

Optimisation of building energy rehabilitation processes based on BIM-BEM interoperability: Case study of prefabricated panels with 3D printing

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Abstract

Currently, the rehabilitation and renovation of buildings represent significant challenges in the construction sector in Portugal. These challenges are driven by the urgent need to rehabilitate the building stock, prepare it to meet carbon neutrality targets by 2050, and reduce waste and residues in the sector. Therefore, building renovation must be approached comprehensively to improve energy performance and optimise construction and energy costs. To achieve these goals, it is crucial to define a precise approach to renovation projects, including simulations that anticipate the behaviour of buildings and adopt comprehensive design solutions to tailor specific environmental conditions. In this context, there are well-established platforms and tools developed by major professional software vendors. Nevertheless, a gap was discovered in developing optimisation solutions, which enable integrated energy performance assessment of building models and allow the optimisation of facade systems for renovation within a bidirectional framework in a platform. Consequently,

the tool presented in the current work generates facade panels based on energy performance simulation and optimisation results. As a result, a set of generated panel configurations, including dimensions and material alterations, comprise the system that varies along the facades, optimising the building's total energy consumption and production cost. The workflow is detailed, including inferred analyses and suggestions for future improvements.

1. Introduction

The AEC (Architecture, Engineering and Construction) sector in Portugal faces the important transition to a market of industrialised and holistic renovation to meet the goal of the European Carbon Neutrality 2050 program of reducing carbon emissions until 2050 to limit global warming to 1.5°C. In Europe, buildings are responsible for approximately 40% of the final energy consumption, 36% of greenhouse gas emissions, and 60% of the electricity consumption [1]. Therefore, the decarbonisation of the AEC sector is vital for accomplishing the program. In addition, the residential building stock in Portugal is represented mostly by old buildings, as shown in the investigation of A. Horta: 85% of constructed buildings in Portugal were built before 1990, before the issue of building energy performance regulations [2]. According to the energy performance certificate rating, approximately 87% of the residential buildings have a C rate or even less, resulting in poor energy performance [3]. Consequently, building renovation should be done holistically to improve energy performance and optimise construction costs. These goals require accurate design for precise interventions into existing structures as well as performing simulations to predict building behaviour and optimise it. Therefore, BIM (Building Information Modelling) and BEM (Building Energy Modelling) are essential in this process. Meanwhile, additive manufacturing techniques are being used to reduce waste materials and provide a cost-optimal renovation option for the existing building stock through using recycled plastic and natural materials, sensor integration for data provision, and parametrisation via BIM software [4]. This approach optimises the building's source usage and energy efficiency compared to traditional solutions.

Accordingly, plenty of professional software platforms exist in the AEC market. Moreover, most modern software provides API (Application Programming Interface) for developers to interact with their platforms, customising and extending their toolsets. In turn, enthusiasts and researchers worldwide aim to elaborate custom tools for BIM to BEM workflows. With the use of API, they access application methods and model properties to overcome the functional limitations of the platform and meet specific project deliverables. In this way, developers create parametric models to analyse geometrical systems for energy performance and then reconstruct the output to the BIM model or import the BIM model to BEM through custom serialising and parameter mapping and then simulate externally [5]. However, such an approach has some drawbacks, such as the lack of detailed information about the material structure and spatial and geometric metadata during optimisation, which leads to gross inaccuracy in performance estimation. This is inappropriate when rehabilitating and renovating residential stock, especially in dense urban environments. Consequently, the gap was identified in developing tools that allow fully integrated bidirectional workflow in the BIM-BEM framework to find optimal energy performance and regenerate facade configurations inside the BIM platform with all linked metadata on the fly.

Therefore, this work, conducted within a common framework of the ZeroSkin+ research project, is dedicated to developing such a tool to generate facade panels based on optimising building energy performance and additive manufacturing

requirements within the project. 3D printed panel design was elaborated in a related research case study for a traditional Portuguese residential building [6]. Consequently, the tool developed in this work is also attached to the mentioned case study. The panel is designed to imply that it will be adapted with defined variables for every part of the building depending on the overall energy performance impact. These panel configurations are based on input BIM model data and are parametrically linked with BEM simulation results.

