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A BIM-enabled Decision Support System to support large-scale energy retrofitting processes and off-site solutions for envelope insulation

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Abstract. The urgency of renewing the Architecture, Engineering and Construction related processes to increase quality standards and performances while reducing costs and operations time is widely discussed in literature. In this scenario, increasing the energy renovation rate of the existing European building stock is a key priority to support the EU's 2050 decarbonisation targets through innovative solutions. The introduction of prefabricated panels for building renovation – incorporating insulation, mechanical systems, and finishing – can provide the existing buildings with improved structural, thermal, acoustic, and architectural features. The higher quality and safety for the off-site activities, the faster on-site application and the reduction of waste are some advantages of this typology of Modern Methods of Construction (MMC). Several digital and informative tools have been introduced over the last years to customize and integrate the design of prefabricated panels on existing building envelopes (i.e. panelisation tools). However, the comparison of technological alternatives is left to the intuition of designers and managed through the use of several tools that are not interconnected and often downstream the design process. This paper presents a Panelisation Design Tool, which is a Decision Support System (DSS) to help decision-makers in the choice of technological solutions for retrofitting operations during the Early Design Stage. Thanks to BIM integration, some indicators related to different aspects (n Dimensions) are extracted from the model of the panelised building to compare different technologies in a systematic way. The Panelisation Design Tool is tested on a case study building located in the city of Monza, in Northern Italy, used as a pilot in the BIM4EEB European Project. The test aimed at demonstrating the effectiveness of the chosen parameters to evaluate multiple technological solutions in an integrated BIM approach.

1. Introduction

As widely discussed in the literature, there is a strong need for an intense innovation process in the construction sector focused on reducing costs, intervention times, and energy needs. 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 [1]. 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%) [2]. Modern Methods of Construction (MMC) are 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 related digital tools and techniques [3]. 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. Besides ensuring benefits on projects such as better predictability of cost and time, better quality construction, improved health and safety and a faster construction programme [4], MMC are a solid answer to the low productivity of the building sector – currently 1%, compared to 2.8% of the others [1]. The MMC adoption can fill this productivity gap, leading to building industrialisation centred on off-site production.

The adoption of prefabricated panels to average residential buildings, especially for retrofitting operations, will be defined as ‘panelisation’ [5,6]. The adoption of a Design for Manufacturing and Assembly (DfMA) approach to building retrofit optimises the transition from production to assembly, reducing delivery costs and risks [7] thanks to the reduction of installation time by 20% or more [8] and the minimum possible level of intrusiveness (absence of scaffolding).

The design flexibility of fastening systems, external surface finishes and services integration, enabled by digital design and fabrication, allows to address a wide range of requirements demanded to the prefabricated recladding components. Still, the elevated technological complexity and the lower adaptability of panels during the on-site installation requires much more competencies by designers and a higher level of information to reach during the design phase. On the other side, an efficient design & delivery process requires a smoother flow of information, which is still one of the biggest challenges for such a fragmented sector. The broader application of BIM-based tools can support the cost-effective integration of prefabricated solutions among envelope retrofitting choices, optimising several aspects throughout the process. An efficient approach can be articulated according to the n-Dimensions of BIM (3D: Design collaboration - *geometry*, 4D: Construction planning - *time*, 5D: Quantification and costing - *cost*, 6D: Environmental Design - *Sustainability*, 7D: Facility management - *management*), with a platform-data exchange inside and between organisations [9]. The BIM nD platform supporting the selection processes of innovative technologies, where designers lack experience, can be adopted as a Decision Support System (DSS).

Within this context, while the predominant development of DSS tools in the construction sector is increasingly in the direction of BIM [10–14], the fragmentation resulting from the variety and specificity of applications is evident. For this reason, a methodology framework was developed within the BIM4EEB EU research project [15] to streamline the decision-making process, integrate the assessment processes and optimise the iterations necessary for operational decisions related to the use of off-site façade panels for the retrofit of existing buildings.

