Article

Plug-and-Play solutions for energy-efficiency deep renovation of European building stock

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Abstract: Ninety percent of the existing building stock in Europe was built before 1990. These buildings are in urgent need for a significant improvement of energy-efficiency through renovation. Regrettably, so far only five percent of renovation projects have been able to yield energy-saving at deep renovation level. State-of-the-art renovation solutions are available, but costly and lengthy renovation processes and incomprehensible technical complexities hinder the achievement of a wide impact at a European scale. This paper presents research on Plug-and-Play (PnP) technologies supported by Building Information Modelling (BIM) to provide affordable, interchangeable and quick-installation solutions to overcome the main barriers of building deep renovation.

Keywords: Energy-efficient buildings; deep renovation; Plug-and-Play (PnP); Building Information Modelling (BIM); Building Energy Modelling (BEM)

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1. Introduction

Ninety percent of the existing building stock in Europe was built before 1990 and have reached the age for renovation. More than 40% of the existing buildings were built before 1960 when building energy performance standards were not common [1, 2]. There is an urgent need for a significant improvement of energy efficiency through renovation. The existing building stock is the single biggest potential sector for energy saving since buildings account for 40% of the EU's energy consumption, 36% of its CO2 emissions, and 55% of its electricity consumption. Therefore, energy-efficient buildings are crucial to achieve the EU's objective to reduce greenhouse gas emissions [3, 4].

Renovation accounts for 57% of the total building market in Europe, with residential buildings account for 65% of the renovation market in 2015 [5]. However, most of renovation projects are concerned with minor measures. Only 5% of the renovation projects aim to achieve energy saving of 60% or higher at deep renovation level [2].

Previous studies have summarized the financial, technical, process, regulatory, and awareness barriers to deep renovation [1, 2]. The financial barriers are concerned with high upfront costs of renovation; long payback for the key measures; and limited access to finance due to lack of standard approaches for investment in energy performance improvements. In addition to this, sometimes the energy cost is only considered as a minor part of the budget, especially when the energy prices are temporarily low. The technical barriers are: lack of technical solutions for specific building typologies, for instance energy performance improvement solutions for historic buildings; high cost of state-of-the-art technical solutions; high complexity of renovation projects; and lack of training and experience of construction professionals to work with certain methods and materials required to deliver successful energy efficiency renovation. The process barriers are mainly due to fragmentation of the supply chain since there is a lack of single parties willing to offer integrated deep renovation or near zero energy renovation as a service. Certain technical barriers are caused by the complexity of renovation and the burden for home owners to contract various parties (architects, energy advisors, contractors, etc.) for each type of the specialized work. The main parts of the regulatory barriers are due to varying requirements and national guidelines in the EU member states that address Energy Performance Co-efficient (EPC) and Energy Performance of Buildings Directive (EPBD). There are also multiple definitions and categories for energy-efficiency renovation within EPBD and Energy Efficiency Directives (EED). Next to the previous barriers, awareness barriers still exist since most building occupants are insufficiently acquainted with the energy performance aspects of their buildings and the potential increase in comfort and quality of life that deep renovation can bring. Building occupants often receive inadequate advice or information despite the campaigns undertaken by many governments, industries and civil societies.

The objective of research presented in this paper is to break through the barriers of deep renovation and to promote innovative solutions with a high replicability potential at European scale. This paper refers to the EU collaborative research project titled P2Endure, which is focused on practical development and implementation of Plug-and-Play (PnP) solutions and tools for deep renovation of residential and public buildings [6]. The following section of this paper is a brief theoretical discussion on the PnP concept, its origin and its adaptation and adoption for buildings. Subsequently, the research methodology in the P2Endure project is explained, and the preliminary research findings are analyzed. Accordingly, conclusions are drawn on how PnP solutions can break through the current barriers for deep renovation. Finally, recommendations are presented on the roles of PnP solutions for upgrading the smartness of existing buildings through deep renovation and future updates.

