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A GUIDELINE TO SUPPORT THE USE OF OFF-SITE SOLUTIONS FOR FAÇADE RETROFITTING THROUGH BIM-ENABLED PROCESSES

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Abstract. The Architecture, Engineering and Construction sector requires an intense innovation process to reduce costs, intervention times, and improve energy performance. This is particularly true to increase the rate of deep renovations of the existing European building stock and therefore support the EU's 2050 decarbonisation targets.

In this scenario, prefabrication can be considered a game-changer for the construction industry: on the one hand, it enables the adoption of an industrial mindset to the design, manufacturing, and installation of façade components, with the related advantages in terms of time, cost and quality; on the other, it allows for the customisation of components thanks to digital, BIM-based design and fabrication tools. However, its adoption in retrofit operations is still limited due, among other factors, to a lack of practical experience and a limited number of actual demonstration cases.

This paper introduces an operative guideline to support a more widespread use of prefabricated thermal insulation components for the energy retrofit of existing buildings in the framework of a BIM-enabled design and construction process. The guideline highlights the information flow and the role of each actor at every stage of the design and delivery process.

The proposed guideline is finally tested through its application to a case study to show the feasibility of the process and the advantages deriving from the adoption of an industrialised approach to façade retrofit in terms of faster installation times.

Keywords: Energy retrofit, MMC, DfMA, off-site, BIM.

1. Introduction

As widely discussed in literature, the construction sector needs an intense innovation process to reduce costs, intervention times, and energy needs [1]. Achieving a significant energy renovation of the existing building stock would lead to an 80 % reduction in energy demand in 2050 compared to 2005 levels [2]. In this scenario, the European Union faces a double challenge: to at least double the annual energy renovation rate by 2030, and to foster deep energy renovations (i.e., renovations that reduce energy consumption by at least 60 %) [3].

Modern Methods of Construction (MMC) are widely regarded as a promising solution to these challenges and, more generally, to many shortcomings of the construction industry. MMC are a broad term that encompasses different dimensions of innovation, such as off-site construction and the related digital tools and techniques [4]. Off-site construction is an approach to construction projects that seeks to move the construction process away from the site and take advantage of manufacturing approaches and standardisation efficiencies. The advantages of the MMC adoption are mainly the increase of quality (+ 30 %) and safety of workers (+ 80 %) together with a reduction of costs (- 20 %), time (- 20 to - 50 %) and energy consumption (- 30 %) due to better management of resources in off-site activities instead of the on-site ones (- 70 %) [4–6]. The uncertainty of a dynamic working environment, the highly fragmented supply chain of SMEs, the need for skilled workers, the limited digitalisation, the short-term thinking, and a political/governmental/cultural opposition are the main barriers to the MMC adoption. In contrast, horizontal integration of networks, end-to-end digital integration, vertical integration, and networked manufacturing systems are the three keys to implement industry 4.0 in buildings [7].

The energy retrofit of existing buildings requires a tailored approach for each situation, because of the variety, among others, of construction periods, building technologies, materials, local climatic conditions, and site constraints. Additional differentiating issues are local regulations and budget concerns. In parallel to this complex task, construction companies have a limited propensity to innovation, resulting in a productivity gap. In fact, their production rate grows only 1 % per year, compared to the medium growth rate of 2.8 % of other sectors. According to literature [2], productivity can be boosted by 50–60 % by implementing regulation, contract, design, supply chain management, and improving on-site execution by technology innovations and reskilling workers.

These considerations show the market opportunities laying in the development of off-site prefabricated components for envelope retrofitting, reducing building energy demand and simplifying installation procedures while minimising the discomforts for the occupants.

From this point of view, many research projects [8–12] focused on developing new retrofit systems based on totally off-site or hybrid on-site/off-site technologies, while others, such as BIM4EEB [13], worked on the related BIM-based information structure.

A core aspect for the large-scale implementation of MMC is their integration in a BIM approach and the consequent adoption of rich digital communication that can increase interoperability levels, quality of information, and collaboration between stakeholders [14]. Off-site automated activities, facilitated by a BIM approach, have the potential to deliver the most significant growth in productivity in the construction sector [6]. For these reasons, various guidelines, design and assessment tools were developed specifically for new construction [15–17], but their application to existing buildings has been less explored so far. Some research projects aim to streamline the decision-making process and integrate BIM-based toolkits to facilitate the early-stage selection of retrofit technologies [18, 19].

