Adopting Off-site Manufacturing, and Automation and Robotics Technologies in Energy-efficient Building

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Abstract –

Delivering energy-efficient buildings or settlements has become a popular topic amongst architects, engineers, and building engineering physicists. There are many methods for improving building energy performances, both for new build projects and for retrofitting existing buildings. However, the construction industry faces some profound challenges to satisfy the increasing demand for energy-efficient buildings or other solutions and to be able to offer them at an affordable cost. A holistic approach has been adopted to validate whether automation robotics and off-site manufacturing technologies can yield positive changes in the delivery of energy-efficient buildings. This paper emphasizes the potential transformations and possible impacts on the design, construction, and installation process of an energy-efficient building once the advanced technologies are implemented. This paper also highlights case studies in multiple on-going or past European Union (EU) Horizon 2020 research projects as well as private projects to demonstrate the applicability and technical feasibility of the proposed solution. The scenario proposed was used to demonstrate how to apply the proposal in a large-scale residential building project. In addition, the findings from this study will serve as proof of the concept of a larger research project, or as an inspiration for the construction industry to execute energy-efficient building projects in the future.

Keywords –

Prefabrication; Construction robotic; Energy-efficient building

1 Introduction

At present, and in the near future, the build environment has many implications for peoples' lives in Europe. The construction industry consists of a complex value chain and supply chain yet is also one of the major contributors to CO2 emissions and consumes a substantial amount of energy. Building activities consumes up to 40% of the total EU energy usage [1]. Recently, decarbonisation has become a popular topic so new policies and research initiatives are aiming to improve the overall energy consumption rates in new builds and existing building stocks. Many building activities belong to a construction project and the energy consumption rates differ between each activity across the entire building life cycle. For instance, the building operational phase consumes the most energy, which is why it is the area researchers and the extended industries are focused most. However, due to the complexity and fragmentation of construction tasks, it is very challenging to improve the overall performance of an energy-efficient building if it only addresses the operational phase and ignores the others. This paper provides a comprehensive insight into how prefabrication, construction automation, and technology integration have the potential to enhance entire segments of an energy-efficient building value chain from the design stage to the end of the building life cycle. The paper features several EU Horizon 2020 research projects that validate the proposed solutions. These proposed solutions are an emphasis on the design, energy product integration, and construction processes in both new build and renovation projects. Introducing innovative methods and technologies to the construction industry requires cross-disciplinary collaboration between stakeholders, allowing interdisciplinary interaction and promoting collaborative work throughout the building life cycle. In addition, the featured solutions for energy-efficient building construction or renovation can be used as a proof of concept (PoC) for a larger research project within the respective parties [2].

2 Energy-efficient building construction strategy

It is difficult to form a definition that would easily summarize the building construction process, let alone an energy-efficient building construction project. Building construction consists of various phases and tasks; each task involves specific skill sets, tools, and methods.

Buildings are designed, constructed, or located in different styles, materials, locations, respectively, and also sometimes have different functions. Occupants also change over the entire building life cycle. Ultimately, an energy-efficient building should consume less energy yet retain the same performance for as long as possible. To achieve maximum adaptability and flexibility, a building should be designed as a system rather than a collection of individual parts, which creates high levels of inefficiency. More flexibility in design also means the building can easily adapt to potential changes in requirements and demands. The designer should consider all the building phases regarding building energy consumption and evaluate how the energy performance could be influenced by each construction phase throughout the building life cycle.

In general, the building life cycle consists of four stages, including the planning stage, the building stage, the operational stage, and the decommissioning stage. The planning stage includes building site selection, obtaining a building permit, a regulation submission, building material selection, and general organization. The building stage involves logistics, site preparation, construction, site clearance, and building commissioning. Each construction method will have distinct energy requirements and the choice of construction method can instantly influence many aspects within the building phase, such as the selection of construction tools, management method, scheduling, and cost structure. The operational phase consists of usage, repair, maintenance, and upgrades of the building. Based on research, the operational phase uses up to 36% of the total energy consumption in the building life cycle. Moreover, a building should be designed to accommodate the selected technologies as well as to ease the repair and maintenance processes [3]. The decommissioning phase covers disassembly, large-scale alteration, demolition, and recycling. The waste generated by the construction sector is astronomical. In terms of an energy-efficient building, the building should be ungraded and reutilized rather than disposed of in a landfill site. Moreover, to achieve an energy-efficient design, the designer should take into account the embodied energy in the building lifecycle, which means being aware of the energy consumption associated with each building process, i.e., production, design, construction, operation, maintenance, and repair [4].