2. Theoretical review

The term Plug-and-Play (PnP) was coined for the first time in 1995 when the principal founder and the then chairman of Microsoft Corporation, Bill Gates released the new Microsoft Windows 95. He presented among others the PnP capabilities of the new computer operating system, which made it easy to install hardware and software [7]. Windows 95 was the first operating system capable of automatically detecting and configuring a new device attached to the computer, with the possibility of falling back to manual settings when necessary [8]. The main innovation of PnP is found in the user-friendliness since no user intervention is needed except for connecting the device to the computer, thus no procedure is required for installing the driver software and setting up the hardware device. The device is automatically recognized by the computer which loads the particular driver software and, in a few seconds, the device starts working properly [9].

In more than two decades after its introduction, the term "Plug-and-Play" has been widely used beyond the domain of computer science, including in construction. Even though this term has only been used in construction recently, the basic principles of PnP might be traced back to the reconstruction period in Europe after the Second World War. The high demand for fast redevelopment led to industrialization in construction, which was marked by the rise of prefabrication and modular building systems. Such solutions address several key characteristics of the PnP concept, namely: typical functionality, modularity, and dry joints between different components. Furthermore, reduced human intervention, as an essential part of the PnP concept, was realized by shifting on-site manual labor to off-site manufacturing. On-site activities took a new focus on assembly, or in other words: connecting different components [10, 11]. Within this context, PnP solutions also help to minimize human errors during on-site assembly, which is important to meet new building regulations on quality, energy performance, and comfort level.

Beyond standardization and fast on-site assembly, user-friendliness as the ultimate aspect of PnP is addressed by the state-of-the-art solutions for prefab and modular construction through the assembly techniques using simple joints without heavy equipment. User-friendliness for on-site assembly has become a critical issue in Europe due to the scarcity of skilled labors in construction as an implication of the ageing population and the fact that fewer young people have a preference for a career in the construction industry [12]. In the Netherlands, in average there is 3.5% natural outflow of construction site workers. During the period of 2017-2022, 70,000 people are estimated to leave the construction industry due to occupational disabilities or retirement [13]. User-friendly PnP solutions thus answer to the need to cope with significantly lower number of workers and to minimize manual effort on the construction site. The user-friendliness of certain PnP solutions even allow non-professional end-users to choose and install interior components and room units, such as PnP kitchen and bathroom modules, in their dwellings or offices [14].

Along with the emergence of the fourth industrial revolution (Industry 4.0), smart innovation has penetrated PnP solutions in the domain of architecture and construction [15, 16]. Advanced PnP solutions in construction comprise smart building components and Mechanical Electrical and Plumbing / Heating Ventilation and Air Conditioning (MEP/HVAC) systems. The PnP solutions continue to progress in achieving the three key functionalities of smartness in buildings as defined in the revised EU EPBD, i.e. 1) the ability to optimize their energy performance; 2) the ability to adapt their operational modes in response to the needs of the building occupants; and 3) the flexibility of the overall building systems in relation to the surrounding environments or energy grid [17]. These new abilities of the PnP solutions are facilitated by Industry 4.0 technologies, such as Internet of Things (IoT) and Big Data analytics with machine learning. Smart joints with embedded sensors facilitate quick assembly on the building site, connectivity between different PnP components, and real-time data collection. Data about Indoor Environment Quality (IEQ), energy performance, and user behaviors can be collected and processed using Big Data algorithms for the purpose of condition monitoring, predictive maintenance and building optimization [18, 19].

Smart PnP components are usually integrated with Building Automation and Control Systems (BACS) or Building Management Systems (BMS). While historically the building services control systems were mainly concerned with MEP/HVAC devices, nowadays various PnP systems are integrated and the scope of PnP concept in buildings has grown to include both hardware and software elements [20, 21]. The roles of information management and data interoperability have become significant in relation to PnP concept. Building Information Modelling (BIM) grows rapidly and it is needed throughout the whole value chain of PnP solutions, from design, through engineering and off-site manufacturing, until on-site assembly, building operation and performance monitoring. The importance of BIM for deep renovation of prefab component based buildings has been underlined in previous studies [22]. BIM delivers substantial added values to develop and implement smart and high performance products as well as cost-effective and highly-efficient processes that are key to successful deep renovations. Considering the important role of BIM, the research presented in this paper builds upon the state-of-the-art knowledge to investigate and demonstrate BIM-based Plug-and-Play solutions for deep renovation.

