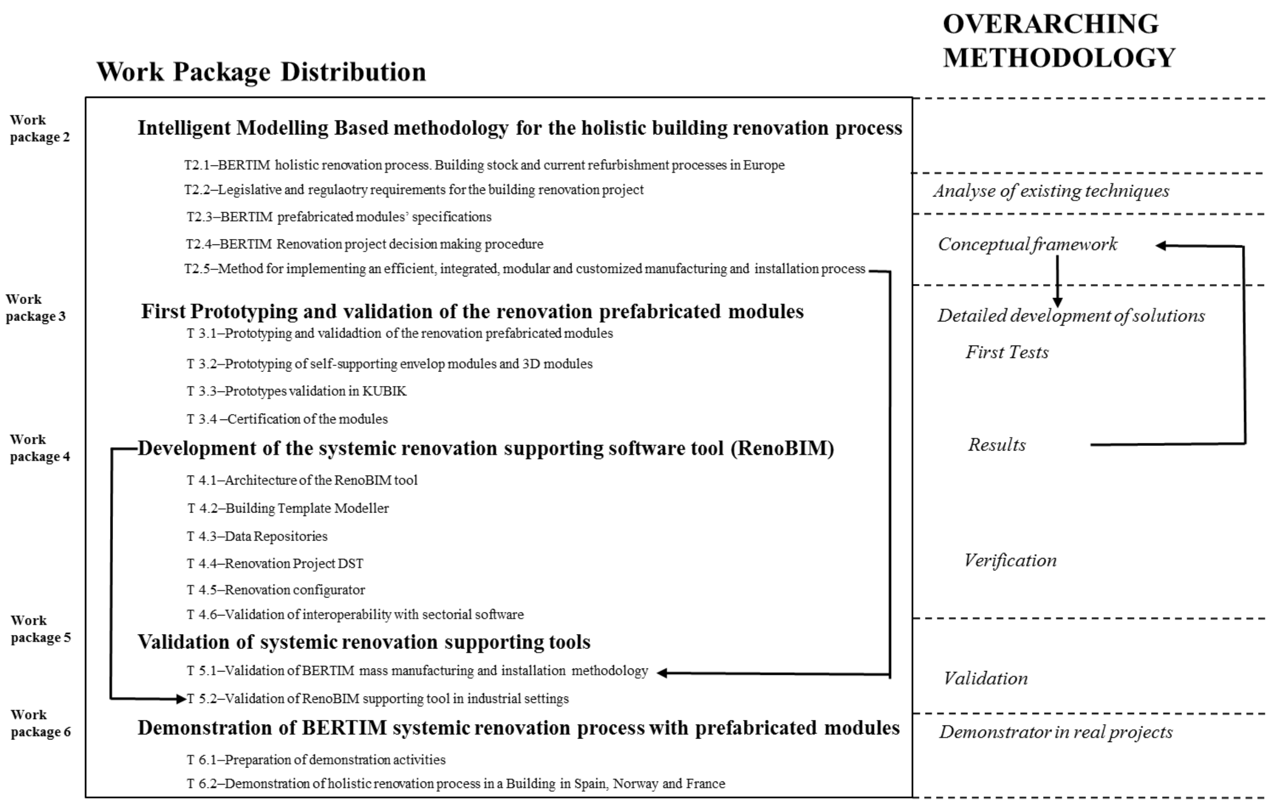

Figure. 3: Scheme of the overarching methodology of the BERTIM project.