A reduction of building energy consumption in building construction as well as in existing building stock is a vital part of the EU sustainable development strategies. Thus, the European Commission has set up relevant policies and directives that are aimed towards supporting energy-efficient buildings. For instance, Energy Performance of Buildings Directive (EPBD) was set up in 2002 [5], an Energy Policy for Europe was announced in 2007 [6], Energy 2020 was enacted in 2009, and Energy Performance of Building Directive was published in 2010 [7]. Due to building processes involving many stakeholders, implementing innovative building technologies requires an extensive cross-disciplinary approach along with strong public-private-partnerships in order to develop a feasible roadmap and applicable solutions for developing an energy-efficient building.

3 Challenges and barriers

The energy-efficient building development has been divided into the following stages: design, building structure, building envelope, construction process, end of life, integration, and cross-disciplinary collaboration. This section will evaluate the challenges and barriers imposed by each of these stages.

The main challenges during the design stage are how to involve every key stakeholder from the earliest phase of the project as well as how to enhance interactions of the stakeholders to achieve cost-effective solutions. The main barrier associated with these challenges is a lack of a holistic approach for organizing construction tasks related to energy-efficient buildings. There are ample opportunities for miscommunication or a lack of communication between key stakeholders. Many stakeholders are reluctant to adopt Information and Communication Technology (ICT) tools and many of the regulations regarding energy-efficient building are complex and varied across the EU. The challenges that relate to the building structure stage are reducing the overall level of embodied CO2 level in all buildings and utilising building structures more effectively. The barrier associated with these challenges is how difficult it is to integrate innovative energy production products with existing building structures. Regarding improving the performance of the building envelope, the main challenges are improving the building envelope energy performance in both new builds and existing buildings, interconnecting innovative materials and technology with the existing envelope, complying with the regulations, and easing the installation process by using alternative construction methods, such as prefabrication. The barriers associated with the building envelope stage are fourfold. First, there is a lack of development in energy-efficient building envelopes. Second, most of the commercialized products are driven by local building code and investments. Third, there are high costs involved in industrialized systems and they are still not wildly accepted. Finally, the compatibility between the innovative technology and the existing building envelope is low. The main challenges and barriers related to the construction process include labour-intensiveness, inadaptability, and lacking innovation and a skilled workforce. The construction sector is slow in adopting prefabrication and the initial investments for implementing an innovative construction method are high [8]. Understanding what the most feasible solution is for transferring the industry from traditional building demolition to deconstruction, upgrading, reusing, and recycling is the main challenge for a building's end of life management. The main barriers with these are a lack of innovative recyclable construction material, the costs of building material recycling being high, and limited institutional, as well as technological, support for deconstruction. The next section summarizes numerous on-going or past European Union (EU) Horizon 2020 research projects to investigate the practicable solutions for the aforementioned challenges. The selected projects also inspired the design of the proposed systems that shall be described in the later section.

4 Methods

Developing energy-efficient buildings or settlements still faces many challenges so it is essential to transform the barriers associated with each challenge into innovation opportunities for the designer to consider during each construction stage. The selected case studies provide a comprehensive insight into technology integration, prefabrication, and automated installation technology, and are focused on either new builds or renovations of a residential building, see Figure 1.

4.1 Case studies

4.1.1 Zero-Plus

The ZERO-PLUS project was commissioned by the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 678407 [9]. In brief, the overall aim of the ZERO-PLUS project is to achieve near-zero and positive energy settlement by using innovative and cost-effective energy production products in Europe. The project consists of four case study countries: the United Kingdom (UK), Italy, France, and Cyprus, which cover various climatic regions in Europe. In the Cyprus case, the Freescoo system is an innovative desiccant evaporative cooling air conditioning system developed by SolarInvent in Italy. According to the structural features of the case study building, an installation wall was developed to simulate the installation processes of the Freescoo system, which can be installed either externally or integrated into the building envelope. The installation wall is comprised of galvanized strut channels, fixture profiles, roof panels, insulation panels, HPL stratified laminated cladding panels, and a maintenance access door. The installation wall components were prefabricated in Italy and then shipped to Cyprus, and the installation took three days to complete. There were two main lessons learned from the Freescoo case study. First, the system was too heavy for manual handling so the optimum method would be integrating the system with the wall element and hoisting it into place using a crane. Second, the installation time was slow due to many smaller loose parts, which could impose challenges when installing the system at extreme heights or while standing on a suspended working platform. Nevertheless, the ZERO-PLUS demonstrates that energy technology can be integrated with a building façade and that prefabrication technology could potentially improve product quality as well as improve installation processes incrementally.