3. Research methodology

This paper presents technical research within the European collaborative project titled P2Endure with a 4-year duration [6]. The project started with a selection of state-of-the-art PnP renovation solutions, which are either on the market or available as prototypes from previous research projects. These solutions were categorized in three groups: 1) PnP components for building envelopes; 2) PnP retrofit for MEP/HVAC systems; and 3) on-site 3D technologies. Research on these solutions is dedicated to increase the Technology Readiness Level (TRL) of the prototypes in order to make them ready-for-market, especially by improving the production and logistic processes to meet high-quantity demand, as well as to arrange for patent or certification procedures for high-quality products. Subsequently, integrated solutions for renovation design and on-site assembly are developed to allow different complementary products to be combined as flexible solution packages for deep renovation depending on the addressed building typologies.

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Next to the renovation solutions, a methodology for cost-effective and time-efficient deep renovation is proposed. The methodology, called as the 4M process, consists of four main stages as shown in Figure 1, namely: Mapping, Modelling, Making and Monitoring. The "Mapping" process comprises 3D laser and thermal scanning accompanied by condition assessment of the existing buildings, a review of the energy consumption records in the preceding years, and an analysis of the Indoor Environment Quality (IEQ) before renovation. The mapping process results in an accurate identification of the building's pre-renovation energy performance and the needed improvements. The "Modelling" uses As-Built Building Information Models (As-Built BIM) as input for BIM-based renovation designing and Building Energy Modelling (BEM) for simulating the performance of viable renovation measures. The "Making" process takes place both off-site and on-site. BIM is used for product engineering and in support of off-site prefabrication. In certain cases, BIM is used for on-site 3D printing with collaborative robotics. Finally, the "Monitoring" process is conducted for energy and comfort. Energy monitoring is done both automatically through smart meters as well as manually through user survey and analysis of energy bills after renovation. For the purpose of comfort monitoring, the Comfort Eye tool is installed inside the building to collect and analyze IEQ data [23].

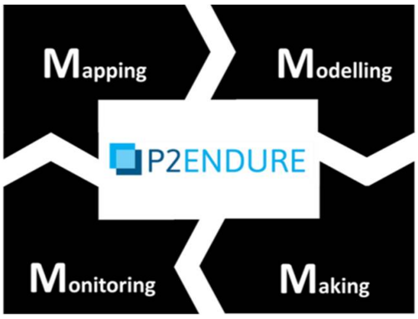

Figure 1. 4M process methodology for deep renovation [6].

P2Endure also optimizes and deploys supporting ICT tools for deep renovation, in particular: a BIM Parametric Modeler, a software application for building inspection using mobile devices, and a lifecycle cost (LCC) management tool. The BIM Parametric Modeler is used to configure and analyze renovation options by estimating the energy performance impacts of individual and combined renovation measures. The building inspection software, which is also available on mobile devices (smart tablets), assists the building specialists during visual / non-intrusive inspection to register the maintenance condition of building and MEP/HVAC components. The LCC tool is able to present an insight into the long-term economic benefits of deep renovation compared to minor renovation and regular maintenance.

Empirical evidence of the effectiveness of P2Endure solutions is gathered from the implementation of 10 deep renovation projects in various EU countries. These real demonstration cases represent the main typologies within the existing building stock in Europe subjected for deep renovation, namely: apartment complexes and low-rise residential districts, nurseries and educational facilities, and historic buildings. The building owners and tenants of these cases are involved as stakeholders to the P2Endure project consortium, so their feedback can be collected to assess the upscaling and replicability potentials of the proposed PnP renovation solutions.

4. Actual research findings

The preliminary outcomes from each stage of the 4M process methodology for deep renovation are described and analyzed in this section.