Multicriteria optimisation is essential to this development when an adaptive facade system seeks to improve building energy performance. To achieve an optimal solution, it is necessary to adapt precise panel configurations for each part of the building. The panel configuration is presented by parameters such as dimensions, thickness, and panel materials. These criteria vary along facades to attain the lowest overall energy consumption. Meanwhile, construction cost is supposed to be minimised and the number of panel types consequently. These aspects, in general, indicate the complex computational task. The developed tool must interactively exchange data with the BIM model to accomplish this task, acquiring the necessary building information for energy performance simulation and generating model components. The primary objective of this investigation is to demonstrate and validate a methodology for bidirectional BIM-BEM model integration. However, it is important to note that the research does not assert the reliability of energy performance results and thermal measures within the scope of the presented work. Instead, the focus lies on the interoperability process, connecting the BIM modelling platform with the energy simulation engine to create adaptive facade panels optimised for enhancing the building's energy performance.

2. Methodology

A methodology implemented in the current work is based on the main goal to generate a facade panel system within the interactive workflow, transforming the existing BIM model of the building for comprehensive energy analysis and finding optimal facade solutions. Meanwhile, the workflow keeps users inside the BIM platform disembarassing from tedious data exchange.

According to the defined optimisation task, the workflow has a recursive structure. It consists of inputs, procedural definition, and outputs within a script loop in the flow-chart presented in Figure 1, marked by red, blue, and green filling accordingly. The loop that the tool passes during optimisation contains an input panel configuration and output energy performance value that enables the evaluation of specific system configurations and adaptation throughout loop iterations.

A procedural definition of the tool is written in Grasshopper VPL (Visual Programming Language) and Rhinoceros environment connected to the BIM authoring platform Autodesk Revit through the "Rhino.Inside" plugin, while some dedicated modules use Python language for communication involving GUI (Graphical User Interface) and API. The configuration input includes the dimensions and material structure of the

facade panel system, and it is controlled by a “genome” set of values that automatically alter through the optimisation solver. Another input is determined by the user through UI (User Interface) and requires a panel component file, panel dimension constraints, and a weather data file. UI is designed with the Remote Control Panel tool connecting the script definition with the host modelling application for input values control. Meanwhile, one more input source is analysed directly from the BIM platform, which provides all the necessary data about the initial BIM model for energy performance simulation through API. This data includes construction elements, spaces, used materials and their thermal characteristics, as well as the location of the building. All inputs are presented in red in the flowchart in Figure 1.

Further, the inputs are transformed into procedural definition, and computations are performed to convert the BIM model into an energy model. Then, the energy model proceeds to simulation with the EnergyPlus engine, called from the script definition. The simulation uses the “Ladybug Tools core SDK”, an open-source library from the default package installer. The “core SDK” can be executed in IronPython, enabling the integration of the tool to interact with the Revit API effectively. The optimisation part is developed with the Galapagos solver at the end of the loop. The simulation output value is concatenated with the total count of panel types to be evaluated by the optimisation solver and to close the loop by altering another configuration setup. The transformations executed in the procedural definition are presented in blue in the flowchart in Figure 1.