This paper presents a general-purpose guideline on the BIM implementation for prefabricated thermal insulation components, developed in the framework of the European research project BIM4EEB. The guideline aims to go beyond the specific aspects of each construction technology, while focussing instead on the information exchange across the design, fabrication and delivery process of the off-site panels and between stakeholders (among others, Architect, Engineer, Façade Designer, Manufacturer, Supplier and General Contractor).

2. METHODOLOGY

To develop the guidelines, the first step was an analytical review of previous research projects and off-site products already available on the market. The design, production, installation process, and the information exchange were investigated through literature, reports, available technical information and interviews.

In the second step, the information gathered was used to produce a scheme of the steps and information exchange taking place across a general, technology-neutral, off-site process. The Information Flow defines the path of data through each stage, the actors involved and the necessary tools.

In the third step, an analytical guideline was developed, in a form that would be useful both to designers interested in using prefabricated façade panels and to companies developing such solutions. The guideline is presented in the form of a process matrix, highlighting the information flow at each stage of the process and providing information about the actions required from the relevant actors.

Finally, the guideline has been tested on a real-life case study building model to assess the feasibility of the information flow and the applicability of the different process stages.

3. GUIDELINES

The guidelines support designers in identifying the information required at each stage of the process, streamlining the information exchange and enabling more effective communication with the other stakeholders involved (e.g., Manufacturer and Client). On the other hand, a guideline is also useful for manufacturers who plan to enter, or already are in, the field of off-site panels for the retrofit market, which is often characterised by an ad-hoc approach to each application because of its relatively short history. In this case, manufacturers can organise their technical information in a way that is compliant with the guideline and can also activate early engagement strategies to support the adoption of their products in retrofit operations.

The information gathered from existing prefabrication technologies, EU-funded projects [8–10, 20] and interviews with European manufacturers made it possible to arrange the whole design-to-construction process of façade panels according to phases with general applicability, independent from the specific construction technology. The following diagram (Figure 1) presents each phase with its purpose (task) and its outcome, i.e., the information it produces for the following steps of the process. This articulation will constitute the basis of the proposed framework.

The framework (Table 1, Appendix A) shows the inputs, actions, and outputs in a clear, step-by-step process matrix, particularly suitable to highlight the correlations between the various steps and the related project phases. The steps column (second column) describes the general scope for each stage. Then, the main objectives (third column) are identified, together with the required input activities (fourth column) carried out by other design team members; these activities are preparatory and necessary for those more strictly related to the panelisation activities. Finally, under the output activities column (fifth column) and the data/model development column (sixth column), the required actions are summarised both from the process and the modelling point of view. The Process Matrix is discussed among European manufacturers and design teams to suggest a step ahead in the Knowledge-Based Engineering [21] adoption compared to the existing professional procedure and the scientific literature [22, 23]. Compared to other workflows, the proposed one started from the adoption of “panels place orders” during the Concept Design, allowing parametrical tools to generate various possible solutions based on the façade designer expertise, the manufacturer limitation in the production phase

