Automation process in data collection for representing façades in building models as part of the renovation process

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Abstract

A key barrier in building façade renovation processes versus new designs is that an initial building model on which the design process is based rarely exists and that the technologies usually employed to create it (e.g., based on point cloud scanning) are costly or require modelling skills. This situation is a clear limitation, especially in early decision stages, where the level of detail required is not very high and the analysis and studies to consider the renovation plan (e.g., simplified energy simulations and renovation potential, or estimation of the number, types, and dimensions of the prefabricated modules incorporating solar panels) highly depend on such digital models. This paper introduces a process that, based on freely available data such as open GIS sources (local cadasters, OpenStreetMap...) and façade images, can semi-automatically generate the 3D building model of the existing conditions and, in a second step, can also suggest the prefabricated façades module layout for building upgrades. Additionally, no on-site visit is needed. When the upgrade is focused on the façade, a big opportunity is identified for generating the building model and a realistic representation of its envelope, only using online data sources as input. The process developed consists of a set of easy-to-use software tools that can be used independently or combined in a workflow, depending on the available data and starting conditions. Time-saving is the main benefit, which also contributes to reducing costs.

Keywords

semi-automated data acquisition, prefabricated façade panels, building envelope renovation, open data, interoperability, IFC

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1 INTRODUCTION

Critical success factors in the construction industry are multiple and diverse due to the high number of stakeholders, disciplines, and technologies that coexist in this sector. According to Knotten et al. (2017), communication and decision-making are key in building design management, while other authors (Oluleye et al., 2023) also highlight data-driven digital tools and pre-demolition auditing as principal success factors.

The importance of a well-managed project in every construction work highly affects the quality of the result. The better managed the project is, the better the intervention will be. This is important with new buildings but especially relevant for renovation activities (Noori et al., 2016), where the built environment and surroundings strongly affect and condition the potential upgrading designs. In such a situation, the project needs to be defined using a reliable and descriptive basis of the building that is about to be renovated, also implying a good radiography of the actual status.

When alternative interventions and potential renovations are assessed, getting a fair representation of the existing building becomes a necessary input to properly make the assessments needed (Wang et al., 2022). But at the same time, the effort to capture that information needs to be proportional to these initial steps of the process when the decision to renovate has not yet been adopted and when the resources and budget are still very limited. The use of BIM technology has rapidly grown among AECO (Architecture, Engineering, Construction, and Operations) professionals but is still primarily used for new designs and with several challenges, such as the cost of equipment and software, lack of skilled workforce, and a very fragmented industry, mainly composed of SMEs (European Construction Sector Observatory, 2021). Considering the existing building stock, the available digital information is scarce and dispersed across various owners, formats, and accessibility levels. There is a growing research interest in GIS-BIM interoperability (Zhu & Wu, 2022). Still, practical implementation is typically limited to large vendors such as ESRI or Autodesk (ESRI, 2023), skilled users, and extensive construction or infrastructure projects. The equation gets more complex if we add energy estimation aspects to the data flow automation (buildingSMART, 2022).

In parallel, there is an urgent need to quickly upgrade the current building stock, which is why several initiatives are strongly promoting this change by means of renovation to significantly reduce the impact of the buildings and the AEC sector on the environment. Europe's decarbonisation strategy is fully oriented and aligned with these rehabilitation goals, and the impact of the façade and its insulation and the benefits of on-site renewable energy capture are labelled as two of the most critical. The use of industrialisation and prefabrication has also been identified as a key driver to support this transformation. The main advantages of adopting this manufacturing strategy when envelope refurbishment is considered are less obtrusive work for the inhabitants, shorter periods on-site, better and safer working conditions, and, in general, higher quality control of the overall intervention along its different phases. Moreover, adopting such a prefabrication approach also enables the possibility to incorporate additional systems and solutions, rather than conventional ones used in envelopes, representing a clear opportunity to incorporate solar collecting solutions into the building envelope (Elguezabal & Arregi, 2018).

However, compared to manual processes, renovation processes with prefabricated modules require more data and a better data flow. With manual methods, the operator manipulates the material based on the measurements made by themselves directly on the site while working with it. With prefab technologies, the products are produced off-site, requiring major coordination with the building measurement, as well as high accuracy when the on-site assembly process is materialised.

Previous studies for façade data acquisition have focused on 3D Laser Scanning (Omar & Nehdi, 2016; Alizadehsalehi &Yitmen, 2016). Preliminary approaches for data acquisition with 3D laser scanners were focused on matching geometries for as-built documentation. These cases involved graphic documentation that could be compared, meaning the CAD file. One of the preliminary studies was developed (Bosché, F. 2009). It comprised matching a two-phase construction steel profile recognition to a previously drafted 3D CAD. It was not an automatic procedure, though, but rather mainly used for as-built documentation. Later, the automatic reconstruction of as-built building information models from laser-scanned point clouds was developed (Kim, C., Son, H., Kim, C., 2013). However, these are time-consuming and relatively expensive procedures that cannot be used in the early stages of a façade renovation project because, at that point, the financing is usually unclear.

Summarising, there is a critical necessity to renovate a large number of buildings in a quick and efficient process, supported by digital tools and prefabrication techniques. But, for doing that, the early decision-making process establishes the starting point to 1) make the owners of bad-performing buildings aware of their actual situation, 2) describe the potential impact and benefits of a renovation intervention, and overall, 3) assist the owner in adopting the decision to renovate using studies and data that support that resolution.

Thus, there is a clear need to "democratise" the BIM adoption, especially in early decision stages, by offering solutions that 1) reduce the number of needed tools and license costs, 2) automate the capture of existing free data sources, and 3) have almost no learning curve. Using online data such as GIS and OpenStreetMap can improve this situation because it adds extra information to the generation of the building model.

According to this context, the main contribution of the research is an online data flow or tool that generates a building model based on open BIM formats. This is a semi-automatic process, which is fast and accurate enough for our needs. Furthermore, it can be achieved without visiting the site, only requiring pictures of the different façades. Among other aspects, building owners, promoters, or engineers should have a comprehensive understanding of the building's geometry, orientation, location, and other data that is needed to consider alternative renovation scenarios and to make estimates in an early stage of the project about the costs of investment, the need for insulation or the capabilities for harvesting solar energy. To achieve this, it is necessary to have a geo-located 3D model of the building that can accurately depict the building's shape and structure and the ability to fit the prefabricated modules as an over-cladding system. This is where the layout of the prefabricated walls and solar panels comes into play. A proper layout can give a clear idea of how many solar panels can fit on the building envelope, what cumulated irradiation they receive, how much insulation is needed, and how much investment is required. This paper explains the latest updates on a tool that allows for semi-automated online building modelling and the layout of prefabricated modules with solar panels. This tool generates a detailed 3D building model and layout of the prefabricated modules by using building images and OpenStreetMap floor plans. The tool provides two main outputs. One is the building model that can be used as the basis to estimate, with some other specific tools, the potential energy savings. The second output is the layout of the prefabricated modules, which includes and optimises the placement of solar panels. The major benefit of the tool is that it can be used without the need for on-site measurements by technicians. By using the outputs of this tool, building owners, promoters, and engineers can make informed decisions about the installation of prefabricated modules with solar panels and get an initial estimation of how economically viable and energy-efficient the renovation project could be.