The first outcome from the "Mapping" stage is based on the '3D scan to BIM' process, which started with collecting existing as-built documentation of the building, such as drawings and specifications, which were available in analogue or digital format. Analysis of the available information was used to define the most optimal protocol for 3D data acquisition through laser

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scanning. As such, the 3D point cloud models resulting from laser scanning could complement the information from the available as-built documentation. The 3D point cloud models were used as reference models to create BIM. Although to a certain extent geometric recognition could be done by post-processing software, no fully automated procedure was available to develop BIM from 3D scan data. This limitation was confirmed by recent studies and actual practice [24]. Despite this limitation, '3D scan to BIM' as implemented in two real demonstration cases of P2Endure, has delivered adequate As-Built BIM for deep renovation [25]. The result from the deep renovation case in Warsaw, Poland is illustrated in Figure 2.

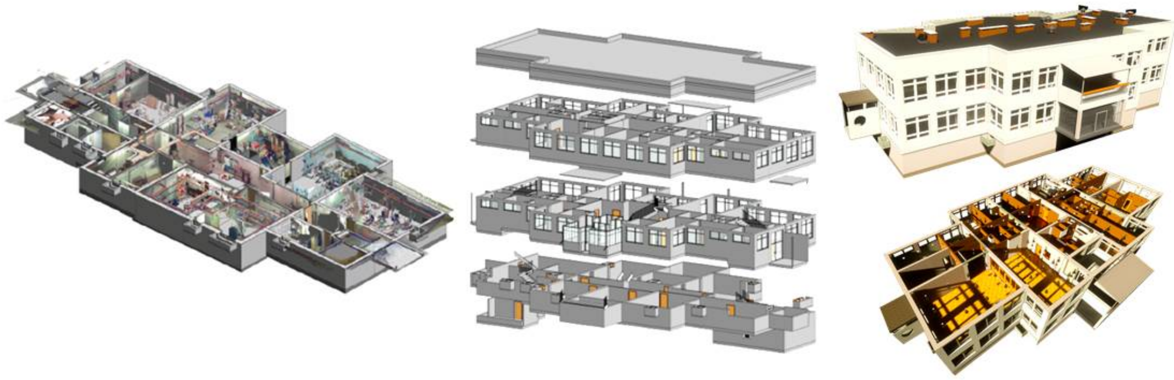

Figure 2. Result of '3D scan to BIM' from deep renovation case in Warsaw, Poland [25].

Next to laser scans, thermal scans were also performed on the existing buildings to detect thermal-related issues which compromised the buildings' energy performance. The thermal images, either two or three dimensional, could be superimposed to the BIM models based on the technique developed in a related EU research project titled INSITER [26]. The As-Built BIM models were imported into the software tool for building condition assessment [27]. This software generated a decomposition list of the building components, which was used to assign the condition score to each component based on a visual inspection. The condition scores were then taken into consideration whether certain building parts should be maintained, repaired, refurbished or replaced depending on the selected renovation options.

The "Modelling" stage has delivered preliminary BIM of renovation designs along with their energy performance estimates, which were calculated through Building Energy Modelling (BEM). The BIM Parametric Modeler tool imported an As-Built BEM model in .idf format derived from EnergyPlus (read explanation in the next paragraph) and used this model to make configurations of suitable renovation solutions, for instance: façade retrofit by applying multifunctional panels and reversible windows [28]. The energetic and economic properties of the renovation solutions are analyzed to present an overview of the impacts of various renovation options, as shown in Figure 3.