4.1.2 BERTIM

BERTIM was also funded by the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 636984 [10]. The objectives of the project were to enhance a building retrofitting process by deploying an integrated timber frame façade module system and to develop an efficient manufacturing method for the timber façade. The timber façade module uses prefabricated windows, heating, ventilation, and air conditioning (HVAC) systems, and insulation materials were integrated ingeniously. The design, manufacturing, installation, and life cycle management systems were supported by an advanced Building Information Modelling (BIM) application. One of the challenges when installing an additional layer of the façade element on an existing building was that the installation surface was not completely flat or level. To solve this issue, an innovative interface design was proposed, which consisted of three components: one part connected to the surface, another part fastened with the façade module, and a middle piece sandwiched between the two parts. An existing building, located in one of the Tecnalia's testing facilities in Derio, Basque Country, Spain, was used as the pilot project to validate the logistics, the installation process, and the thermal performance of the BERTIM project. The project demonstrates the benefits of using prefabrication technology in a renovation project. In addition, the innovative interface connectors developed during the project enabled accurate installation results and revealed the potential of implementing automated installation methods by using construction robotics.

4.1.3 Hephaestus

Hephaestus was also founded by the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 732513 [11]. The key objective of the project was to improve the glazing wall installation process by adopting an innovative Cable-driven parallel robot (CDPR). The CDPR consists of five components, which include the

CDPR structure, the CDPR body, the modular end-effector (MEE), the loading bay, and the control station. The CDPR can be installed on a roof structure or on a floor level that can support the weights and force of the system, respectively. The optimal installation location of the CDPR varies and depends on the individual building's load-bearing structure. The CDPR enjoys great manoeuvrability across the vertical plane of the building due to the eight winches and pulleys located on the top and ground levels. The MEE is divided into upper and lower sections. The upper MEE enables the system to detect rebar positions, drill, install fixtures, and fasten the fixtures in the correct position. The lower MEE is equipped with a vacuum system that is used for picking and placing the curtain wall element as well as the stabilization system. The pilot project was carried out from late December 2019 to early January 2020 at the Tecnalia facilities in Derio, Basque Country, Spain. During the pilot project, the overall performance of the CDPR was evaluated, but because the project isn't over yet, there are still some challenges that have to be solved (i.e., calibration time, size of the different components, etc.). Hephaestus has greatly inspired the proposed design that will be described in the later section. First, the project is a useful starting point case that can be augmented by adopting automation and robotic technologies. Second, the project provides a systematic approach and features applicable integration of software, sensors, and hardware in the context of the curtain wall installation. Third, the project demonstrates that CDPR is able to pick up and position large, heavy building components and is relatively highly accurate.

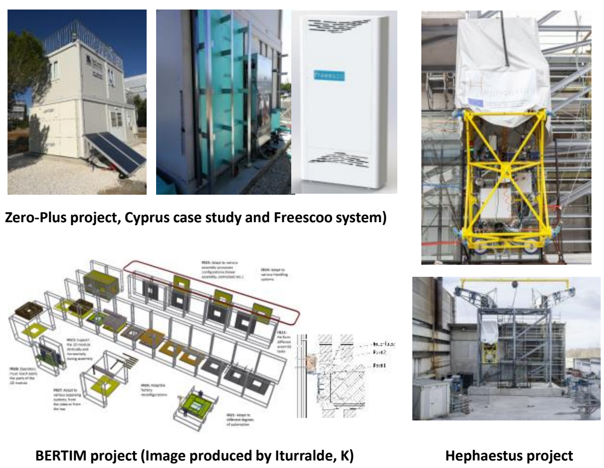

Figure 1. Top left: Zero-Plus, Bottom left: BERTIM, and Right: Hephaestus

5 System development

The demand for energy-efficient buildings are increasing in Europe and fulfilling the demand must be done either through new build projects or renovations of existing housing stocks. Conventional construction activities associated with new build project or renovation projects, however, are often inefficient, labour-intensive, and impose a high level of health risks to the workers. A novel construction system that focuses on the construction of a low-rise residential building by using prefabricated building components and assembled by automated on-site construction system is proposed in this section. Energy production technology is merged with the prefabricated façade module to ease the installation and maintenance processes by using construction robotic technology that was inspired by the aforementioned projects.