2 SOA AND INNOVATION

Different stakeholders participating in building envelope renovation agree that façade upgrading with prefabricated modules needs to be more efficient, as stated by the European Commission (European Commission, 2020). There is a general need for a more automated process to achieve a safer and more effective process. The renovation of building envelopes using modules has not taken off, as anticipated, despite the effort put forth in the research programs. The European Commission's latest call for research project proposals (European Commission, 2020) was asked to, among other things:

A “Demonstrate retrofitting plug & build solutions and tools reaching NZEB standards suitable for mass production by the industry for buildings under deep renovation.”
B “Decrease of retrofitting time and costs by at least 50% compared to current renovation process for the same building type.”

These issues highlight the fact that there are still problems in the field of prefabricated module-based building refurbishment. The requirement for mass customisation is still present, as seen in point a). Contrarily, point b) reveals that the “current renovation process” or, in other words, the manual process is more practical, affordable, and effective than approaches that use prefabricated modules. Therefore, there is a real need for improvement in façade renovation with prefabricated modules.

Figure 1 explains all stages. Please note that the prefabricated modules are supported by connectors

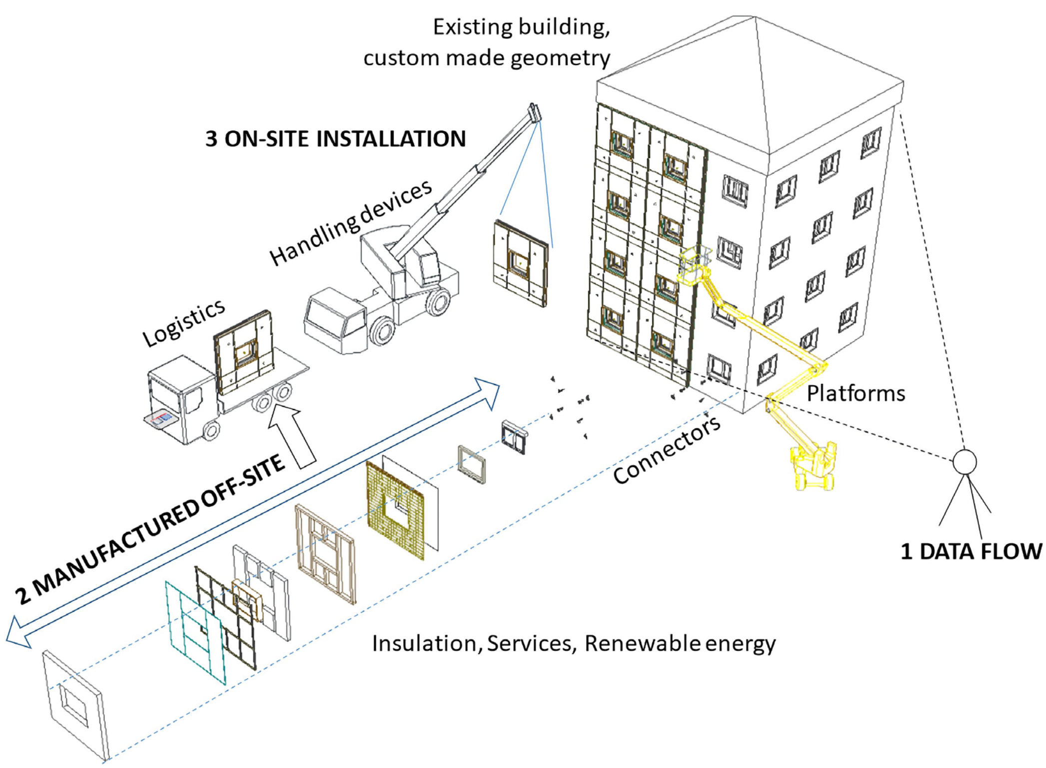


FIG. 1 Building renovation process with prefabricated panels for the envelope

Records obtained in previous research projects (Iturralde, K. et al., 2022) show that the time for on-site data acquisition of the building was 0.15 hours per façade square meter. In the analysed cases, data acquisition was made with a Total Station and targets. Besides, according to these previous studies, the prefabricated layout definition takes 0.34 hours per square meter. Defining the layout of the prefabricated modules means adjusting a standard or normalised façade type (i.e., from a certain company) to the geometry of the existing building's façade. For the initial stages of the project, when the decision-making takes place, the objective of this research is to reduce the time for façade and building modelling as well as the layout definition by at least 90 per cent; a reduction that directly impacts cost savings. This percentage was determined as a benchmark during the research project proposal and based on previous studies (Iturralde, K. et al., 2022). The objective is to minimise the time of data flow during the renovation processes of existing buildings. These previous studies, such as research projects such as BERTIM (BERTIM, 2019), have shown that, in the initial stages, it is essential to reduce iterative measurements of the building and that reducing the data flow to almost zero is crucial. Since reducing the time of the entire data flow process to zero is predicted to be difficult, 90% has been defined as a challenging objective.

3 METHODOLOGY

The implementation of the workflow is a two-step process. The first step involves the creation of a 3D model of the building and its various features. Once this is done, parametric algorithms can be applied to the façade, which are able to generate prefabricated module placements on the building.