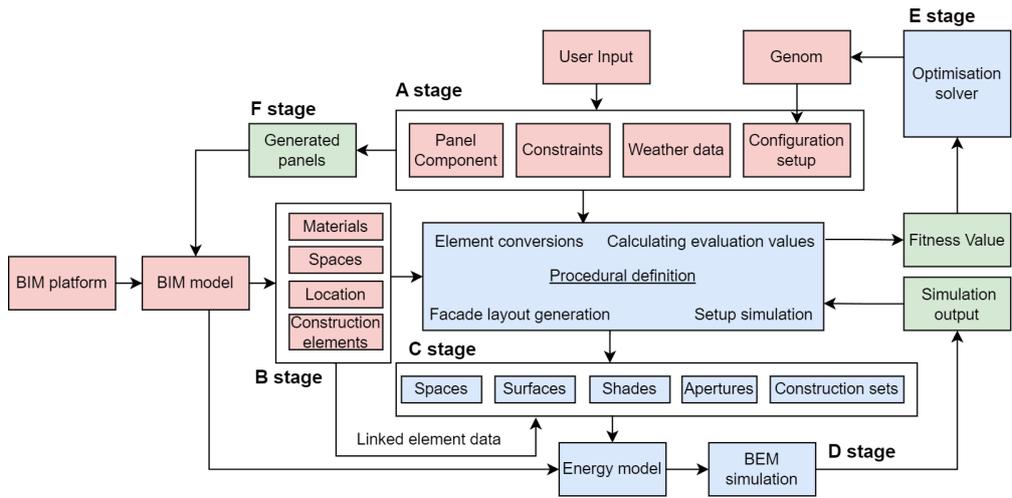
Finally, facade panels are generated based on the selected configuration as an output of the loop, and the BIM model is updated. It is worth noting that panel generation is not performed automatically for every loop iteration. It would slow down the overall optimisation process. Instead, an analytical surface representation is used by default in preview mode to evaluate the panel layout while the panel generation button is created separately. In this way, users can assess the facade panel system and compare design options effectively before the actual generation of the model. Outputs of the definition are presented in green colour in Figure 1.

As a result, the proposed workflow utilises the developed tool represented as an add-on with a user interface running directly from the BIM platform. Meanwhile, the add-on requires an initial model with default entities to be modelled (walls, floors, rooms, etc.). In the interface, the user can set up an existing BIM model for facade layout and generate panels by controlling geometric and material constraints, taking back energy performance simulation assessment results.

While generally comprising the recursive structure and having three distinctive parts in the workflow loop (inputs, procedural definition, and outputs), the algorithm is divided into six stages: A – loading panel component defining configuration variables and constraints; B – extracting BIM model data; C – generation of facade grid layout; D – conducting energy performance simulation; E – optimising panel configuration; F – generating facade panels. The next chapter explains the common scripting logic behind each algorithm stage.

Figure 1

Flowchart reflecting all stages included in the loop. Red - inputs, green - outputs, blue - internal procedural modules.



3. Development and Implementation of the tool

According to the methodology, the script is aligned with the step-by-step execution of each of the six stages of the algorithm described earlier. In the first stage, the user loads a panel component and defines constraints for the configuration search: dimensions constraints, material types, and thickness types. Dimension constraints can either be predefined in the panel component model or through minimum and maximum values defined by the user in the interface (Figure 2, left, dimensions range in Figure 3, right). A set of parameters represents a material type in Figure 3, left. These input material parameters include name, thickness, thermal conductivity, density, and specific heat. In this case study, predefined materials in the imported panel model are used, and the solver algorithm picks the best fit by cycling through the types. Nevertheless, it is possible to embed the code block into the program to create new materials based on user input parameter set values. A predefined number presents each thickness type. The acquired data is combined into lists of materials and thicknesses, which are then merged into a configuration matrix with three scalars: building side, material, and panel thickness (Figure 2, right). Sliders are employed to control the selection of configurations in the matrix (grey tabs in the interface - Figure 2, left). The selection of panel configurations is distinct for each facade side of the building. So, all panels within a single facade will share the same thickness type and be distinguished by UV dimensions only (UV denotes the axes of the 2D space of the local coordinate system as XYZ coordinates are taken to identify 3D space). Meanwhile, generated panel types may vary between facades to adapt to an optimised solution.