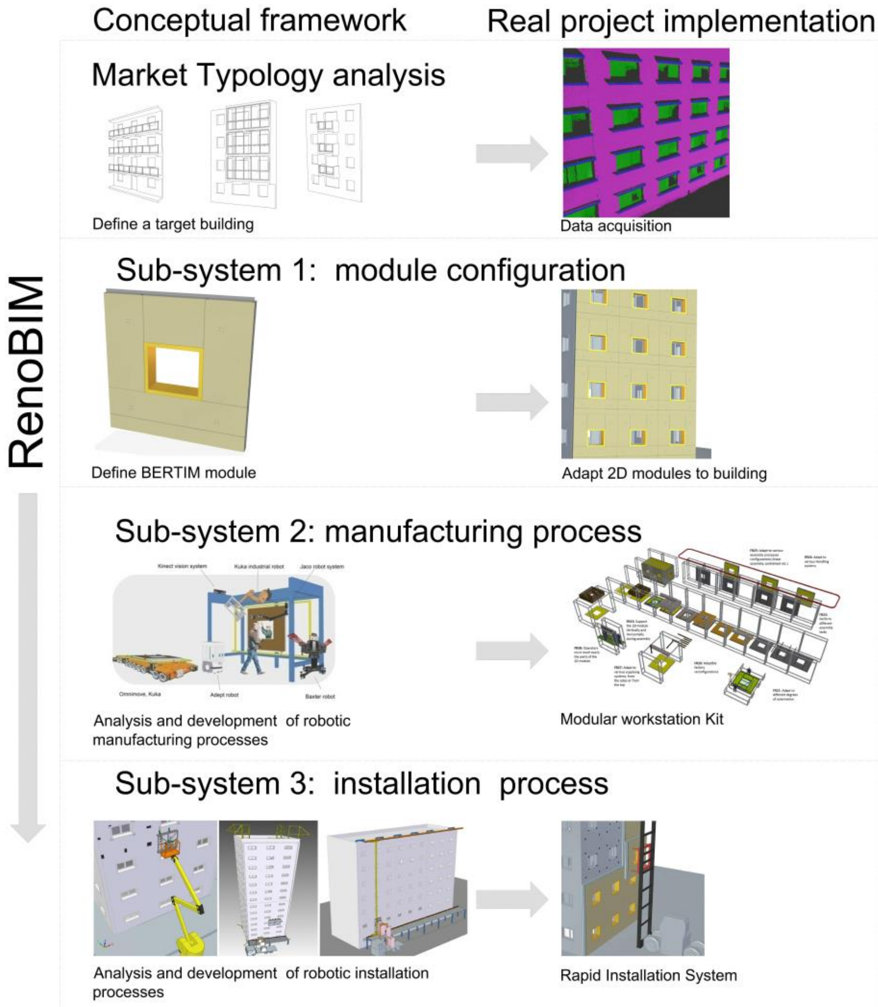

Figure. 4: Three sub-systems in the BERTIM project.

3. CURRENT RESEARCH PHASE

The research project is currently in month 24, out of 48, which means that half of the project has been already achieved. Most of the information is subject to confidentiality, but there are three main aspects that can be pointed out.

3.1 Definition and development of prefabricated timber panels and its manufacturing and installation processes

In the BERTIM project, 2D and 3D modules will be used. The 2D panels of light wood frame are modular systems that are anchored to the existing facade and are destined to their energetic rehabilitation. They integrate both the insulation and the elements of carpentry and can eventually be embedded inside the building community facilities (water supply and ventilation). The envelope 2D modules holds ducts and pipes to distribute the fluids from the installation to the dwellings, assuring a deep renovation with very low intrusiveness. The 3D modules also in timber are self-supporting and are located on the roof of the building and can be used either residential, increasing the living space of the building, or as a technical room to house centralized facilities of the building. These 3D modules have the possibility of incorporating renewable energies on the roof. In cases where it is possible to install a 3D installation module in the roof, it will contain services of heating, cooling, mechanical ventilation, DHW with solar panels coming from the ducts and pipes embedded in the panel. Furthermore, the 3D residential module, raising a floor on the existing building may be implemented as also a business model to allow the funding of the renovation works.

The main criteria for designing the selected products (2D envelope module without installations, 2D envelope module with installations, 3D installations module, 3D residential module) are set regarding the general specifications of prefabricated modules. The most relevant design criteria for the 2D envelope and 3D modules are defined below:

- Energy Efficiency criteria: Insulation solutions, façade's thermal performance assessment with BERTIM solutions, analysis of condensations in the panels, assessment of HVAC energy consumption reduction
- Services design criteria, specifically for 2D envelope modules with installation and 3D installation modules: Insulation requirements for building outdoor ducts and pipes, thermal analysis of 2D installation module and design specifications for panels with embedded installation.
- Structural design criteria : Modules design, existing building structural performance and modules' support elements design criteria
- Fire resistance criteria: Fire resistance and Reaction to fire of external façade

Apart from the general criteria, each manufacturer has their own restrictions and limitations in the design of the modules, due to the manufacturing system, transport and installation procedure. Those restrictions are analysed in order to define the final design of the module.