A prefabricated, fully assembled building system was used as a case study building for developing the proposed on-site assembly factory. The system is commercialized in China and it consists of the precast foundation system, structural frames, steel bracing system, precast external wall panel, precast internal wall panel, precast floor panel, precast canopy, precast roof panel, and precast stairwell. The prefabrication rate of the system is over 95% and, during on-site assembly, scaffolding is no longer required.

The proposed semi-automatic construction system features an on-site factory equipped with CDPRs that could travel on preassembled rails. The proposed on-site factory consists of ten key parts, see Figure 2.

1. On-site factory structural frame: the structural frames will arrive on-site as steel components and will be assembled by a spider crane.
2. Cable robot structure: the cable robot structure supports winches, pulleys, and cable routing systems and there are two branches of the structure that support two connecting planes.
3. Winches and pulleys: the winches and pulleys are installed on the cable robot structure and the lower supporting structure and in principle, the payloads should be more than 2.5 tons.
4. CDPR: there are two sets of CDPRs installed on either plane of the on-site factory that are equipped with a vacuum platform that is able to hold and position the precast external wall panels.
5. Lower supporting system: the lower supporting system supports the lower winches and pulleys and is equipped with a rotating set of rail wheels that is similar to the system used on trams or trains while the dimension of the wheels will be determined by the specification of the track gauge.
6. Temporary rail: the temporary rail track will be laid in a similar manner as traditional railway tracks but will depend on ground conditions, project budgets, and time as to whether the rail track will be laid on wooden sleepers or precast concrete track supports.
7. Gantry crane: the function of the overhead gantry

crane is to hoist and position precast floor and roof panels, but it is retractable, so it can reach out to the picking area.

8. Control room: the control room contains the main electrical cabinet, control units, power supply, and operator stations and is fully waterproof and highly mobile.
9. Temporary stabilization pillar: the stabilization pillar consists of two parts, the underground precast concrete footing, and over-ground pillar and he on-site factory structure will be connected to the over-ground pillar while it is in operation.
10. Temporary horizontal stabilizer: the horizontal stabilizer is used to provide additional strength of the on-site factory structure, but it can be disassembled and exchange to the working plane where the CDPR is not installed.

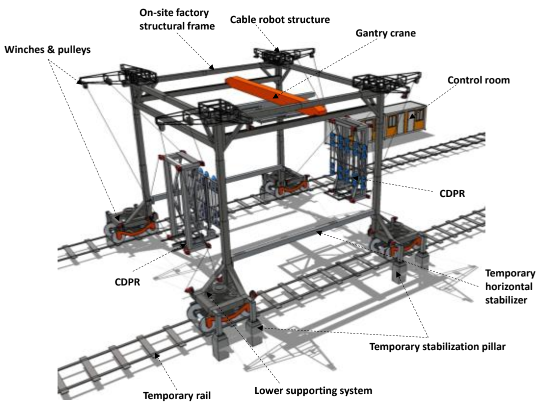

Figure 2. The proposed CDPR

The site will be prepared according to the construction plan. Once the location is confirmed, the precast concrete footings will be installed and the steel structure of the building will be assembled manually with assistance from the spider crane. Meanwhile, the precast external walls, floor panels, internal walls, and roof panels will be delivered and stored on-site. The on-site factory structure will arrive on-site partially assembled. The entire on-site factory structure, winches and pulleys, cable robot structure, and gantry crane will then be assembled and the temporary stabilization pillar is to be connected to the precast concrete footings. At this point, the on-site factory is stabilized and the CDPR can be installed and calibrated. Then the precast external wall panels are picked up from the picking position. The CDPR positions the wall panel at the correct installation position. The worker will carry out the final positioning and fastening task while the precast floor panels and internal wall panels are installed by using the overhead gantry crane. Figure 2 and Figure 3 demonstrate how the CDPR would operate at the front elevation of the building. Once the front wall panel is installed, the CDPR will be dismantled and reassembled on the side plane of the on-site factory. To cope with various weather conditions, the roof opening of the on-site factory can be covered with a waterproofing material. The direction of the temporary rail depends on the construction site configuration, but can be longitudinal or transversely. In addition, once the assembly task has been completed, the on-site factory shall be towed by the lorry to the next assembly location. The visualization of the building and the settlement are shown in Figure 3.