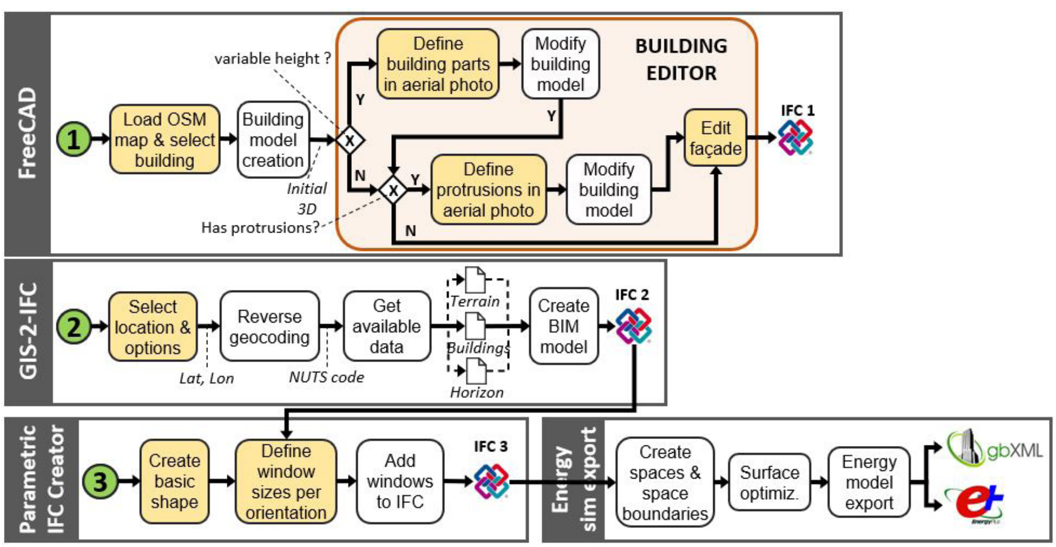


FIG. 2 Workflow for online building modelling methods

3.1 ONLINE BUILDING MODELLING OF EXISTING CONDITIONS

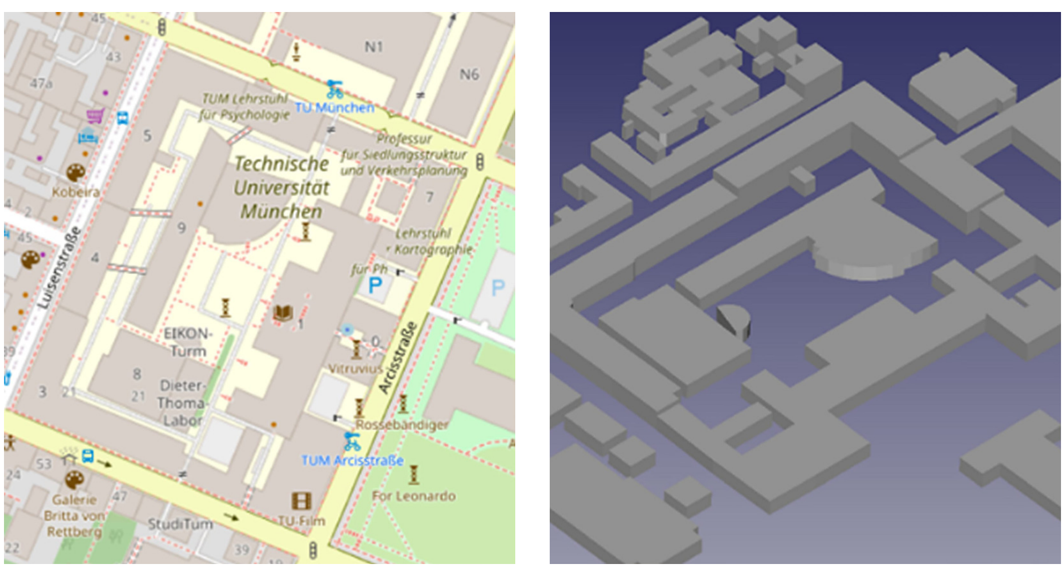
Before proceeding to any digital workflow, the first step is to model the existing conditions since old buildings rarely have any digital representation (Volk et al., 2014). To manually create it could be time-consuming and require basic modelling skills (Kadhim et al., 2021). In addition, there is an increasing availability of open data sources and digital formats concerning the building stock, although at different levels of detail, quality, availability, or reliability. In general, these sources provide information about the building layout or footprints and some basic attributes, although they do not usually inform about the internal distribution of the building. However, when the renovation process only involves interventions in the façade, this can be sufficient for our purpose.

Figure 2 shows the workflow covered in this paper for the online data acquisition part and its further use for other purposes, e.g., energy simulation. Numbered circles 1, 2, and 3 represent different possible starting points, which will depend on the available information about the existing building or the user type. They can be used independently and produce an IFC of the existing building (namely IFC 1 and IFC 2), but could also be combined in more complex workflows, even involving external tools. Yellow-shaded boxes represent user-driven actions, whereas the rest represents automated processes executed in the background with no user interaction.

Option 1: FreeCAD-based approach

This approach (starting point 1 in Figure 2) focuses on the information from OpenStreetMap and pictures given by the client/building owner. The tool creates a building model while the promoter interacts with it. OpenStreetMap (OSM, 2023) was used for preliminary semi-automated data acquisition and the subsequent initial building modelling. For that purpose, an algorithm was developed to semi-automatically generate the shape of the building (see **Figure 4**). Computational design tools and software, such as FreeCAD (FreeCAD, 2023), were used to merge information taken from online databases.

First, the user exports a map section from OSM as an XML file. The user then opens FreeCAD and uses the 'Load.osm' file command to select the exported map file. The command creates a CAD object for each building in the OSM file with the correct layout (**Figure 3**). However, at this point, the exact height of the building and the roof shape are unknown; thus, the height is indirectly estimated from the number of floors (assuming a typical floor height, e.g., 3 m).



a *b*

FIG. 3 A map section in OpenStreetMap (left) and the same map section after import in FreeCAD as a 3D model (right)