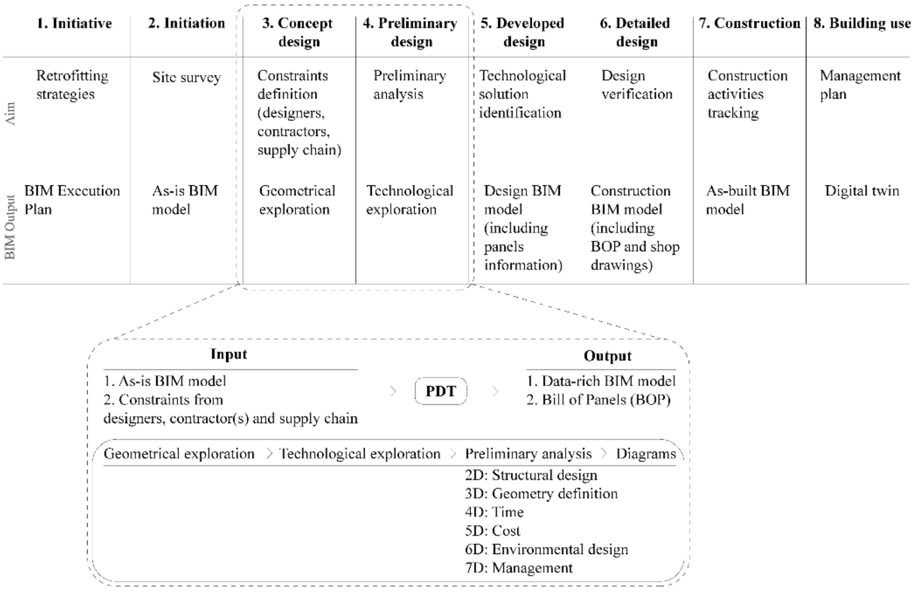
2. Research Methodology

This paper focuses on the application of a DSS for the panelisation process, showing how the proposed Panelisation Design Tool (PDT) can support decision-makers (among others, Architect, Engineer, Façade Designer, Manufacturer, Supplier and General Contractor) in the choice of the best-fitting technology by comparing key metrics and parameters. The purpose is to optimise the design choices in a BIM-enabled process applying the PDT to one of the case studies of the BIM4EEB project.

The proposed framework (Cucuzza et al., Currently under evaluation) consists of a process map graphically showing the inputs, actions, and outputs, providing a data information flow (Inflow) that can be clearly understood by all users involved in the process. Starting from this framework, the PDT focuses on the Early Design Stages, exploiting the geometrical results according to the initial inputs (as-is BIM model and stakeholders constraints) (**Figure 1**), analysing all the technological options and creating graphs to compare them easily. The data-rich BIM model with the Bill of Panels (BOP) is the output of PDT to be spread to all the involved actors.

The practical test follows the reported process, aiming to exploit the potential of interoperability between different softwares for the management of metadata (BIM-based), for parametric analysis (parametric design) and the production and management of spreadsheets, by creating a bridge between them. This lean process would promote large-scale energy retrofitting through a BIM-enabled approach, ensuring complete transparency of the progress during the project and eliminating clash problems that frequently occur due to lack of communication between parties.

According to the framework, in Concept Design Stage, there is a first geometric exploration step, followed in the Preliminary Design Stage by a technological exploration to choose a panel and integrate it in the Design BIM model for the final checks (Stage 6 – Detailed design). This PDT exploration is based on the results obtained during the preliminary analysis, on the project's targets and regulations requirements. Once the panels are geometrically and technologically defined, they are included in the Construction BIM model for the next stages (Stage 7 – Construction). The PDT technological comparison method is based on the use of a radar diagram according to the n-dimensions of BIM, letting the different stakeholders select the best-fitting solution. In this way, an additional evaluation tool is acquired that can be grafted flawlessly into the framework.



	1. Initiative	2. Initiation	3. Concept design	4. Preliminary design	5. Developed design	6. Detailed design	7. Construction	8. Building use
Aim	Retrofitting strategies	Site survey	Constraints definition (designers, contractors, supply chain)	Preliminary analysis	Technological solution identification	Design verification	Construction activities tracking	Management plan
BIM Output	BIM Execution Plan	As-is BIM model	Geometrical exploration	Technological exploration	Design BIM model (including panels information)	Construction BIM model (including BOP and shop drawings)	As-built BIM model	Digital twin

Figure 1. Flowchart and Panelisation Design Tool process

The design of the prefabricated panels fitting the specific case study generated by the PDT will contain the necessary information to interface with production and site operations. The outputs are the Design BIM model, the panel catalogue (BOP) and the comparative radars between different technologies (n-Diagram).