3.3-Validation in experimental building Kubik

KUBIK by Tecnalia is a full-scale R&D test facility for the development of new concepts, products and services in order to improve energy efficiency in buildings. KUBIK offers a flexible infrastructure able to build realistic scenarios with different building components and systems, for that is compulsory to make possible the assembly and disassembly of them. This permits not only in service performance assessment but also help to develop and to evaluate assembly and erection procedures. KUBIK allows the validation of products or systems in conditions close to those of service. This speeds up the product development and reduces the risk of malfunction of highly innovative products or products without previous experiences on the market place. The experimentally-obtained results enable diagnoses and proposals for potential product improvements to be made.

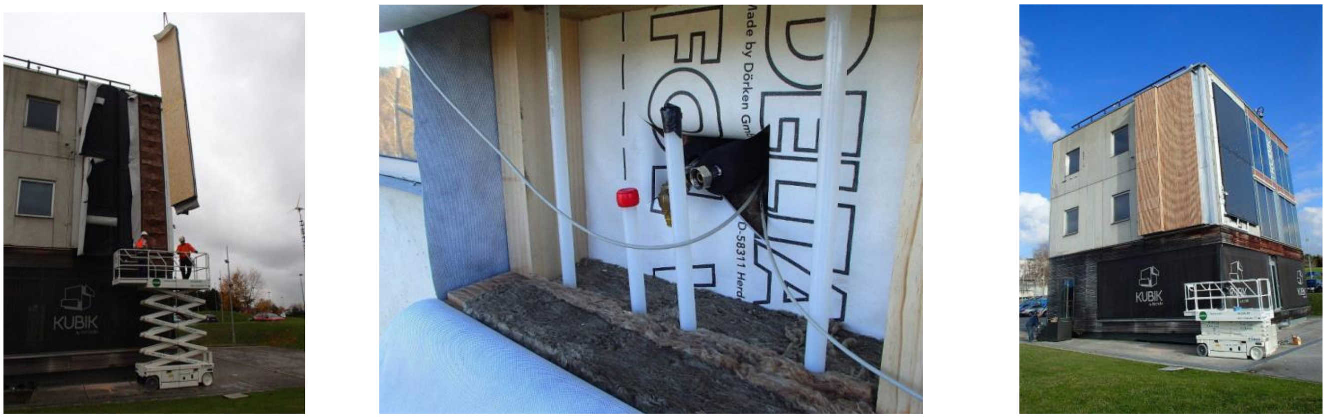

Figure.5: The demonstrator at the Kubik building, based on the installation of the modules, fitting the services and final finishing.

Two kinds of 2D envelopes modules have been tested: modules with embedded installations and without installation. Envelope modules will be placed on the facade to be rehabilitated in KUBIK at the 2 levels. This façade is a typical Spanish construction wall from the 70's, that consist of a cavity wall: brick, air cavity and brick (U-value 1,6-W/(m2K). This wall is intended to represent conditions of an actual building, as built and in service, as opposed to controlled laboratory conditions. The configuration of the panels has been chosen in such a way that different joins between panels can be studied. It means the assembly of: two installation panel of 3m height , two standard panels of 3m height and one standard panels of 6m height , as it is defined in the Fig.

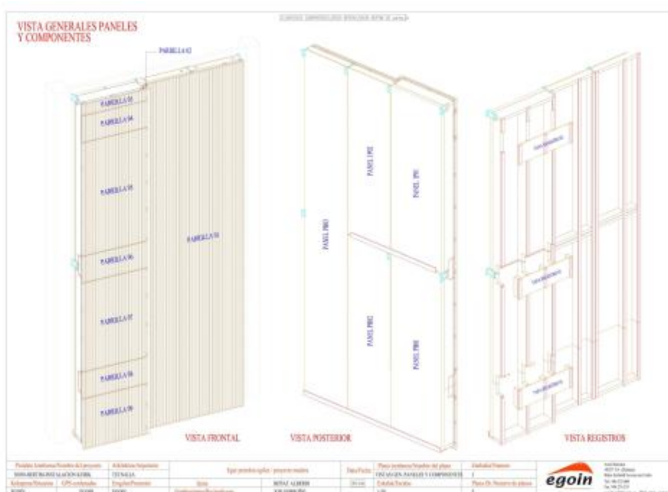

Figure 6. Drawings of the layout in Kubik

The standard panels are made of timber frame and the installation panels made of CLT have embedded air and water ducts. The finishing of the panels implemented in KUBIK is made of wooden slats supported by battens. The installation panels are provided of removable covers with the purpose of accessing to the critical points of the services in order to proceed with common maintenance operations. In addition there is another removable cover in the horizontal section where the installation panels are joined aimed at assembling the services after placing both panels.