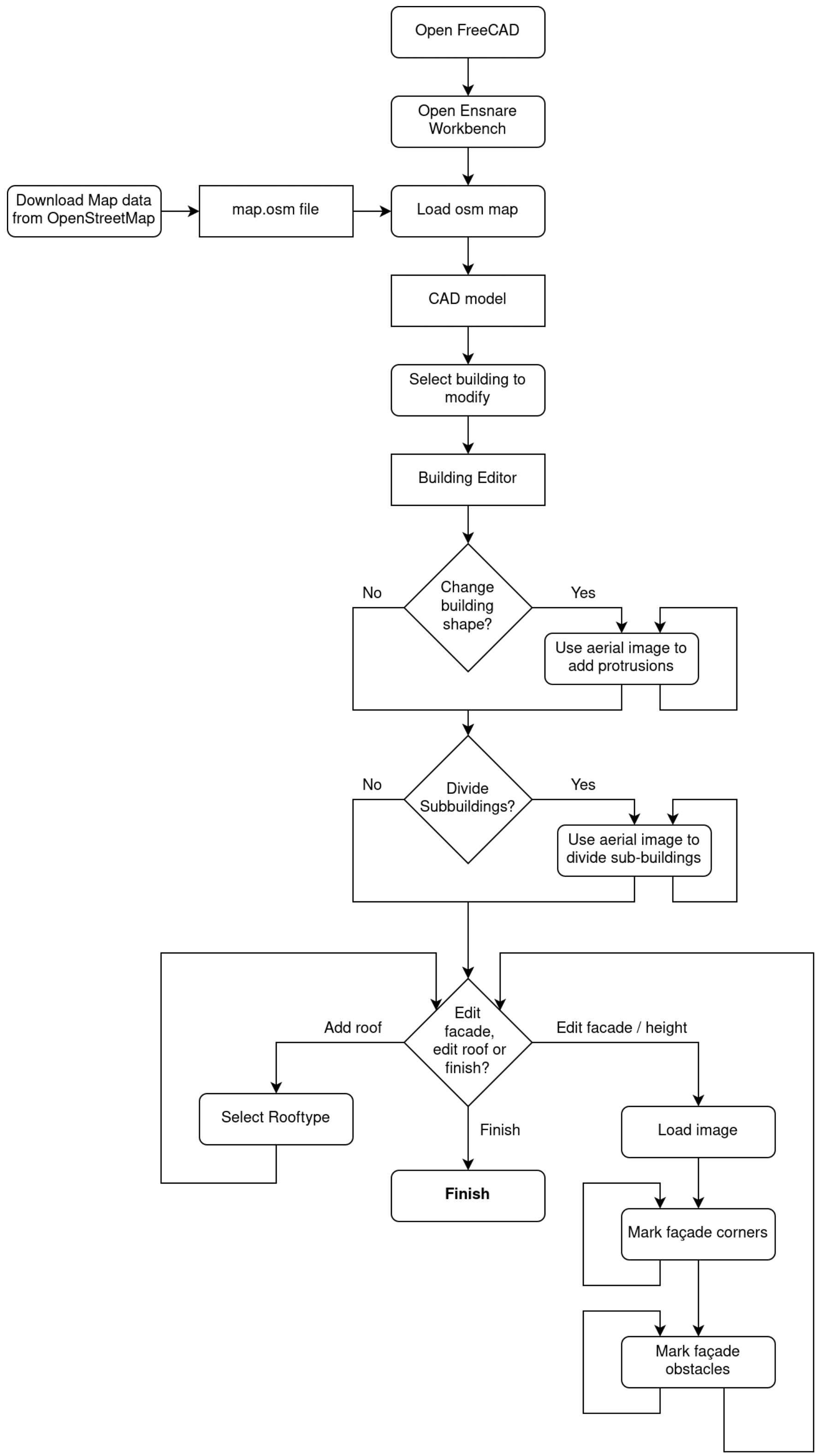
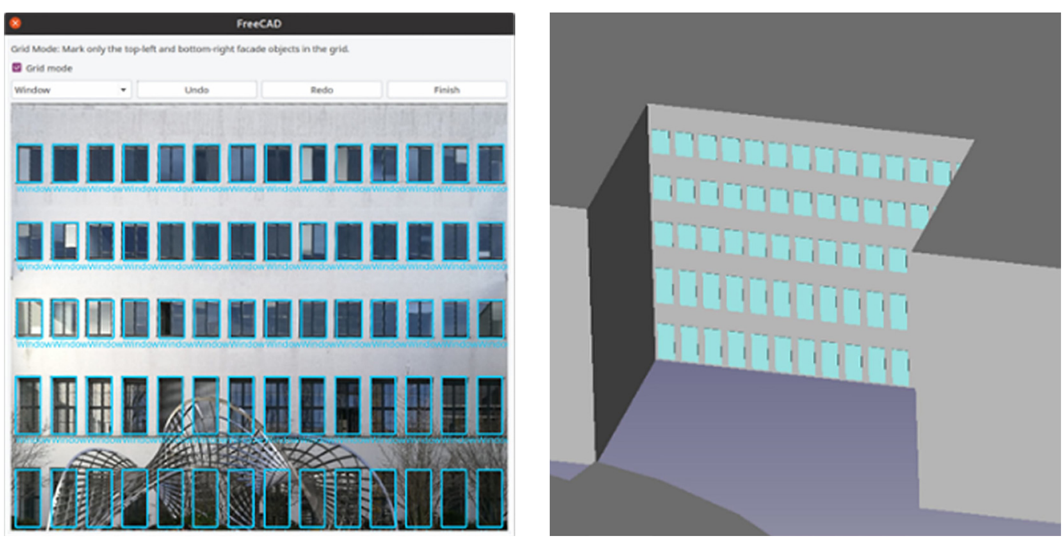


FIG. 4 Scheme of the online data processing

Next, the user selects a façade in the 3D view and uses the 'Adjust façade' command. The user then selects a previously taken photo of the façade, which is opened in a new window. In this window, the corners of the façade can be marked. With the corners given and by assuming a rectangular façade, we can locate the vanishing points. Through a series of geometrical operations based on the plane folding of the quadrangle, we were able to obtain the geometrical restitution. In this way would could revert the projection of the façade and determine the original proportion between width and height, as shown in **Figure 5**, right. This is a well-known procedure of geometry techniques (Izquierdo Asensi, F., 2000). Note that the image of the visual interface generated in Python itself is not linear; it only serves to visualise the algorithm (the code itself in Python is linear). Since the length of the façade is known from OpenStreetMap data, we can multiply it by the proportion to calculate the building height. The height is then adjusted in the 3D model (see **Figure 5**).

FIG. 5 Left, Tartu demo building façade with marked façade and gable area. Right, screenshot of the Python code, the algorithm for computing the height-width proportion from a façade image on the very same Tartu demo building

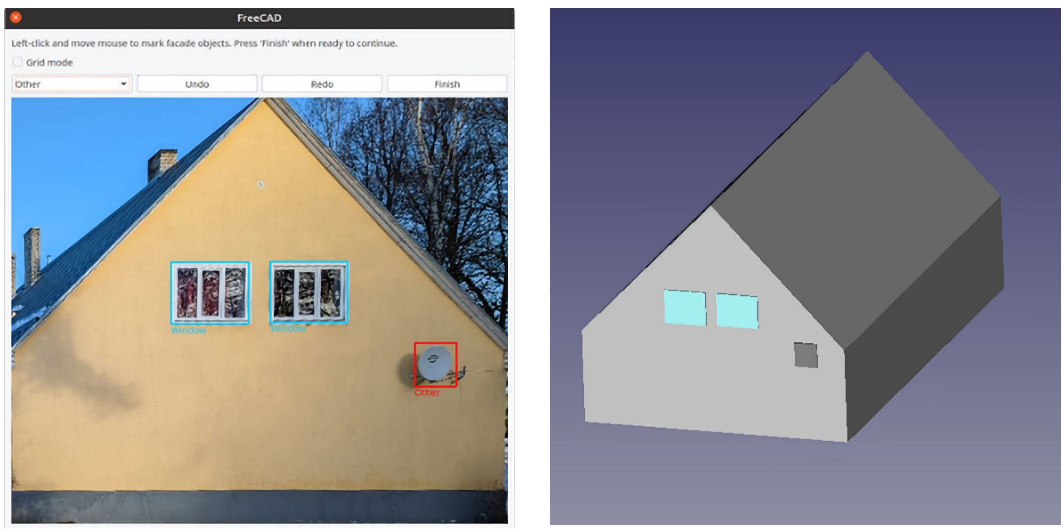


a *b*

FIG. 6 Marked windows with the grid function on the transformed façade image of the main building of the Technical University of Munich.

In the following step, a perspective transformation is performed on the façade area to make it rectangular. In this transformed façade image, the user draws bounding boxes around façade objects and selects the appropriate object type, for example, a door or window. A grid selection mode is available for marking many objects in one step since objects like windows are frequently positioned in a grid. When the user has marked all objects on the façade, they can finish the step, and the objects are added to the 3D model (see **Figure 6**). To better explain this step, a façade with a grid of multiple windows is shown, in this case, one of the façades of the main building of the Technical University of Munich (see **Figure 6**).

When the user marks more than four corners for the façade, the additional points are interpreted as roof points. The roof shape is then extruded along the length of the building to create the roof in the 3D model (see **Figure 7**).



a *b*

FIG. 7 Different types of marked façade elements and pitched roofs

With the process described above, the building model can be defined. Several tests have been carried out with satisfactory results, as shown in **Figure 6** and **Figure 7**. The difference between the obtained data and the measured building sizes ranges between 1 and 3 per cent of the building. The differences are tolerable because this solution is supposed to be used at the first stages of the façade renovation project; the initial phase where the model's reliability level is still expected to be lower than the one required for later detailing phases (Polly, Kruis & Roberts, 2011). The measurements at this stage are used only for estimation. With this building model, the layout of the modules for the renovation intervention can also be determined automatically.