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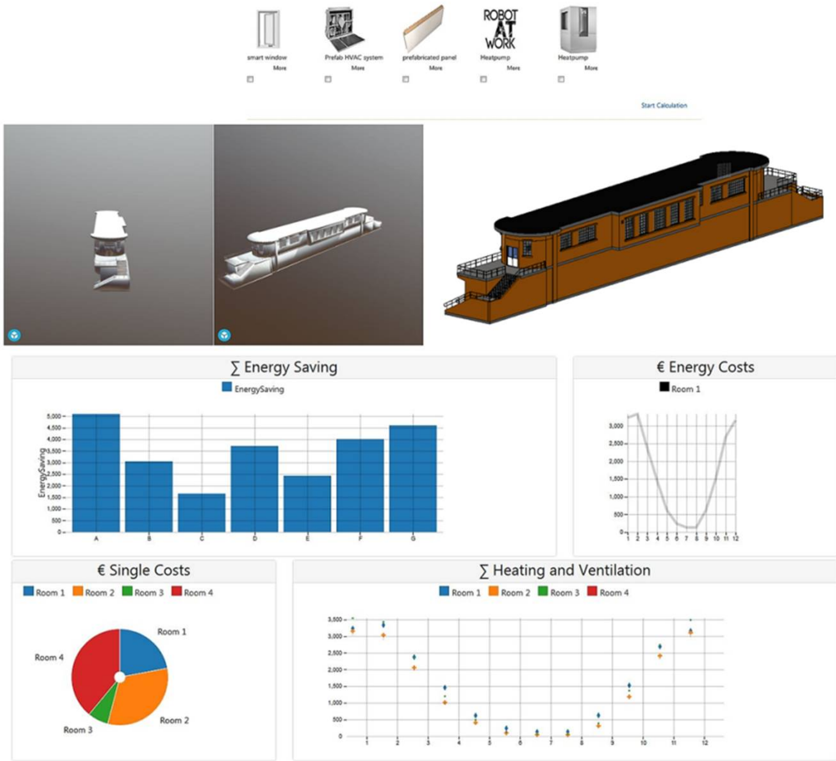

Figure 3. Result of the BIM Parametric Modeler for deep renovation [28].

P2Endure tested several methods for 'BIM to BEM' since there was still no commonly accepted and fully-reliable method for BIM-based energy simulation [29]. The first 'BIM to BEM' method included the following steps: Simplified BIM in AutoDesk Revit format – Export to .idf – model modification and energy modelling using Google SketchUp with Legacy Open Studio – Export to .idf – energy simulation using EnergyPlus – calculation validation. This method for BIM-based energy simulation is cost-effective due to the use of open-source software such as SketchUp, Open Studio and EnergyPlus. However, this method is suitable for rather small-scaled buildings due to the risk of losing information at import-export of complex models and the demand for manual adjustments. The second method relied on IFC open standard for BIM, and the process went as follows: Simplified BIM in AutoDesk Revit format – Export to .ifc – model modification using IFC Builder – energy modelling using CYPETHERM LOAD and CYPETHERM HVAC – energy simulation using EnergyPlus – calculation validation. This method is suitable for large buildings thanks to a simpler process for importing BIM model to the CYPETHERM. The CYPETHERM software is able to recognize geometries and surfaces in BIM, and it is interoperable with certain tools through a cloud-based service that facilitates data exchange. Additionally, there is a possibility to export object libraries that can be used in future modifications. An example of the achieved result of 'BIM to BEM' for analyzing the renovation measures is taken from the real demonstration case of a nursery building in Genova, Italy where the energy simulation indicated that installation of reversible windows would yield 28% of energy saving, installation of the reversible windows and internal insulation would yield 57% of energy saving, and adding condensing boiler to both measures would yield 62% of energy saving that was required to meet the deep renovation level [30].

The preliminary outcomes of the third stage in the 4M process methodology, the "Making", are: lightweight multifunctional panels for façade retrofit; reversible windows with an optimized design and an scaled-up prefabrication process; rooftop retrofit modules based on lightweight steel structures; and on-site 3D printing of façade layers using collaborative robotics [31]. The multifunctional panels were produced by Fermacell in Germany where a set of full-scale mock-ups for P2Endure were developed and examined. The panels could integrate ventilation with heat-recovery systems. The panels were designed for easy installation without heavy equipment or

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structural changes to the existing building. At the deep renovation case in Warsaw, Poland, BIM was used to create the modules for the panel while taking into account the assembly techniques and combination with other renovation solutions, as shown in Figure 4.