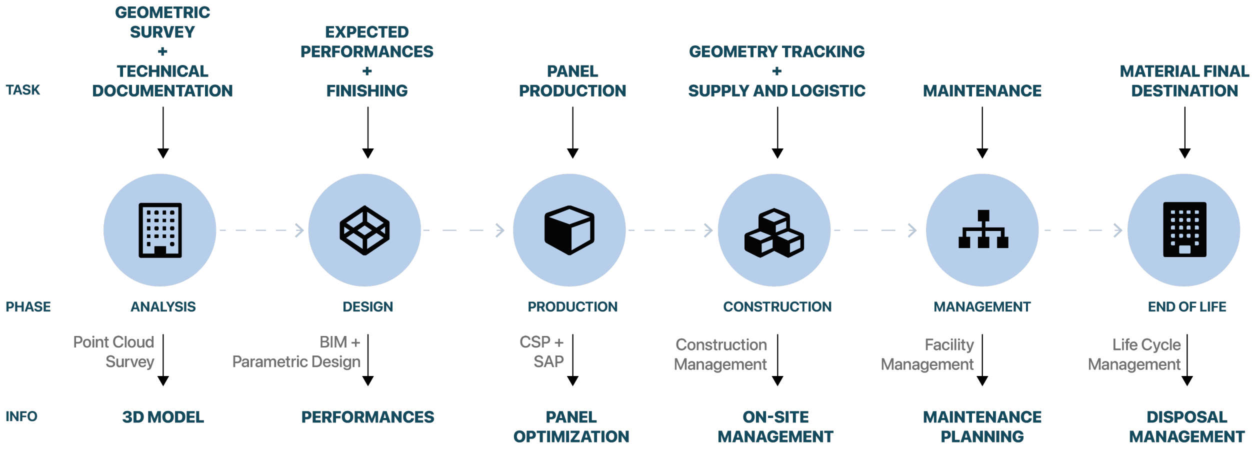

Figure 1. Information flow for panelisation process.

and the site-specific constraints. The proposed solutions are meta-technological products – underpinned on real ones – avoiding the risk of redesigning the entire façade after the manufacturer engagement and, simultaneously, allowing the progressive information enrichment throughout the process thanks to the BIM-based design process.

Stages 1 and 2 refer to the acquisition of information about the existing building, while the design phases (Stages 3–5) concern the project of the panels increasing the level of details thanks to the iterations that the parametrical instruments enabled (design optioneering). Finally, Construction, Building Use and End of Life (Stages 7–9) describe the transmission of the data-rich model between the designer and the manufacturer, avoiding the potential loss of information with consequences in the management and disposal phases.

At the same time, returning an informed model from the manufacturer to the designer and contractor makes it possible to integrate the assembly sequences smoothly into the site activities. This holistic perspective can significantly reduce construction time, allowing parallel activities on the actual construction site and in the factory.

3.1. Case Study

The framework for the design of prefabricated thermal insulation components was tested on a case study to verify that the steps of the process and the information flow can be used in practice. A simplified version of one of the demonstration sites of the BIM4EEB research project – a multi-storey multi-owner building located in Monza (Italy) – was used for this purpose.

The exercise focuses on the first stages of the framework (from 1 to 5), demonstrating its effectiveness and how to select the configuration that best meets the requirements set by the client. The output (design of the prefabricated panels fitting the specific case study) will contain the necessary information to interface downstream with production and site operations (Stages 6 to 9).

- Stages 1, 2: the data flow was defined and the as-is BIM model was produced based on a survey.
- Stage 3: the first phase of the optioneering process was performed about the geometrical aspects of the façade panels. Meta-technological objects were used as placeholders to reproduce different panelling hypotheses evaluated with the stakeholders. Each time one panelling option was analysed, an automated optimisation (considering specific dimensional constraints) was conducted using a bespoke script, following the goal of maximising the number of equal panels, minimising the total number of panels, and reducing or eliminating unique panels. The software then provided a datasheet identifying individual elements (Figure 2).
- Stage 4: starting from the first optioneering iteration results, several automated parametrical tools performed detailed analyses. Once the dimensional and technological information were included, it was possible to evaluate construction details, such as corner solutions. These are crucial topics to be assessed in the early stage because they influence the whole retrofitting operations behaviour in terms of heat loss, thermal bridges, and aesthetics. Each alternative was fully defined, and spreadsheets were exported for Client evaluation and selection of the technology.
- Stage 5: the chosen panels were exported back into the BIM environment, and a complete IFC model was shared with the manufacturer for validation (early-stage contractor and supply chain engagement). After an early-stage discussion with the manufacturer, the panel layers were designed in detail, defining the specific materials, thickness and other properties, anchors positioning, and dimensions. A detailed structural analysis was also performed in the BIM environment, automatically defining the positions of anchors in the BIM model through a dedicated script. Once the model included the panels and the anchors, it was possible to proceed with the detailed energy analysis, eval-