The PDT is tested on a real case study building, where a traditional insulation system (ETICS) is compared with two prefabricated solutions: lightweight concrete panels and Timber Frame panels (**Figure 2**). These two off-site technologies were chosen for their flexibility and ease of application and technical data availability, thanks to literature and the research team's experience. Moreover, the two solutions allow to analyse some design differences: concrete panels are smaller and do not include any windows or systems, while, on the other hand, the timber frame panels can reach bigger dimensions and include windows and systems in each module.

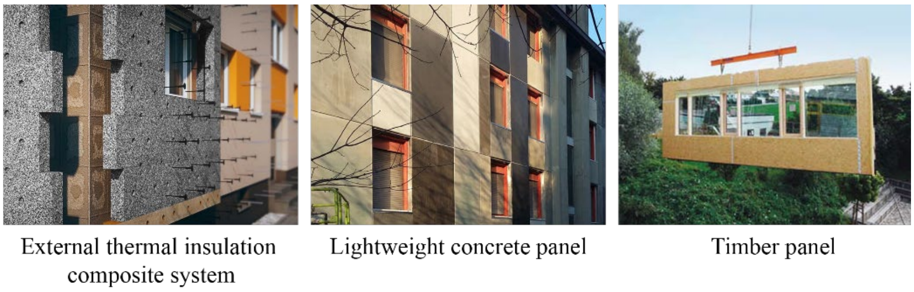

External thermal insulation composite system
Lightweight concrete panel
Timber panel

Figure 2. The concrete panels are characterised by smaller sizes, vertical elements, while the timber is a larger, fully integrated solution with windows and services.

The aim of the PDT is to provide analytical information about geometry, energy efficiency, technology, structure, buildability and sustainability, reported in a radar diagram. These aspects are summarised in a selection of parameters that are significant, easy to understand and sufficiently variable to support the decision-making process. Starting from a previous research [5] carried out by the authors, the selected parameters were broadened, adding time, cost and operational-related parameters. Results are then converted into a BIM n-Diagram, grouped by typology and averaged by parametrising the analytical values obtained. The clusters of parameters and the proposed indicators to compare different technological solutions are the following:

- Structural Design (2D):
    - No. Anchors/Total Area [anchors n°/ m2].
- Design collaboration (3D):
    - No. Different panels/Total panels [-];
    - No. Total panels/Total Area [panel n°/ m2].
- Construction planning (time) (4D):
    - Installation time [h/ m2].
- Quantification and costing (cost) (5D):
    - Total cost [€/ m2].
- Sustainability (6D):
    - Thermal transmittance U [W/m2K];
    - Global Average Heat Exchange Coefficient H't [W/m2K].
- Facility management (7D):
    - Life cycle [Primary Energy renewable/Primary energy total].

3. Case study

The case study for testing the PDT is an 8-storey social-housing building with 65 flats, in the City of Monza, which had undergone a major renovation in 2019 by the public owner (ALER - Azienda Lombarda per l'Edilizia Residenziale). The first input file is the as-is BIM model (Errore. L'origine riferimento non è stata trovata.), acquired from the BIM4EEB BIM Management System as an open data format (IFC).

Figure 3. Real building and BIM model of the Case Study

The second input file is a spreadsheet with panel size constraints for each technology by all the stakeholders (architect, engineer, manufacture, logistic and transport, etc.). The process starts from the existing geometry scanning and the definition of the detail solutions for loggias, balconies and corners solution (priority to one panel, or a 45° cut). The panel height is linked to the storey elevation: as a matter of facts, panels need be fixed to slabs due to structural reasons. For this purpose, the gross surface area of the envelope of 5800.0 m^2 is scanned to place the anchors in correspondence to the reinforced concrete structure.

According to these input data, the tool calculates different possible geometrical layouts and generate the relative panels' catalogue, categorising them for orientation, floor, typology, and number (BIM 3D – Design collaboration). This output is relevant for the installation phase, together with the localisation and the number of anchors on the existing façade, to calculate the installation time and cost (BIM 4D – Construction planning, and 5D – Quantification and costing).