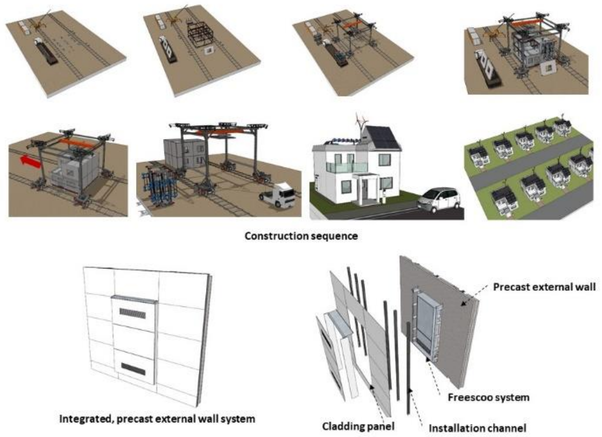

Figure 3. The construction sequence and the integrated precast external wall system

The proposed system features an integrated, precast external wall system, which is integrated with the energy production products. To demonstrates the design, the Freescoo system is utilized as an example. The integrated external system consists of four components, including the precast concrete wall panels, the Freescoo system, the installation channels, and the cladding panels. In the proposed scenario, the integrated wall system is installed by the CDPR and the installation channels along with the cladding panels are installed by the worker once the building structure is completed. The design provides proof that to ease repair and maintenance activities, a building should be designed as sequential parts and components. Energy production systems and mechanical systems can be integrated with the building envelope so as to be accessed, disassembled, and serviced separately.

At the time of this writing, the design presented in this scenario has been developed only as a conceptual idea to demonstrate the overall concept. The drawbacks and specific issues that need to be taken into consideration while continuing to develop the conceptual idea are:

- The construction site needs to be relatively level. If the slanted level of the site is too great, the site is not suitable to adopt the proposed design.
- The temporary rail requires additional groundworks, (i.e., increased construction time and costs) so

achieving economy of scale is key.

- The on-site factory might take significant time to assemble and calibrate, therefore the time spent on assembling the on-site factory needs to be taken into consideration when planning the project.
- New health and safety legislation is required when introducing human-robot collaboration for on-site assembly tasks.

6 Future work and recommendations

The outcomes from the Hephaestus project demonstrated the potential of implementing automation and robotic technologies for improving the overall performance of a specific construction task. The results from the BERTIM and Zero-Plus project indicate that the adoption of prefabricated façade elements and the integration of energy production technology can improve the installation process as well as renovation tasks over the building lifecycle. The proposed system in the paper encapsulated the outcomes of the three projects to embrace building prefabrication and construction automation in the context of energy-efficient settlement construction. To continue developing the PoC, there are still many obstacles and challenges. First, building prefabrication technology has not been wildly accepted by the conventional construction industry. Second, initial investments are high and the operation might be limited geographically. Third, the construction task involves many stakeholders and the construction industry is known to be one of the most fragmented industries, making the adoption of a new building method, material, or technology extremely challenging, highlighting the significance of cross-disciplinary collaboration. An energy-efficient building should be designed as an open building system rather than a single-use permanent structure to be disposed of once the building life runs out. The initial costs of construction automation may be high, nevertheless, the embedded costs over the building life cycle will decrease incrementally due to higher construction quality and easier repair and maintenance procedures [8]. To further develop the proposed concept requires financial assistance, policy incentives, and institutional support from the construction industry and government bodies. Furthermore, the proposed design shall serve as a foundation for a larger research project in the future, when the design, production, installation, management, operation, and human-robot collaboration can be validated through lab testing and pilot projects.

7 Conclusion

The paper proposed an innovative semi-automatic construction system in conjunction with an integrated, precast external wall system with an aim to improve construction efficiency and quality and to enhance building performance throughout the entire building life cycle. The proposed system was inspired by investigating several selected European Union (EU) Horizon 2020 research projects. Each project provided specific insight on how to implement prefabrication and construction automation technology in the context of energy-efficient settlement construction. The proposed construction system is based on the concept developed in the Hephaestus project. The system incorporates a CDPR equipped with a concrete vacuum end-effector, overhead gantry crane, and control room, supported by a structural frame. The system functions like an on-site construction factory, and moreover, it travels on temporary rails that follow a pre-planned construction master plan. Unfortunately, there are also challenges imposed by the industry to further developing the PoC. Some of the issues and barriers cannot yet be verified, such as the construction industry's reluctance to change, the lack of development in the energy-efficient building envelope and integration methods, the lack of skilled labour, and awareness of cross-disciplinary knowledge. Furthermore, using the proposed concept to inspire the construction industry and focusing on solving energy-efficient buildings with innovative, practical, and feasible approaches could bridge the gap between academia and the construction industry.

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