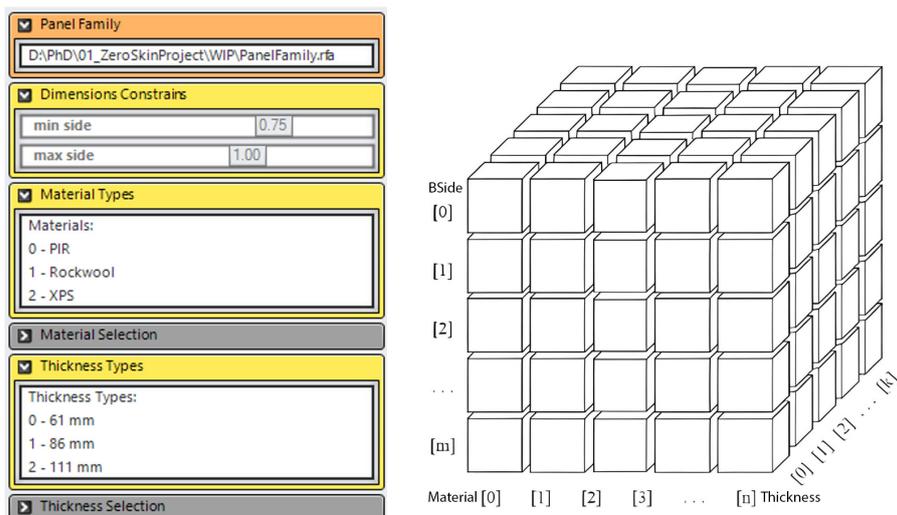


Figure 2
Interface for loading panel and constraints (left), configuration matrix (right).

C - Conductivity
W/m*K

D - Dencity
Kg/m³

SH - Specific Heat
J/kg*K

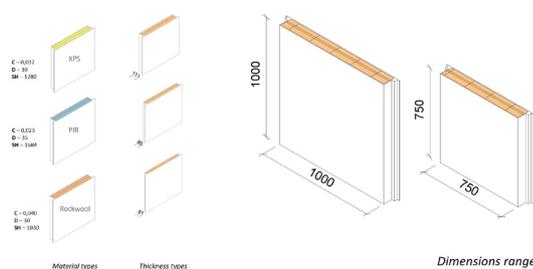


Figure 3
Material types and their characteristics (left), panel thickness types (middle), panel dimensions range (right).

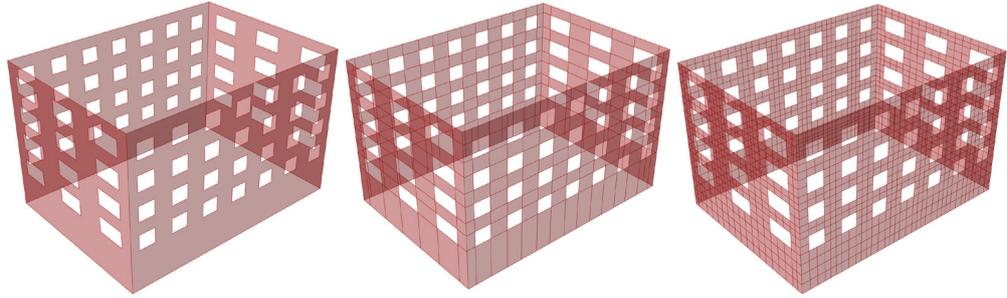
In the second stage, model components are extracted to prepare the analytical model for simulation processing. Consequently, the next object categories get extracted from the model: walls, spaces, windows, floors, and materials. Since all BIM elements will be translated to EnergyPlus classes, from a geometrical point of view, most of them will be represented as flat surfaces and potentially lose geometrical model integrity. Therefore, it is necessary to rebuild the model component's geometry to detect intersection events for further nest association between elements. For this purpose, Bounding Box geometry is inferred from all model instances using distinguished methods for each category. A common approach for this operation is to extract the basic surface of the component instance and then extrude it in the normal direction of its local coordinate system.

In the third stage, based on the extracted shell of the building, four facade sides are divided into grid layouts aligned with opening outlines. The resulting grid cells will be used to allocate generated panels. So, the geometrical centre of a cell will be the location point for each panel, with its dimensions written to panel parameters. Meanwhile, cells must be constrained by input panel maximum and minimum dimensions defined earlier in the 1st stage.