The main goals of this prototype in Kubik are the following ones:

- Energy assessment of the BERTIM envelope modules achieved from the characterization of dynamic thermal characteristics of the envelope based on empirical data driven models will be determined.
- Heat losses assessment in the ducts and pipes embedded in the installation panel
- Analyse of the interaction between existing building and timber envelope according mechanical performance and hygrothermal behaviour.
- Validation of the BERTIM panels design that will provide feed-back to improve the detailed design further.
- To track and gather information about the manufacturing and installation process, especially regarding to timing and logistic issues. Once the data have been collected and analysed, these will be used as a benchmark in following tasks, regrading the optimisation of the process..
- Resolution of minor constructive details identified on jobsite
- Identification of less effective activities in order to reduce down-time costs, optimize the time of manufacturing and on-site works and decrease material wastes.
- To figure out the limitations of the erection and installation due to climate conditions, transport conditions, status of the existing façade, among others.

The limitations figured out in the process and the inefficiency in some activities are described in the chapter of conclusion of the current deliverable , giving inputs for improving the whole process thanks to the industrialisation of the manufacturing and automation during the assembly.
From this task, mainly conclusions related to improvements in manufacturing and installation of the prototype are achieved. Furthermore, the 2D modules will be validated on terms of energy efficiency during the experiment developed in KUBIK facilities

3.3-Development of RenoBIM tool

The tool will act as a collaboration platform where potential clients (building owners) and manufacturers define and assess the renovation project adapted to the stages defined in the decision making methodology. Thus, in a preliminary stage, the client can evaluate if the renovation using BERTIM solutions is technically feasible (according to accessibility, legislation or structural criteria entered via web forms) and if so, RenoBIM provides initial indicators related to energy savings, cost of return on investment. In order to do so, basic questionnaires to gather the existing conditions and geometry of the building are being developed. In this stage, RenoBIM can be seen as a marketing tool for manufacturers' solutions, who can engage potential end-users with a minimal effort. Gathering information of many potential end-users in different locations through the web tool can also serve for a market analysis that can provided valuable inputs to manufacturers.

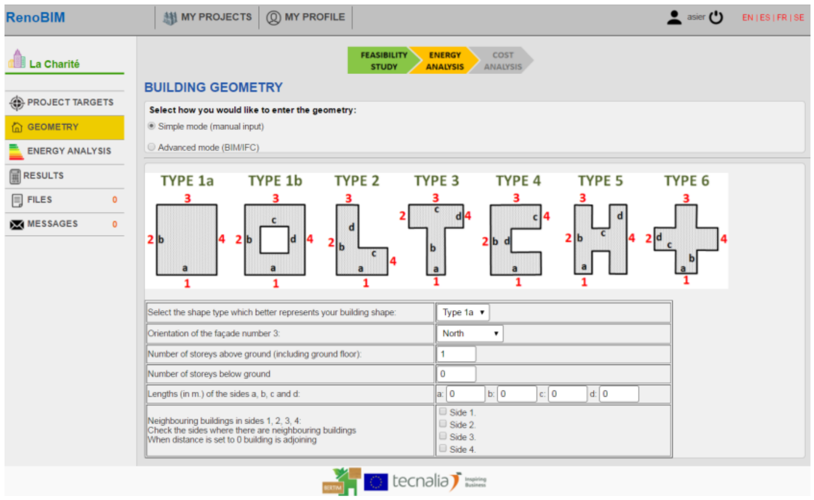

Figure 7: Sample data entry questionnaire for feasibility phase

Additionally, RenoBIM will also offer the possibility of a more detailed analysis based on a real BIM model of the building. This situation will typically occur once client and manufacturer are engaged in a contract, but is not necessarily restricted to that. For this situation, a guideline has been developed in the project in order to properly scan the building to be modelled considering BERTIM requirements. The analysis done in this step will be more accurate since we have a realistic geometry model of the building.