Several tests were carried out with different buildings, such as a demo building in Milan (depicted in the following **Figure 8**), and Level of Detail 4 (Löwner, M. O et al., 2013) was approached.

a b

FIG. 8 The demonstration building in Milan, the original on the left, the version obtained with the aforementioned tool on the right

Sometimes, the user of the tool might not be able to manually select the elements in a façade. For this reason, automated detection of building limits and windows using CNNs (Convolutional Neural Network) was approached. This can facilitate the detection of corners, as can be seen in **Figure 9** and **Figure 10**. This capability will be re-adapted to link the process with the BIM generation.

FIG. 9 Automatic building edge detection in the demo building located in Tartu (Estonia)

FIG. 10 Automatic detection of windows

Option 2: IFC generation from GIS and open cadastral data.

The starting point 2 in **Figure 2** covers the automated IFC generation from open GIS data sources. The process starts with a location selected by the end user (e.g., by selecting it in a web map). Next, location-based information must be retrieved. Typically, open data sources can be universal, e.g., OpenStreetMap, which is collaboratively maintained by individuals, or limited to some geographical scope (national, regional, or city level), which is the case with cadastral systems maintained by public administrations. Thus, the location-based information must be obtained from the selected coordinates (usually given in latitude and longitude), a process known as "reverse-geocoding". Many equivalent services exist for this purpose; for this work, Nominatim has been used, a service offered by OpenStreetMap. However, the output of the web service does not offer a standardised output; neither in terms of language (although we could force it to use English or the local language), having a homogeneous naming convention (and output language), nor in terms of attribute naming. This is more difficult to address since administrative units are not the same in Europe: Spain has provinces, France has departments and regions, and so on; thus, the output tags vary greatly (**Figure 11,** left). This will happen with any reverse geocoding service. To solve this, Eurostat provides a unified framework named Nomenclature of Territorial Units for Statistics or NUTS (European Commission, 2021a). Thus, from the country code (e.g., "es" or "fr") and the postcode, which is offered by the reverse geocoding, the NUTS code was obtained using the correspondence tables which are freely offered by the EC (European Commission, 2021b). NUTS codes follow a hierarchical coding (e.g., Spain is "ES", the Basque Country is "ES21", and the province of Biscay is "ES213".

```
"address":{
  "road": "...",
  ...
  "city": "San Sebastián",
  "province": "Guipúzcoa",
  "state": "País Vasco",
  "postcode": "20011",
  "country": "España",
  "country_code": "es"
}
```

```
"address":{
  "road": "...",
  "suburb": "Saint-Michel",
  ...
  "city": "Burdeos",
  "municipality: "Burdeos",
  "county": "Gironda",
  "state": "Nueva Aquitania",
  "postcode": "33000",
  "country": "Francia",
  "country_code": "fr"
}
```

a

Service	IN	OUT	URL	Output	Metadata
Cadastre Biscay	ES213		<url>	Buildings	...
Cadastre Spain	ES	ES21	<url>	Buildings	...
Cadastre France	FR		<url>	Buildings	...
OSM Buildings	*		<url>	Buildings	...
Open Elevation	*		<url>	Terrain	
PV-GIS	*		<url>	Horizon	

b

FIG. 11 Sample Nominatim outputs (left) and internal service configuration mapping (right)

Then, an internal configuration file was created (see the simplified concept in **Figure 11**, right) where, for each open data service, the applicable (or eventually excluded) NUTS code(s) are defined: e.g., the Spanish cadastre applies to all of Spain (ES), except the Basque Country (ES21), and the cadastre for Biscay is only applicable at the province level (ES213). Additionally, OSM is universally available in Europe and not filtered by location. Thus, from a given NUTS code, we can filter out which data sources (and their URL) we can access (or not). This configuration file provides metadata

(such as the type of output or detail), which has helped to better filter the information or select the most appropriate one with several available. Finally, for some use cases like solar analysis, it can be interesting to include the terrain and solar masks (visible horizon) in the output model. This is done by accessing two extra web services: 1) Open Elevation API (Lourenço, 2017) to obtain a grid of points with their elevations and 2) the horizon values are obtained through PV-GIS (European Commission, 2022), an online tool for solar panels production estimation, which offers an API-based access.
A simple web application has been developed to seamlessly integrate this workflow and make it available for any non-expert, as shown in **Figure 12** . The user only needs to click the location in a web map, and the model is automatically created and displayed in 3D within a few seconds while also being configurable in dimensions and level of detail. This can be implemented in web browsers and viewed online thanks to the cesium.js JavaScript library and downloaded in IFC, optionally with horizon and terrain, as shown in the rightmost image.

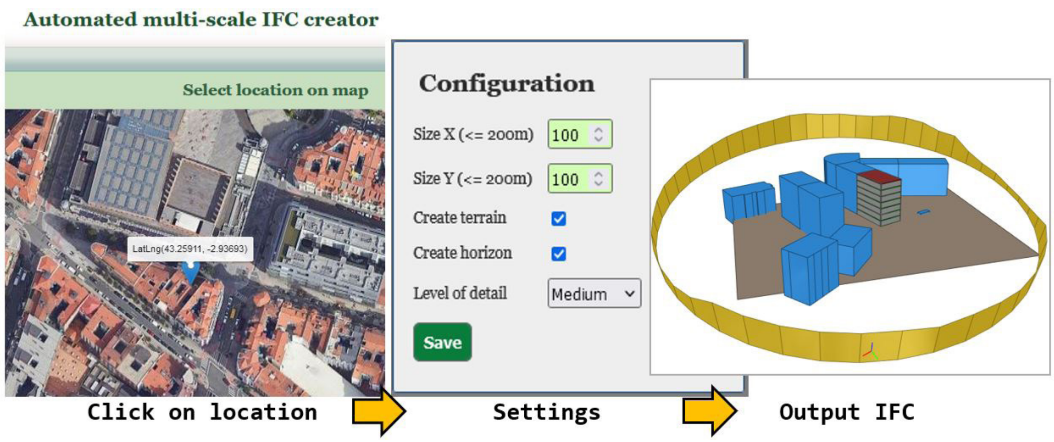


FIG. 12 Web application implementing the GIS-2-IFC workflow

The main benefit of this approach is that simplified models of any residential building from many EU countries can be obtained in BIM/IFC format in a few seconds, online, with a couple of clicks. This enormously reduces the initial data acquisition time. The obtained model can be sufficient for merely estimating some façade dimensions or orientations or other kinds of outputs. However, using it for energy simulation purposes requires additional information, such as windows or internal spaces. These use cases have been tested by integrating the generated output with external tools, as explained in the following sections, thanks to the benefits of relying on open BIM formats (IFC).