First, the building shell is deconstructed, and the four sides' surfaces are filtered by their normal direction vector. Once these side surfaces are extracted, they can be split by openings prepared in the previous stage. When each facade dimension

and UV basis of local coordinate systems are derived, the process proceeds to the grid layout (Figure 4, left). Next, control points of facade surfaces are grouped by UV coordinates and grid lines are created and defined by start point, tangent directions in the surface coordinate system, and length equal to the respective dimensions of the surface. As a result, a grid layout is formed and aligned with the facade openings (Figure 4, middle).

Figure 4
Facades (left), Grid layout – 1st stage (middle), Grid layout – 2nd stage.



The final step involves subdividing the created grid into smaller cells, if needed, to fit panel dimension constraints. For this purpose, grid cells are shuttered into equal segments based on input numbers of divisions for UV directions. Then, segment lengths are validated for overconstraint. If the panel length exceeds the dimension range, the input number of divisions is adjusted until the segment length fits within the constraints. Ultimately, the facade grid is subdivided, matching the input constraints (Figure 4, right). The prepared grid can be transposed to the simulation part of the script definition.

EUI (End Use Intensity) value in kWh/m² and total count of panel configurations are used to assess panel configurations via building energy performance impact. Both values are supposed to be minimised to achieve better building performance. The energy model is calculated through a connected energy simulator engine to the parametric model of the building, and the results for assessment are displayed through UI in the BIM application. This part of the script utilises classes, methods, and properties from the Ladybug library and Honeybee components.

Creating an energy model based on the BIM model components extracted earlier and the input constraints defined in the first stage is necessary to perform the simulation. Besides, it is required to load an EPW weather file, which can be accessed online for specific project location. Also, some non-graphical project data is used, such as Building Name, Direction of Relative North, project base point coordinates (origin), and wall material structure. This data is acquired automatically from the model with Honeybee components.

The energy model should contain spaces, surfaces, apertures, shades, weather data, materials and construction sets to run the simulation. Previously, nesting dependencies between faces, apertures, shades, and panels were already defined as rebuilding model elements. At this stage, analytical surfaces can be added for all the space

instances with apertures and shades assigned to the host face. Materials are translated into opaque construction sets, which are further assigned to surfaces grouped by specific sides of the building. Ultimately, the energy model is created from the list of spaces and nested analytical elements. When the energy model is ready, the last step to run calculations is to set up simulation parameters and write an energy model from the Grasshopper environment in IDF format, which EnergyPlus then run.

It is worth noticing that simulation runtime became an important limitation in the workflow. The calculations during optimisation require additional data processing called externally from the EnergyPlus application. Moreover, in this workflow, the Honeybee simulation component requires internal additional translation from OSM to IDF format to run the simulation, which is not the most efficient solution in terms of runtime. Therefore, a single simulation span during the optimisation process is extended drastically in time running from the BIM application, compared to stand-alone simulation. Consequently, optimisation is a rather hardware-demanding and time-consuming process, particularly in this workflow. Alternatively, to accelerate the simulation process, the BIM model can be converted to the topological representation of the elements with the Topologic library [7]. Topological elements would lighten the processing and shorten the algorithm's definition of associations between components.

The weather file is used to gather environmental conditions for the simulation setup. It is also required to input the run period (specific time range including summer and winter picks) and check the types of calculations to run. The run period is controlled by sliders in the “Inputs” section of the script definition. Both inputs and outputs of the simulation are also available in the interface (Figure 5, left). As a result, the simulation outputs are used to evaluate facade design adjustments. They can be used both for manual configuration setup and for the optimisation solver algorithm to run automatically.