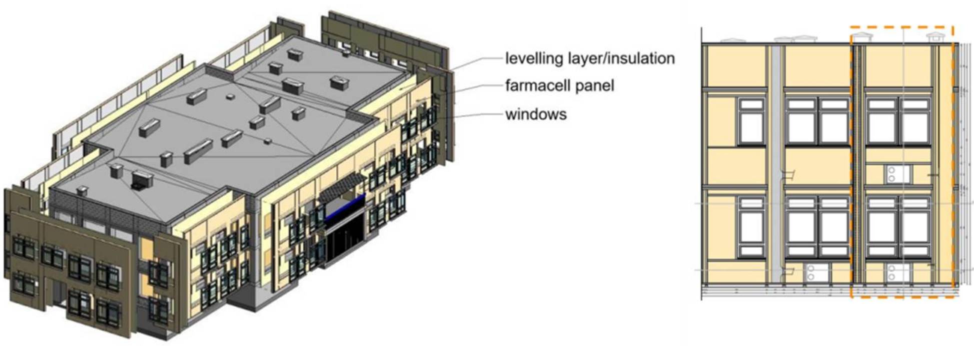

Figure 4. BIM-based application of Fermacell panels for renovation case in Warsaw [31].

The reversible windows in P2Endure were developed by BG TEC in Poland [31]. These windows have dual thermal properties to keep the warmth inside the building in winter time, or to reflect the solar radiation and accommodate fresh air to the building during summer. Each window is fitted with low-emissivity (Low-E) glass. Depending on the desired thermal performance, the window frame allows the users to rotate the glass by 180 degrees either manually or mechanically. Another PnP product, rooftop retrofit system, was designed by PANPlus in the Netherlands. The rooftop retrofit system consists of lightweight steel modules that can be manufactured and installed depending on the need of the to-be-renovated buildings. Rooftop retrofit has a substantial contribution in terms of energy saving, especially for existing buildings without adequate roof insulations. Additionally, rooftop retrofit improves the architectural quality of the building and creates space for additional rooms or to accommodate building utility systems in relation to the retrofitted MEP/HVAC systems. PnP solutions in P2Endure also includes on-site 3D printing for deep renovation as developed by Robot-At-Work and Invela from Denmark; shown in Figure 5. 3D printing is done with collaborative robotics, which includes high-precision façade rendering or plastering by coating the exterior wall with materials to level the surface, and robot assisted milling that allows for three dimensional designs.

Figure 5. On-site 3D printing for renovation in Korslokke, Denmark [http://www.robotatwork.com].

“Monitoring” as the final stage in the 4M process methodology in P2Endure has not yet delivered results as the renovation projects are still ongoing. Regarding energy performance, monitoring is performed before and after renovation. So far, this has been done manually based on energy bills and user surveys. In the future, energy data collection through smart meters will be implemented. Regarding IEQ, monitoring activities have commenced with the installation and calibration of the Comfort Eye tool. It is a low-cost sensing device for the real-time monitoring of IEQ, focusing on indoor thermal comfort and air quality. It relies on a microcontroller and a set of sensors with embedded algorithms to derive the Predicted Mean Vote (PMV) index for multiple subjects. A device can monitor a room of 10m x 10m. In P2Endure, the empirical data is collected before and after renovation in both summer and winter periods in order to allow for evidence-based analysis of the comfort improvement through deep renovation. In addition to IEQ information, the Comfort Eye tool can provide complementary information about the building envelope

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performance. Since thermal maps of indoor surfaces are acquired continuously, they can be used to investigate the temperature variations in correlation with the insulation properties of the wall, as exemplified in see Figure 6.

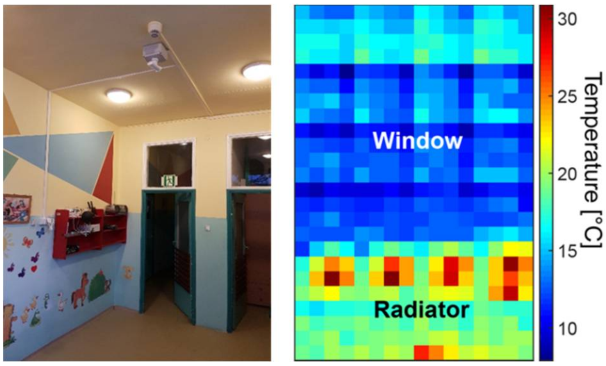

Figure 6. Comfort Eye sensor installed in P2Endure deep renovation case in Warsaw and the thermal map of the exterior wall observed from the room.