Option 3: Integration with external tools and automated export to energy simulation

The output generated via Option 1 or 2 is an open format (IFC), which means it can be integrated with other tools in a chained workflow. To showcase this process, an integration with the Parametric IFC Creator was conducted. The tool (bottom lane marked as Option 3 in Figure 2) permits creating from scratch an IFC from basic shape parameters, orientation, window sizes per orientation, etc.
In this case, the shape was already generated from the cadastral import; thus, only the windows needed to be added to the tool, saving time. This tool also implements the algorithms for BIM-2-BEM conversion proposed by Mediavilla et al. (2023), which permits obtaining a ready-to-simulate file with no BIM or energy modelling expertise required on the user's side. This presents a big potential for early decision stages in building renovation since no detailed model is needed but an estimation of the possible alternatives and their expected impact.

Figure 13 shows a workflow conducted using the Milano demo building (Italy). The steps can be described as follows: (1) Overview of the building in a satellite image; (2) the result of generating the basic IFC model from OSM with the approach previously explained (Option 1); (3) the model obtained by creating regular windows in Parametric IFC Creator; (4) the same building but with a highly irregular window layout (without the user interface); (5) the previous model exported to gbXML, the standard for model exchange between energy simulation engines (Green Building XML, 2022) and seen in a Aragog web viewer (Ladybug Tools, 2020), and (6) a single storey (space) of the gbXML building.

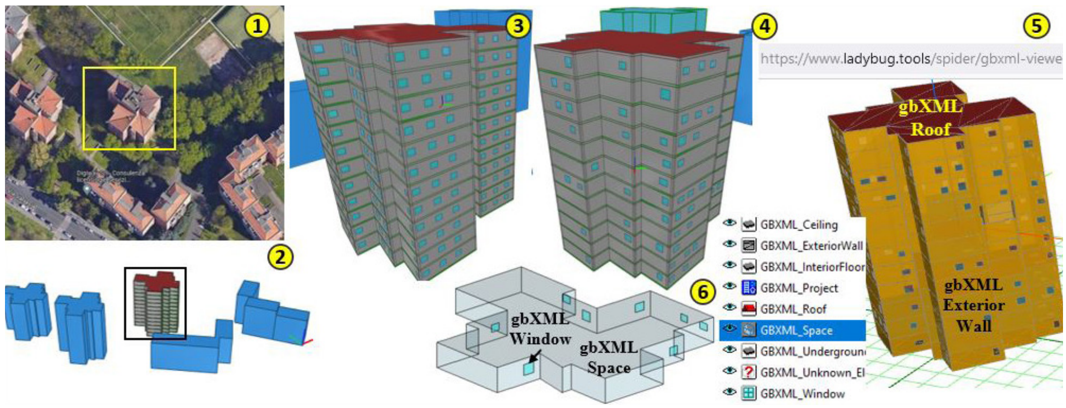


FIG. 13 Model preparation for energy simulation with the demo-building in Milano

However, even if this approach has a real potential, it still has some limitations. In a real building, not all floors are identical; some could include balconies, which can affect the energy demand calculations but also affect the estimation and layout of the prefabricated panels we need to install for renovation. Thus, an additional integration path is being explored in the ongoing research by considering both previously mentioned IFC generation methods in an integrated way, as explained next.

Integration of both IFC generation approaches

The different methods to generate the existing IFC presented earlier have their own benefits and limitations, so it seems reasonable to try to extract the best features of each and integrate them into a more optimised workflow, as shown in **Figure 14**, which is part of ongoing research. It starts from the GIS-2-IFC approach based on the online tool presented before. The main difference is that instead of generating an IFC, it generates a JSON file, which will be further used to create the IFC, i.e., the IFC generation logic is encapsulated into a new JSON-2-IFC component (the third one in **Figure 14**), so the workflow between different tools is limited to manipulating the base JSON file. **Figure 15** shows the basic structure of this JSON file, which primarily originates from the GIS-2-IFC module but still lacks windows and other salient elements, which are added in the building edition part approach 1 in **Figure 2**. This, in turn, produces a new JSON file of higher façade resolution, which is the input for generating the final IFC file, compatible with energy analysis tools.

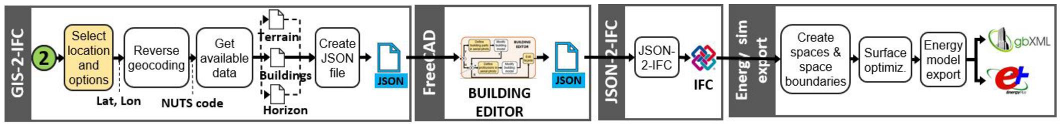


FIG. 14 Integrated workflow

FIG. 15 Structure of the exchange JSON file

The JSON file is a hierarchy representing the building, its storeys and heights, the objects in each storey, and their 3D geometries. Each object is tagged with the IFC class name (slab, wall, roof, window, etc.) and different types of geometries are supported (extrusions, boundary representations, and boolean operations). It resembles the IFC structure, but it is much simpler and easier to implement and modify by developers; thus, it is being used to store all the temporary modifications of the building model before generating the final IFC. A snippet of the JSON file is shown in **Figure 15**, where the GIS-2-IFC approach creates the main structure and then, in the image-based editor, window and balcony objects are added relative to the corresponding walls.

3.2 PREFAB LAYOUT DEFINITION

As said before, the design of the prefabricated modules for building renovation can lead to time-consuming procedures. In the tool developed for this research, a parametric algorithm determines the prefabricated layout automatically, including the optimisation of the solar panels' surface. This is achieved by applying a set of parameters that are adjusted to different façade topologies. For greater accuracy, extra data given by the building owner can be helpful, such as the vertical distance of the window from the floor.

The foundations of the developed FreeCAD model are a sketch and a spreadsheet. In the sketch, an abstracted two-dimensional drawing defines and visualises the placement and size of the elements of a module. The desired placement and size are controlled through adjustable parameters, which in FreeCAD are addressed as constraints. Most of these constraints are defined in the spreadsheet, while the rest are referenced in the sketch. Constraints (such as the height of the window) are first accessed through the spreadsheet, where they are given a value, then referenced with an alias, and finally linked in the constraints of the sketch in the form of a formula. This way of linking the data offers a parametric workflow. For modifying the constraints, it is only necessary to change the value of that constraint in the spreadsheet, and the model will be adjusted accordingly.

Regarding the solar panel's dimensions, several panel sizes are selected in this research project. Their dimensions are listed in the spreadsheet. For every case, the correct size of the solar panel for the module needs to be chosen, and its dimensions then need to be selected as values for the constraints.

The three-dimensional module model comprises several building elements belonging to the back frame and the panels on top. This is optimised for the later module assembly.