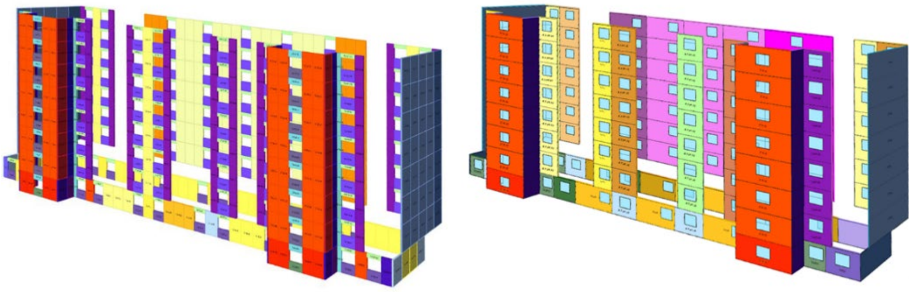


Figure 4. Geometrical layout of concrete (on the left) and timber (on the right) technologies. Colours define different element typologies according to the panel's catalogue.

Besides the number of anchors per panel, the structural analysis of timber frame panels is checked according to mullions deformation and the number of screws necessary to fix the external and internal skin of the panel to its substructure (**Figure 5**). This analysis suggests that the interoperability workflow can fill a typical gap in the information flow [5], saving time for the Detailed Design Stage. Thanks to the software interoperability, it is possible to directly exchange model between the parametrical design tool and the structural FEM (Finite Element Method) analysis software, able to process details of single panel connections (screws/anchors number and typologies) and seismic performance of the whole exoskeleton behaviour (BIM 2D – Structural Design).

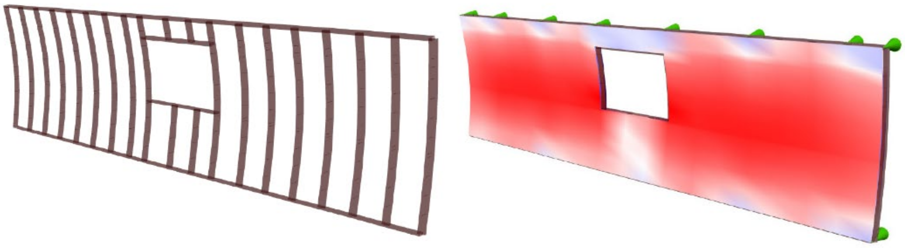


Figure 5. Deformation study of timber frame panel according to its mullions, transoms and anchoring points

The following level of the analysis concerns the building physics from the statical assessment of the single panel thermal resistance (U, Thermal transmittance value) and the investigation of the whole building envelope performance by the Global Average Heat Exchange Coefficient H't (W/m^{2}K). This second parameter also embeds the heating losses due to the linear thermal bridges (highlighted with different colours in **Figure 6**), carrying out the effective flux swap between the building and the external environment (BIM 6D - Sustainability).

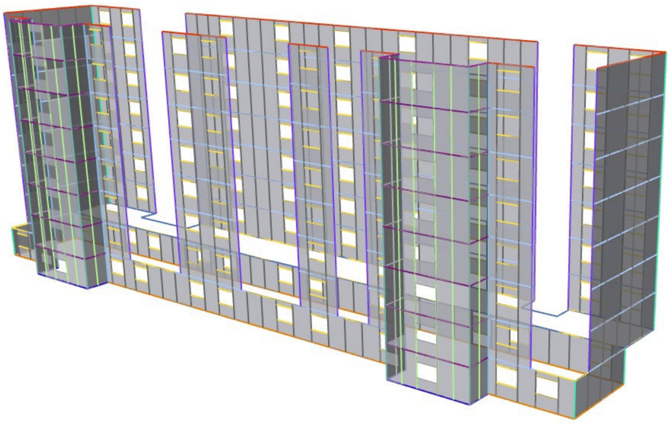


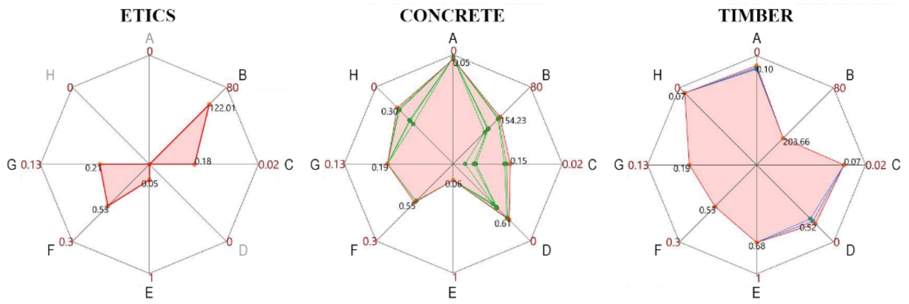
Figure 6. linear thermal bridges highlighted with different colours for the Global Average Heat Exchange Coefficient H't [W/m2K]

The last dimension for the comparison is the seventh (BIM 7D – Facility Management). The management performance is synthesised into the LCA analysis (ISO 14040) by comparing every technological solution's renewable and non-renewable primary energy. Resources depletions are collected into Impact Categories and then to une single impact result (Global warming potential, Primary energy or UBP) concerning phases from raw material to manufacturing, distribution and recycling through the embodied and operational energy consumption (SIA 380/1) during the Building Use Stage (EN 15978:2012).