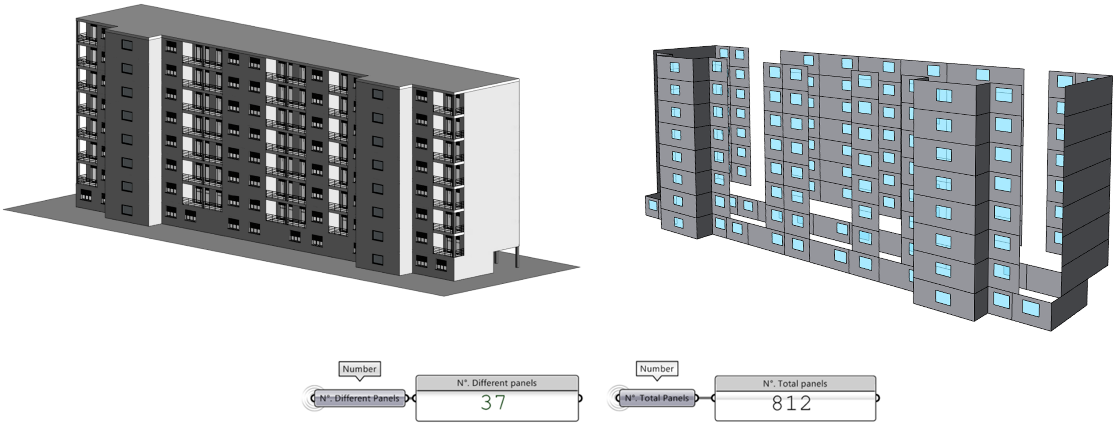

Figure 2. As-is BIM model and First panelisation phase with meta-technological panels. The total number of panels and the number of different panels considered is automatically displayed.

Figure 3. Perspective view of the BIM model with the selected panelisation.

uate thermal bridges, and check compliance with local regulations. At the end of Stage 5, a fully verified and integrated BIM model was ready to be shared with all the stakeholders, particularly downstream with the manufacturer.

In this whole process, and particularly in Stage 5, the manufacturer's ability to use and return an information-rich model is fundamental to ensure the smooth application of the guidelines.

The capability to receipt, manage, transform and transmit the information required for each actor during each stage was verified thanks to the check of the final IFC model and the other additional documents (bill of panels, manufacturing drawings, installation drawings and technical documentation), although it was not possible to test the guideline with the actual production and installation of the panels.

4. Conclusions

The paper aims to propose a guideline to support the design of prefabricated thermal insulation components for facades of existing buildings within a BIM-based approach. This guideline can encourage wider market uptake of off-site systems for retrofit operations, contributing to maximising efficiency in building renovation, reducing the renovation working time, enabling more accurate building quality control, and implementing a BIM-based renovation business for construction companies as part of the European transition towards a digital built environment.

The guideline presents, in a systematic way, the digital information flow necessary to support the design and delivery of prefabricated façade panels, with the specific data and involved actors correlated to the various stages of the process. Thanks to the abstraction of current practices and procedures, the guideline has broad applicability and is not technology-dependent and country-specific. Finally, it was tested on a case study to assess the practical feasibility of the process, including aspects such as the possibility to retrieve the necessary data and the information flow between different software and tools.

The guideline represents a relevant tool to support designers who intend to adopt prefabricated façade systems in their retrofit projects, clarifying what information is required at each step of the process, from/to whom it should be provided, and what decision-making tools can be used. Furthermore, the guideline also supports construction companies/manufacturers of façade systems, anticipating what information should be made available to the other actors of the process to ensure a smooth integration of the prefabricated panels in the BIM-based workflow early-stage engagement of the industry when possible. The integration of rules and constraints provided by all the actors – including manufacturers, architects, construction site managers and façade designers – at the beginning of the process, together with the BIM willingness to increment information across the stages, can be a step ahead in the adoption of Knowledge-Based Engineering in the design for manufacture of prefabricated façades.