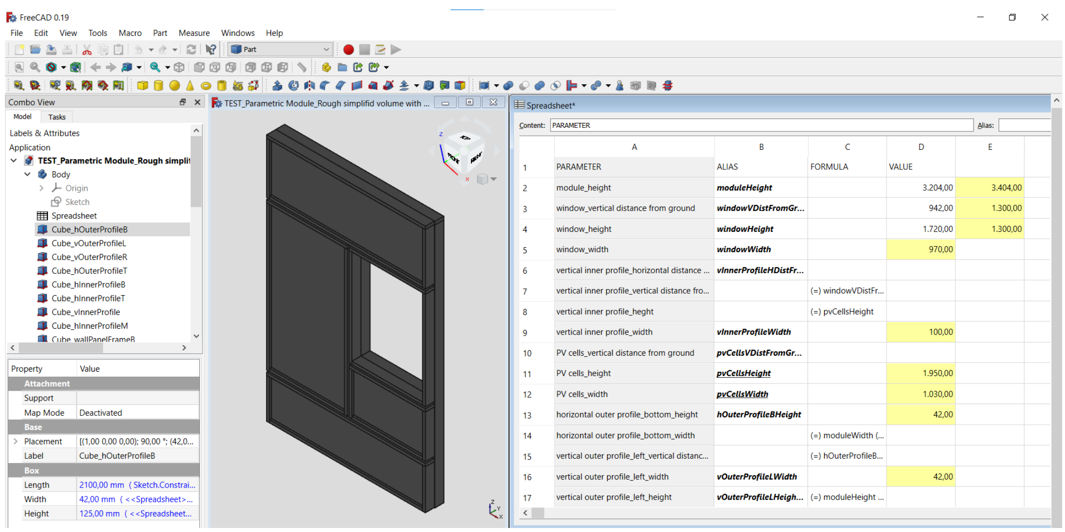


FIG. 16 Different types of marked façade elements

Currently, a scenario is developed in which the façade symmetrically admits modules that are all geometrically equivalent. In this scenario, the problem simplifies placing a solar panel and accompanying registration area within just one module since it can be used to reconstruct the rest of the façade. Tackling more complex façades is a future task.

The façade, module, solar panel, registration, and window must be abstracted as 2D regions in the plane. Under this abstraction, the placement of the solar panel and registration area is a packing problem with the additional goal of maximising the solar panel area.

A module is represented as a rectangular region in the plane whose lower left vertex is at the origin, as shown in Figure 17. The other features (the window, the solar panel, and the registration area) are rectangular regions subjected to the following constraints:

- A feature must be contained within the module.
- No two features may overlap.
- The registration area and solar panel must maintain some proximity.
- The registration area must be placed in a way that it can be reached by a neighbouring module.

The approach is a greedy method that finds the first feasible configuration for a given solar panel. To ensure maximal surface area, the approach starts with the solar panel of maximal area and then moves on to the solar panel of second maximal area, and so on, until all possible solar panels have been exhausted (see red boxes in Figure 17). The layout of the modules also includes the registration area of the pipes and cables (see yellow boxes in Figure 17), the perimeter of each module (see blue boxes in Figure 17), and the perimeter of each window (see green boxes in Figure 17). The size of the façade is shown on the x and y axes in Figure 17.

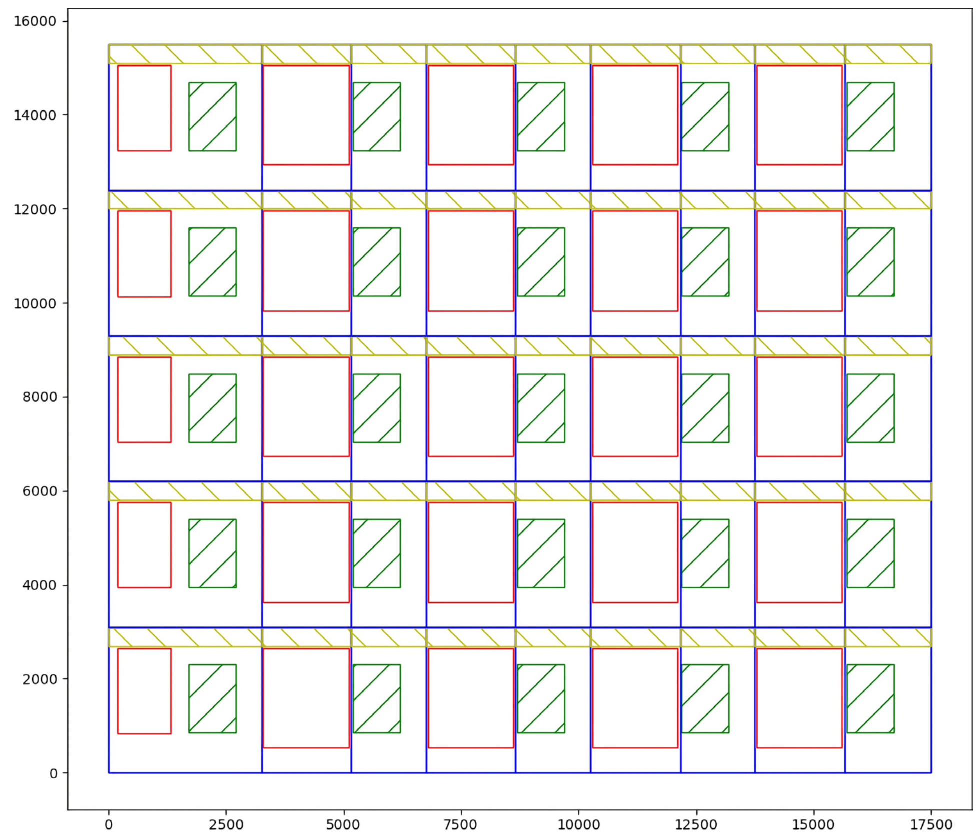


FIG. 17 Automated maximisation of the solar panels (red) and sub-division of the modules (blue), including the registrable area of two façades (yellow)

The implementation of the approach is done using Python (version 3.6.9) without any external libraries. The solution is found by the function optimal placement based on the following inputs:

- The length and height of the module
- The local coordinates of the bottom left corner of the window, its length, and its height
- A list of dimensions of potential solar panel
- A list of dimensions of possible registration areas
- A margin that specifies the distance between features, and the boundary of the module
- A step size which controls how many configurations are tested.

With the definition of the existing building model and the prefabricated module layout, the demo building in Milan can be drafted as shown in Figure 18.

FIG. 18 Visualisation of the automated generation of the layout in the Milano demo building

4 RESULTS AND DISCUSSION

The main contribution of the research presented describes a flexible workflow for drastically reducing the time and cost of the IFC model generation process of an existing building for façade renovation purposes. It combines automated, georeferenced multi-building IFC model generation from open data sources with easy-to-use interfaces for façade details edition (e.g., windows or balconies). The tool has been proven in more than 25 apartment buildings, with successful results, as shown in Figure 19.
Depending on the final use and taking this initial digital representation of the building as a baseline, it also covers modules for generating a simplified energy model or for generating a prefabricated panel layout of the renovation project. This layout is automatically generated based on the dimensional criteria and constraints of the modular solution. Figure 20 shows the results of the semi-automated generation of the layouts in some buildings.