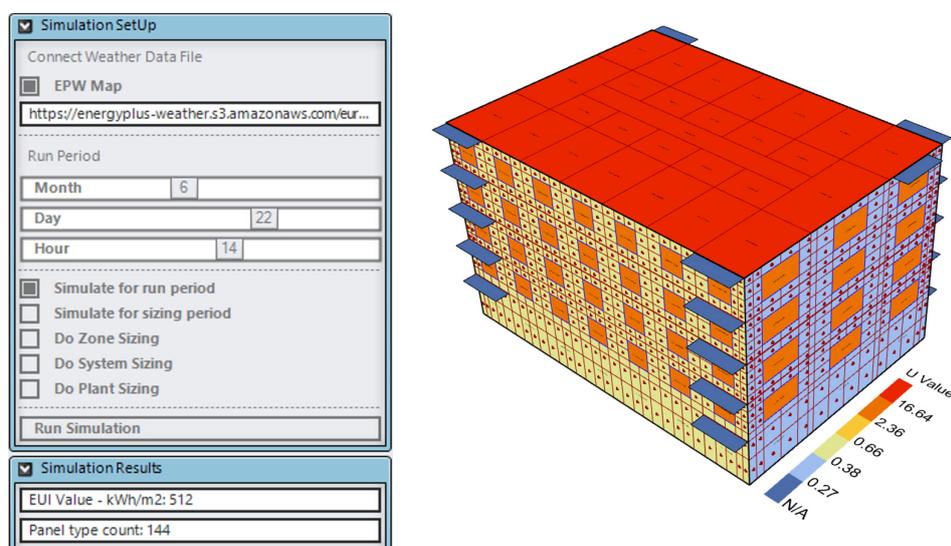
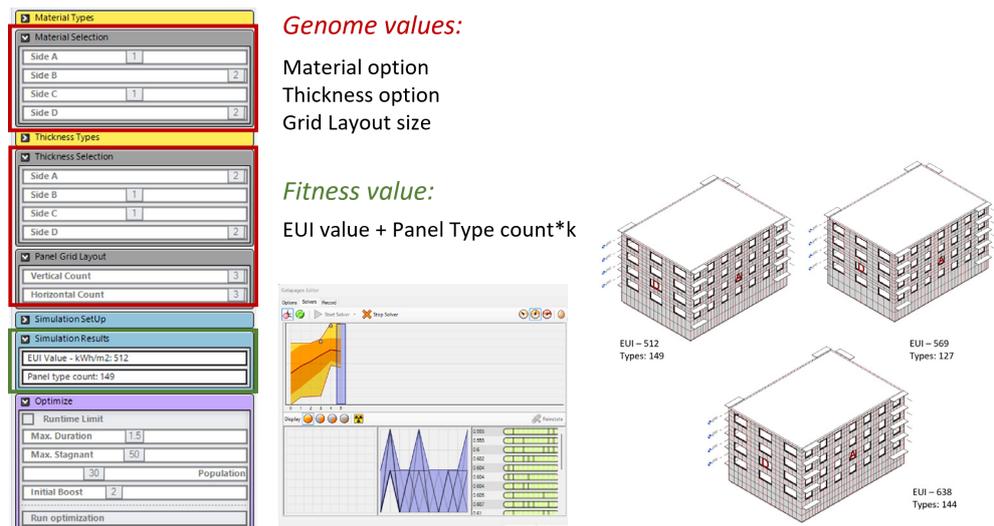


Figure 5
Simulation setup interface (left), analytical surfaces divided by panel grid with U-value in the centre of each panel (right).

Optimisation is an alternative to the manual configuration setup described earlier for automatically assessing multiple configurations and panel generation. The built-in Grasshopper evolutionary solver– Galapagos– is implemented in the proposed workflow. Galapagos is based on the evolutionary computational algorithm principle [8]. In essence, this solver populates the fitness landscape (or “model space”) from combinations of input variables (or “genes”). Each combination is a random individual (or “genome”) in the first population (or “Generation Zero”). A solver is intended to evaluate every genome’s fitness (function extremum to reach). Then, in the next generation, the best-performing genomes from Generation Zero are bred to produce offspring and narrow down the model space. Meanwhile, less successful individuals are excluded from the process. This iterative approach continues through generations until the solver achieves the best fitness value. The solver finishes optimisation work when it reaches a limited number of populations, a certain amount of generations without progress, or a defined runtime.