Furthermore, the BIM model will be the basis of a 3D configurator of the renovation project, where the user can visually define different façade splitting configurations (including rendering aspects) optimized to each manufacturer requirements (e.g. size of panels) and providing a cost estimation based also in the rendering material selected). This module is based on Web3D technologies and the output configuration will be sent to CAD/CAD tools (e.g. Dietrich's) in order to produce the final details and sent to CNC machines, minimising the risk of any possible pre-fabrication mistake.

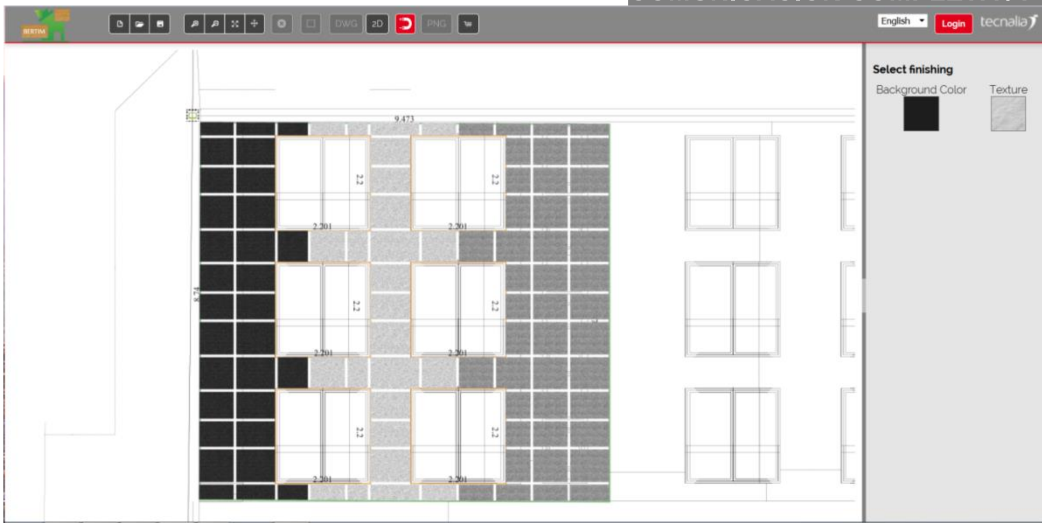

Figure 8. 3D configurator based on the real BIM model of the building

The key aspect in the whole RenoBIM process is that it relies on the support of Open BIM workflows, using the IFC standard and implementing interoperability mechanisms among tools. Thus, the different tools involved (BIM authoring tools to create the existing model based on 3D scanning), 3D configuration inside RenoBIM and CAD/CAM software will exchange the data using IFC. It is also worth noting that automated energy simulation is provided by using the Open Source engine EnergyPlus. With this aim, an exporter from IFC to IDF (the input file format for Energy Plus) is also being created, adapted to BERTIM needs. These Open BIM workflow will enable the reduction of renovation operation time, customized mass production, and lower financial risk for investors.

4. PRELIMINARY RESEARCH OUTCOME AND FUTURE WORK

The **re-design, manufacturing and installation** of a prototype within the BERTIM project has led to identify the areas of improvement areas in every phase of the process to improve its efficiency, which will be tackled in further steps of the project and demonstrated in real cases Therefore, the further steps must be focused on some issues that would need to be solved in order to improve the manufacturing and installation process, described below:

- As regards the data acquisition of the existing building, it must be accurate enough to get the level of detail necessary for the installation of prefabricated solutions for renovate the envelope and handy enough to be introduced in a BIM model which manage the whole process. In the analysed case the most suitable technique has proven to be the laser 3D. Nevertheless, new data capturing technologies can be addressed to overcome lacking building information in a cost-effective way.
- In the manufacturing process, it is convenient the automation on some manual processes, such as timber cladding, placing of services etc… in order to achieve a cost-efficient product and avoid waste of material.

- Regarding the installation process, some improvements may be addressed to enable and speed up the execution works on-site, such as the substitution of the flexible installation placed between the panels and existing building by high density mineral wool attached to the actual panels off-site, the development of specific products needed for wrapping/connecting pipes and ducts with vapour barrier, and the upgrade of mechanical systems to allow a fast and easy connections with the existing building.
- Some constructive details regarding the interaction with the existing building have (e.g. steel plates) had to be sorted out on-site, involving an important time consuming and making higher the installation time.
- CLT could be replaced by OSB in 2D modules to make the product more cost-effective and faster to manufacture.
- The placement of insulation on-site (flexible insulation over the existing building and inside the removable cover in the installation panel) takes too much time in comparison with the whole process. It might be necessary somehow to add this insulation to the module in the factory. Moreover, it would be beneficial to apply high density mineral wool attached to the actual panels off-site instead, so that the time consumed on site would be diminished. Special care should be taken when detailing the junction between panels, as gaps/thermal bridges should be avoided.
- The installation process is strongly limited by weather conditions. The insulation placed on site should not be soaked in order to keep its thermal properties.