5. Conclusions and discussions

This research paper investigates and demonstrates Plug-and-Play (PnP) concept and solutions for building deep renovation. Based on the empirical findings from the P2Endure research project, it concludes that PnP solutions can break through the barriers to renovate the existing building stock in Europe. The financial barriers can be resolved by affordable PnP renovation solutions which are produced in a large volume. Cost saving will also be achieved by using simple and universal joints during on-site assembly, so the PnP solutions do not need tailor-made techniques for each renovation project. Another contribution to resolve the financial barriers is found in easier and more reliable calculation of Return on Investment (RoI) of the PnP solutions since their performance levels are standardized. Standard PnP installation procedures will, in turn, resolve the technical barriers in terms of renovation project planning and construction skills. The process barriers in the renovation supply-chain will be broken since the market will become more open as PnP solutions imply that substitute products and services are available so dependency on a single party is minimized. The regulatory barriers due to non-uniformity of definitions and performance target can be resolved especially by smart PnP renovation solutions that meet the standard definition of smart buildings and Smart Readiness Indicators (SRI) included in the revised EPBD. Finally, the awareness barriers can be removed as the building occupants have become familiar with the PnP concept thanks to advancements in ICT and home appliances.

The P2Endure's 4M methodology is useful to clarify the PnP approach throughout the whole deep renovation process. During "Mapping", As-Built BIM derived from '3D scan to BIM' actually becomes the main information carrier or platform where other pieces of information (such as existing documentation, user survey and condition assessment reports) can be 'plugged in'. During "Modelling", various renovation products and measures can be 'plugged in' to BIM for configuring the optimal renovation design and make simulations of the energy performance. During "Making", the PnP products are assembled on-site without the need for heavy equipment or complicated joints. Finally, during "Monitoring", a PnP IEQ monitoring tool is deployed while PnP data exchange mechanism through smart meters and IoT sensors will be made available in the near future.

There remain several bottlenecks of PnP deep renovation. Although integration and interoperability are in the essence of PnP concept, certain limitations still exist in all 4Ms. In "Mapping", there is still no fully-automated procedure or tool for '3D scan to BIM'. In "Modelling", there is no common agreement yet established to solve the interoperability issues related to BIM formats and BEM tools. In "Making", many providers of various PnP renovation products have limited willingness to investigate the optimal integration solutions with products other than their own. In "Monitoring", constraints still exist to data exchange due to incompatibility of smart meter standards in different countries as well as the ongoing discussions on data privacy.

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Towards the future, PnP deep renovation based on P2Endure research methodology is important to upgrade the smartness of the existing building stock in Europe. In P2Endure, upgrading the buildings' smartness has begun by digitization of building and energy information through BIM and BEM. Follow-up research should be dedicated to automation and standardization of procedures and tools to reduce time and to increase accuracy in As-Built BIM creation and BEM simulation. Furthermore, smart / advanced materials should be used for on-site 3D printing. The PnP renovation components, such multifunctional panels and reversible windows should be made smart as well through integration of smart sensing, actuator and control systems. Smart monitoring after renovation which covers various aspects, i.e. energy performance, health and comfort, and lifecycle cost, should continuously be upgraded, too. The collected real-time data should be linked to As-Renovated BIM to generate and maintain BIM-based Building Renovation Passports. This is fully aligned with the long-term policy of the European Commission for energy-efficient buildings [32].

Upgrading the building's smartness needs to be done through gradual updates. Take the smartphone industry for instance; the most successful apps release one to four updates every month [33]. So, expecting that one-time deep renovation would be able to make the existing buildings smart and future-proof is not realistic. PnP deep renovation provides a solid and flexible basis for future updates of building's smartness, which need to be planned appropriately. Scientific research on a sustainable strategy for continuous upgrade of building's smartness is, therefore, strongly recommended.

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