4. Findings and discussions

Beyond the scores given to every parameter for each technology (**Figure 7**), the tool's purpose is to give decision-makers an instrument to analyse different solutions from a holistic perspective. The analytical value of every parameter described in the Errore. L'origine riferimento non è stata trovata. **paragraph** is limited to standards and regulations or best practices domain. The radar is built to have one single axis for a single parameter: the best score is next to the octagon perimeter, while the closer is the point to the axis origin, the worst is the performance in that field.

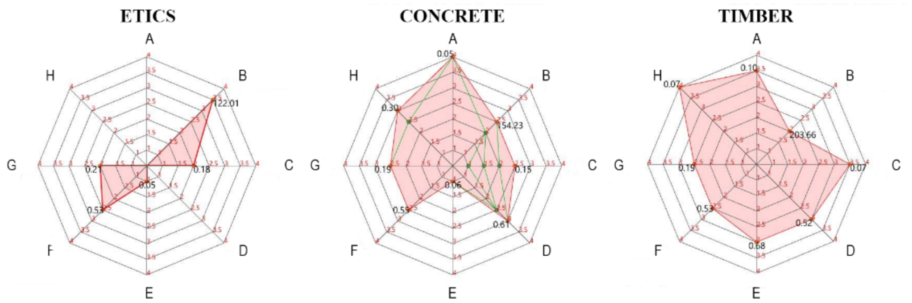
Analysing analytical values for each variable (Errore. L'origine riferimento non è stata trovata.), the ETICS solution shows no results for the panel numbers and typologies (parameters A, D, H) because of its continuous surface on the external wall. In contrast, the number of panels (parameter H) is considerably lower (0,07 panels/m^2) for timber solution compared to concrete (0,30 panels/m^2) because of the larger size they have. On the other side, due to the bigger dimension of timber panels, the number of different elements over the total number of panels is higher than the smaller and repetitive concrete elements (parameter A), also resulting in a faster on-site application (C). The material cost affects the total cost of panels resulting in a 25% saving for concrete to timber; still, the lower cost/m^2 is obtained by the ETICS solution because of its lower technological complexity. If the Thermal Transmittance has a better score for off-site panels than traditional insulation, the inclusion of H't represents clearly the higher performance of ETICS in joints and corners, the weakest point for prefabricated solutions. Finally, the LCA analysis (parameter E) result is sixth time lower for concrete and ETICS because of the embodied carbon contained into the timber panels.



A.No.Different panels/Total panels [-]; **B.**Total cost [€/ m2]; **C.**Installation time [h/ m2];
D. No.Anchors/Total Area [anchors n°/ m2]; **E.** LCA [Primary Energy renewable/Primary energy total];
F. Global Average Heat Exchange Coefficient H't [W/m2K];
G.Thermal transmittance U [W/m2K]; **H.** No.Total panels/Total Area [panel n°/ m2].

Figure 7. Analytical Spidergram for ETICS, Concrete and Timber panels

Although the selected parameters are able to highlight the main differences between the three solutions, to easier compare closer numbers, the Analytical Spidergram (Errore. L'origine riferimento non è stata trovata.**igure 7**) is transformed into a Marked Diagram (**Figure 8**) by assigning a mark to every parameter from zero (in the figure centre) to four. The solutions for every single technology (multiple green and blue lines for concrete and timber panels) are immediately comparable even though they have closer analytical values. This way, users can choose the preferred technological solution by selecting the best performing solution.