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A. APPENDIX – TABLE 1

Stage		Step(s)	Objective(s)	Input	MMC-related panelisation activities	Data/model development
1	Initiative	• Define project scope and objectives (e.g.: Facade, MEP, New volumes).	• Establish retrofitting strategy; • Identify renovation areas; • Verify regulatory feasibility; • Agree on data extraction requirements.	• Develop BIM implementation strategies and incorporate them into BIM Execution Plan.	• Capture rules for as-is modelling and MMC adoption.	• No data yet. Time for data-flow definition.
2	Initiation	• Site survey and building(s) 3D modelling.	• Analyse the existing building and set a common base for future work.	• Accurate survey of the building (laser scanner or other methods); • Collect technological, historical and occupancy information; • 3D Model development and information collection; • Develop as-is model of the building, including basic information (structural grid, thermal transmittance, etc.).	• Early assessment of opportunities for MMC adoption.	• As-Is BIM model.
3	Concept Design	• Develop early-stage design coherently with the project scope and objectives.	• Explore feasibility of panelisation strategy; • Define geometrical alternatives.	• As-Is BIM model; • Knowledge-based constraints.	• Geometrical and design exploration; • Use meta-technological objects to generate design optioneering; • Develop parametric placeholders panels to understand possible issues.	• Include information such as massing (panels placeholders), meta-technological information and basic information (structural grid, thermal transmittance).

Stage		**Step(s)**	**Objective(s)**	**Input**	**MMC-related panelisation activities**	**Data/model development**
4	Preliminary Design	• Develop and test the prefabricated solution; • Early Supply Chain involvement.	• Early evaluation of technical alternatives.	• Client feedback from Stage 3 • Acquire performance targets, in particular U-value.	• Technological alternatives exploration for reaching project target; • Generate datasheets from objects for approval of functional, environmental and finishes requirements; • Identify Supply Chain and producers for technology evaluation.	• Develop multiple models with data sheets about technical alternatives.
5	Developed Design	• Design analysis and calculations.	• Confirm full conformity to scope and objectives of the project; • Early engagement of Contractors and Supply Chain.	• Client feedback from Stage 4; • Perform energy simulations of the existing building to understand possible issues for the retrofitting; • Perform structural simulations of the existing building to understand possible issues for the retrofitting; • Perform LCA simulations of the existing building to understand possible issues for the retrofitting.	• Add more details to BIM objects (both geometry and data); • Validate panelling technological solutions through early contractor and supply chain engagement; • Use analytical tools and calculations to compare technological alternatives; • Generate detailed part and whole models for different disciplines for early coordination; • Final choice of the panel technology; • Parametric time and cost validation.	• Include details of the chosen technical solution in the BIM model.
6	Detailed Design	• Production design for fabrication; • Digital prototype of the panels.	• Develop full model with information from the manufacturer.	• Integrate Supply Chain information about resources and time.	• Develop overall construction programme schedule and assembly sequencing; • Incorporate inputs from Supply Chain into the BIM model; • Develop fabrication and installation sequences, resource management plan, etc.; • Generate digital prototypes of the panels to verify the construction process; • Detailing of panels (connections, special parts, etc.).	• Construction model including highly accurate information from Supply Chain.

Stage		Step(s)	Objective(s)	Input	MMC-related panelisation activities	Data/model development
7	7.1 Pre-Construction	• Accurate fabrication model.	• Enable fabrication of components.	• Accurate BIM model from Stage 6.	• Generate shop drawings for fabrication from models or integrate fabrication information from the manufacturer into the BIM models.	• As-built model Incorporating information from previous stages and construction activities.
	7.2 On-site Construction	• Training; • Virtual building.	• Enable construction in line with scope and objectives of the project; • Inform users about construction activities (time and location).	• Construction model updated with Pre-Construction information.	• Track construction activities and resources based on planned programme and planned assembly sequence; • Validate installation on-site and update as-built model. • interface and communicate with users about construction activities.	
8	Building Use	• Life Cycle costs; • Facility Management attributes; • Maintenance program.	• Represent the as-built asset; • Produce ordinary maintenance plan.	• Maintenance information from Supply Chain; • As-built model from Stage 7.	• Integrate as-built model with the Facility Management system; • Integrate information about maintenance in the as-built BIM model.	• As-built models are up-to-date and accessible to the property management and tenants; • Represent the building in use, including dynamic feedback information from BMS and FM (Digital Twin).
9	End of Life	• Program End of Life.	• Produce End of Life actions plan.	• Digital Twin model from Stage 8.	• Develop End of Life support documentation.	• The model is up-to-date and will continue evolving.

Table 1. Process Matrix for energy retrofit with off-site façade panels.