About the **embedded services** in the modules, there can be several commentaries and approaches.

- Using regular connectors to attach the BERTIM module to the existing façade produces some tolerance in the positions of the pipes embedded in it.This tolerance is handled where the different 2D module ducts are connected, between consecutive modules or to an existing duct net in the dwelling.
- Using PEX pipes gives flexibility to the system to handle with the length differences due to the temperature differences for different operating conditions if the maximum lengths are 6-7 meters.
- Two different options of joints have been designed and used later in KUBIK: First option has more rigidity and it is a good option to couple pipes between modules.And the second one is a common flexible hose, giving more flexibility to the installers to connect to indoor part of the water loop.
- The continuity of vapour barrier should be maintained after the pipes have crossed it. Therefore, vapour barrier tape should be used to assure the continuity.
- Depending on the layout of the project, different hydraulic components should be needed to place in the water loop. For instance, in KUBIK layout, an air bleed is needed, leading to add a removable cover to allow accessibility for maintenance and commissioning services.
- The facility boxes are filled with insulation to reduce the thermal losses from components and to maintain the thermal resistance of the entire module.

Regarding the **thermal performance of the modules**, it can be said that in general terms, the assessed BERTIM assembly constitutes a successful retrofit intervention. As shown by a full scale experimental testing, the application of the BERTIM solution results in a 4x to 6x increase in the thermal resistance of the wall. Thermal properties of the BERTIM system are derived from the experimental dataset in KUBIK. In some cases (S11), the thermal assessment positions the BERTIM system in the vicinity of design values calculated in the design process of the experimental setup. However, several axes (S21 and S22) are more conductive than design values. This underperformance can be attributed to differences between the theoretical model and the as-built prototype. Although no clear conclusion can be drawn, some of the following causes may have occurred:

- The presence of an air gap between the BERTIM assembly and the original wall, in the case where the complete airtightness of this air layer cannot be guaranteed, can potentially result in infiltration of external air by natural or forced (wind-driven) convection. In Kubik this air gap is filled with compressible insulation material, Although this configuration makes it more difficult for such phenomena to occur, uneven insulation may happen due to different air gap thickness. In the tested assembly, care was taken on site to seal all joints between panels.
- Theoretical calculations assume perfect execution, which is rarely, if ever, possible on site. The authors believe that the workmanship in the tested assembly reflects general construction practice, and the experimental study is representative of the in-situ performance of a typical building, as built and in service conditions, retrofitted with the BERTIM assembly studied.

5. CONCLUSIONS

To sum up, we can conclude that the BERTIM envelope panels apparently become a suitable solution for facade refurbishing from the technical point of view. Nevertheless, there is a big room for improvement to get the whole process more effective by means of industrialization and automation of manufacturing and installation process. The future challenge, therefore, will be the optimization of the time during the whole chain of implementation. For that purpose, automated and robotic performances and fast fitting connectors will be implemented in Task 5.1. Moreover, the RENOBIM tool, to be developed further in the project, will help this optimization by linking the main activities involved in the process. Finally, the real and virtual demonstrators will give us the opportunity to show the results of the developments on automation, robotics and software development in the field of building energetic renovation.

AKNOWLEDGEMENTS

The research presented in this paper was fully carried out in the context of the H2020 project BERTIM. BERTIM has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 636984. The content of this report does not reflect the official opinion of the European Union. Responsibility for the information and views expressed in the report lies entirely with the

authors.

REFERENCES

Suh, N.P., 2001. Axiomatic Design: Advances and Applications, The Oxford Series on Advanced Manufacturing

Iturralde, K., Linner, T., Bock, T., Development of a modular and integrated product-manufacturing-installation system kit for the automation of the refurbishment process in the research project BERTIM, 2016 Proceedings of the 33rd ISARC, Auburn, USA

Bock, T., Linner, T., 2016, Site Automation, Cambridge University Press.