A.No.Different panels/Total panels [-]; **B.**Total cost [€/ m2];
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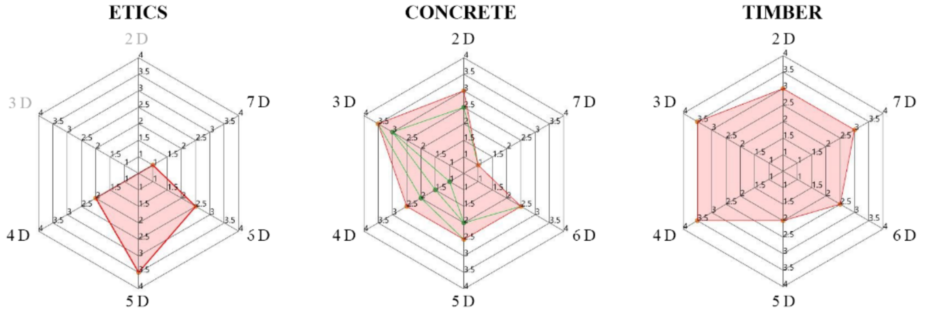
E. LCA [Primary Energy renewable/Primary energy total];
F. Global Average Heat Exchange Coefficient H't [W/m2K];
G.Thermal transmittance U [W/m2K]; **H.** No.Total panels/Total Area [panel n°/ m2].

Figure 8. Marked Diagram with scores for each parameter for ETICS, Concrete and Timber panels

As mentioned before, considering the elevated number of variables analysed and the need to facilitate the choice for non-technician decision-makers, parameters are collected into the related BIM n-dimensions from 2 to 7 (**Figure 9**). That enable a more clear perception of the characteristics of the different materials and a faster evaluation by overlapping the three technologies into the Final Comparison (**Figure 10**), where colours help to highlight ETICS (yellow line), Concrete (green) and Timber (Blue) panels.



2D.Structural Design; **3D**.Geometry Definition; **4D**.Time; **5D**.Cost; **6D**.Environmental Design; **7D**.Management;

Figure 9. BIM nDiagram collecting parameters into the seven BIM dimensions

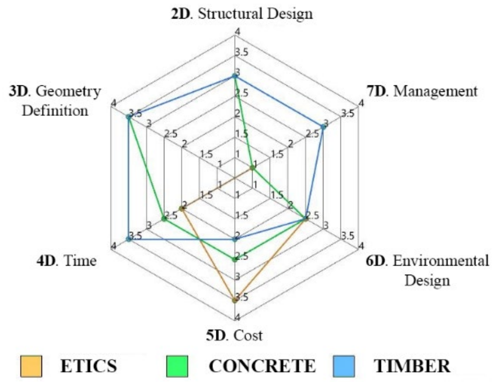


Figure 10. BIM nDiagram final comparison of the three technological solutions

Results can also be represented in an online viewer platform [16]: the designer can upload data of all the options on the server, fully integrated with images and scores, allowing everyone to compare results by selecting a range of acceptable values for every single parameter. This linear process excludes all the results outside the suitable domain decided at every step by the user.

5. Conclusions and further research

The highly specialised construction process steered designers to add complexity levels to projects leading to a tough understanding of several possible solutions by different actors. Furthermore, the integration of MMC in the existing building retrofit processes requires designers to push toward:

- A coherent BIM workflow including various disciplines and actors
- the early engagement of suppliers in the first design process phases
- a more straightforward representation of multiple different scenarios for non-technician
- the application of more efficient technologies for new or recladding existing building envelopes.

In this perspective, the Panelization Design Tool (PDT) performs a fast and multilevel analysis to apply off-site panels. The case study shows that the chosen parameters are useful to diversify results for different technologies, having a multidisciplinary approach to construction according to the nDimensions of BIM. According to the constraints, PDT solved the panelization process, reported as analytical results, and collected as synthetical representation using radars. The instruments' validity consists of the impartiality assigned to each variable (parameters analytical values have all the same weight), the more manageable representation obtained exploiting the BIM nDimensions, and the data-rich BIM model ready to acquire deeper information in the next steps of the design process.

Moreover, the open platform structure assigned to the PDT allows to include and add much more parameters to the analysis, including, for example, the safety aspects (BIM 8D) and the energy performance. From a technological point of view, the inclusion of renewable energy sources and services into the panels is another research field to explore for improving sustainability both from the energy and cost point of view.

The optimisation process leads with the possibility to obtain the best score in one single parameter (like the cost for ETICS, time or management for Timber panels in **Figure 10**). At the same time, the multiparameter approach offers a broader point of view, giving the possibility to decision-makers to pick the best-fitting solution for the specific project, not limiting the choice to a pre-determined solution given by the overall higher value. For example, in the case study in Monza, PDT shows timber frame panels as the best-fitting technology for the given constraints, due to the larger area covered by the BIM n-Diagram.

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