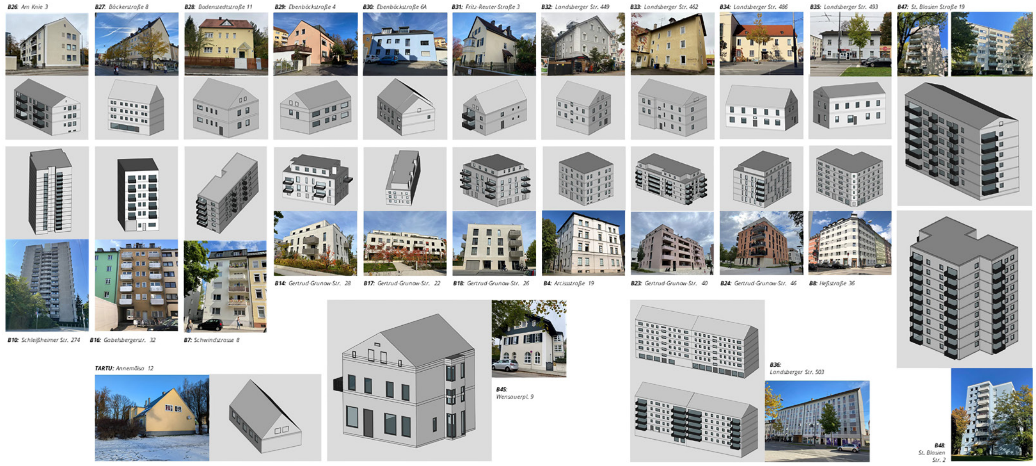


FIG. 19 Some of the building models generated with the tool

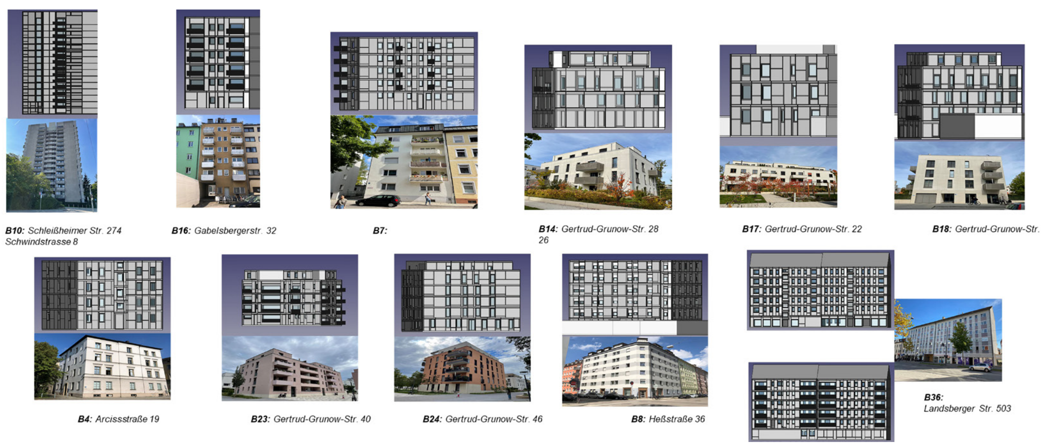


FIG. 20 Prefabricated layout definitions by using the tool

The time reduction in the initial stages is obvious. The techniques developed in this research open the possibility for a competitive building renovation with prefabricated modules compared to current manual means. The main objective of the tool was to reduce time, especially in the early stages of the project when the client does not necessarily have the economic means to finance a building model. With the tools explained in this paper, a complex building like the demonstration building in Milan can be generated in less than 20 minutes or 0.33 hours. The demo building in Milan has approximately 3000 m^2 of building envelope. According to the data given in section 2, by manual means, the whole data acquisition and detailed building modelling should, in theory, take about 450 hours (0.15*3000). This data is high because it implies the necessary and accurate data for manufacturing the prefabricated modules. Therefore, it is not comparable to the time results of the tool described in this paper. On the other hand, defining the prefabricated layout manually can take up to 1020 hours (0.34*3000). With the tools described in this paper, it can take about 25 minutes, although with less accuracy but still sufficient for the early decision-making process.

Therefore, in order to compare the whole data flow, the next stages of the research project will monitor the whole process in a demonstration building. However, it remains difficult to compare the time spent in previous stages because there is no benchmark for such tasks.

5 CONCLUSIONS

The generation of BIM-based digital models of existing buildings has a big potential, and the investment done can easily be recovered during the operation phase due to more efficient and data-driven processes (facility management, digital twins, etc.). Emerging frameworks such as Digital Building Logbooks could boost all the potential of BIM models. However, building owners are frequently reluctant to incur such costs when the decision about renovating has not yet been taken, or its future savings and payback are still unclear.

The obtained building model can be used for an early phase where the client/building owner and other stakeholders can decide whether it is feasible or not to carry out the façade upgrading process. The working time has been reduced to a minimum, and therefore, the engineering work that is needed to guide the decision-making is almost eliminated. This facilitates a more agile process. Thus, the market demands low-cost and easy-to-use tools to orient owners in the early decision-making process, where only go/no-go decisions are needed with some comparative estimation of renovation alternatives. The work presented demonstrates that these decisions can be taken using simplified BIM models that can be generated with high levels of automation and using existing open data sources, some of them freely accessible, complemented with algorithmically created renovation layout alternatives. Once the building owner or the client approves the initial budget given and, thus, unlocks a budget for expending economic resources, travelling to make an on-site measurement of the building becomes possible. This will greatly increase the level of detail and definition of the model, reaching the necessary accuracy that the manufacturing and installation processes demand.

Furthermore, since the output is the open source IFC format, it can be further used for energy simulation, web visualisation or export to dedicated BIM software for detailed design and fabrication once the decision for renovation is taken. This approach enables the possibility to consider alternative data sources to generate the building's digital representation, depending on the different data availability, and it also provides a solution that does not require any expertise level in building modelling.

One key aspect of ensuring workflow integration and its future extensions has been the definition of an exchange JSON file, together with JSON-2-IFC synchronisation mechanisms. Thus, it enables quick adoption and implementation by software developers. Another key aspect for its future success is to import/export information from open sources and based on open formats, e.g., GML or geoJSON for cadastral data or gbXML for energy modelling tools.

This paper also shows the path for a future opportunity to apply machine learning on big data sets of images to detect windows and balconies and to match with BIM models or the application of generative design techniques (i.e., for the automatic proposal and optimisation of façade panels). The recent boom in AI techniques (deep learning for image segmentation, natural language processing, generative design, etc.) showcases the interest in the research community and the potential of the technology.

A final aspect to consider is that the availability and quality of freely available data is rapidly increasing, mainly due to the rise in awareness of data providers (e.g., public administrations) to share data with the public. For instance, although the work presented can work on OpenStreetMap data, it can also process local and regional cadastres, which at the moment of writing are only available as web services for a few EU countries and regions, but its support (e.g., by means of

INSPIRE directives) is growing. It is expected that coverage for all EU countries will be possible at some point. These sources provide more reliable and curated data.

In parallel, there is also a rapid increase in the number of publicly available datasets of various types (building façade images, aerial imagery, material and building typology datasets, energy certificates, etc.), which can be used for machine learning and data fusion with BIM models to recreate not only the geometry but its material and performance properties.

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