In the case of using an optimisation solver for panelisation, all configuration inputs serve as genome values for lookup during the optimisation process. The simulation result (EUI) and the count of panel types are used for fitness evaluation. Both values are gained to minimise, while they should have different weights to influence a solution. This condition indicates a multi-objective problem. Therefore, an “a priori” approach for optimisation using metaheuristics is applied [9]. The fitness values are multiplied by the respective coefficient and summarised as the fitness output. Once the optimisation is finished, the program interface releases the top performance results accordingly (Figure 6, middle). Finally, the user can select the most suitable panel configuration among the best-optimised genomes and display it in the preview mode in the viewport (Figure 6, right).

Figure 6
UI values for optimisation genome input (left), optimisation process (middle), facade configurations preview in viewport (right).



Once the grid and configurations are established, facade panels can be generated. The thickness type, dimensions, and material data are then written to panel components according to configuration. For this purpose, the panel location points, dimensions, and normals are extracted from the facade grid created earlier to position the panel in the model. Materials and thickness are assigned to panels based on the facade side where the panel is located and the configuration chosen for this facade. Finally, all inputs are used to populate panel instances in the BIM model. The result is shown in Figure 7.

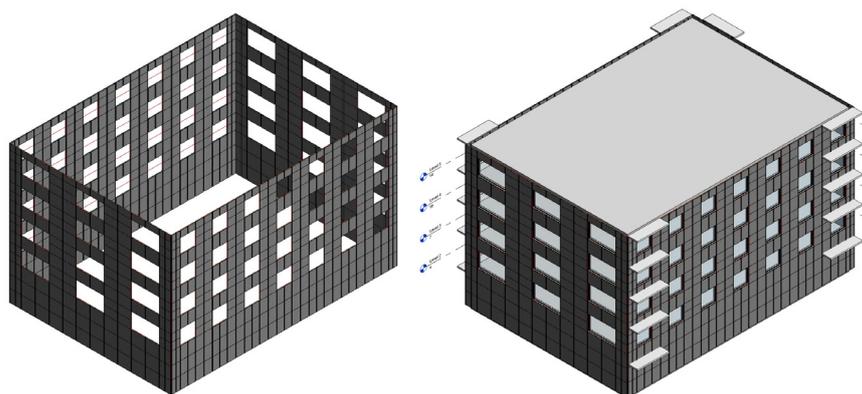


Figure 7
Generated panels (left),
generated panels on the
building (right).

4. Conclusion

The work considered in this article is a part of the ZeroSkin+ research project. This work aims to develop a tool to apply the elaborated BIM-BEM methodology to optimise building energy rehabilitation processes. The case study is the facade renovation of a residential building with prefabricated adaptive 3D printed panels, which are supposed to fit into an optimised system configuration. As a result, the developed tool allows the generation of facade panels based on energy performance simulation and optimisation results integrated within a BIM platform.

The tool encompasses the implementation of panel components elaborated in related research within the scope of the ZeroSkin+ project. Panel design implies parametric variables that can adapt to specific locations on the facade. These variables form the configuration matrix from material, dimensions, and facade side. The selection of configuration for the panel is based on simulation, and optimisation results are handled automatically through an optimisation solver. The simulation requires transforming the BIM model to an energy model and rebuilding element representation and dependencies. All transformations are executed by script, acquiring necessary data directly from the BIM model through API, while constraints and weather data are inserted from the user interface. Further, the adaptive panel system passes through an optimisation solver to optimise facade design. For this purpose, the fitness value is computed based on simulation results and the total count of panel types, while the optimisation genome is connected to the configuration matrix.

Finally, the user can select the most suitable panel configuration among the best-optimised genomes and generate these panels in the initial BIM model on the fly.

As a result of the investigation, the tool for generating prefabricated adaptive panels based on energy performance reveals the potential to customise workflows by combining existing tools to leverage advanced technological stacks seamlessly to find optimised solutions for rehabilitation processes. Meanwhile, the workflow implies direct interaction between BIM and BEM tools. Such a holistic approach allows well-informed design decisions to reach high output precision, especially important for renovation projects in dense urban areas.

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