Urban Retrofitting: A Progressive Framework to Model the Existing Building Stock

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Abstract. Renovating the existing building stock is one of the key tools for reaching the EU 2020 and 2030 energy goals. The effectiveness of building retrofitting can be increased significantly through mass renovation of the building stock. However, the realization of such approach is very difficult due to complexity in the decision making process and lack of high-quality data needed for conducting a meaningful energy simulation. This paper presents a novel progressive building energy modelling framework coupled with BIM level of development to support the utilization of BIM and building energy simulation in retrofitting the existing stock. We use a pilot case study in Finland to apply and demonstrate this progressive framework. The developed framework provides the planners with a systematic and structured guidance for the creation of the BIM and the energy simulation model of the existing building stock in early and advanced design phases. The framework enables the users to predict the energy performance of the building stock with a fair accuracy. It also helps the design team to find and implement the most suitable retrofitting measures for it.

1. Introduction

The majority of buildings in Europe were built when energy efficiency requirements were limited or non-existent. Renovating these old buildings is one of the main EU policy tools to reach the 2020 and 2030 goals energy efficiency and greenhouse gas reduction goals[1]. Despite the availability of technologies, policies and funds, the renovation rate of the existing building stock in the EU is still well below the EU target of 3% per year [2]. The effectiveness of building retrofitting can be increased significantly through mass renovation of the building stock. The mass renovation enables the planners to exploit energy synergies between the existing buildings, utilize district energy systems and take advantage of the economics of scale. An example of this approach has been documented by the SWIVT project, which demonstrated that a district energy system and mass renovation approach can yield an improvement of 30% in the primary energy balance in comparison to a standard single building renovation [3].

In practice, however, it is hard to realize a mass retrofitting due to the complexity of the decision making process, the high number of stakeholders involved and the absence of sufficient information about the existing buildings stock [4, 5]. The use of Building Information Modelling (BIM) in conjunction with dynamic energy simulation can help overcome these challenges, As BIM “offers the best solution for data management and flow throughout a retrofit project from the survey to the building site”[6].
Within the EU funded project NewTREND “New integrated methodology and Tools for Retrofit design towards a next generation of ENergy efficient and sustainable buildings and Districts” a progressive building energy modelling framework coupled with BIM level of development was developed to support the utilization of BIM and building energy simulation for retrofitting projects. The framework enables a multidisciplinary team of planners to generate a fairly accurate representation of the energy performance of a single building or multiple buildings with reduced effort.

The framework offers the planner the possibility to progress between three modelling modes, which we named Basic, Advanced and Premium to distinguish between them, as per the data availability and the energy simulation scope. In each mode, the framework guides the planner in a systematic manner through the process of data collection, as the framework identifies for each mode the minimum required data the planning team needs to collect. This progressive nature saves the planning team a valuable amount of time and resources in the data collection process. Furthermore, due to the progressive nature of the framework, the planners can utilize the framework in parallel with the project development.

2. The Progressive Simulation Framework Data Requirements

Usually an energy simulation is conducted for a newly planned building at an advanced stage of the project in order to verify the building design compliance with certain targets or codes [7, 8]. When dealing with retrofitting projects, understanding the current energy performance of the building and its potential after retrofitting is an important step in the early decision making process of the project. To conduct such a simulation, the building planners need to go through an intensive data collection process which can be facilitated when done in conjunction with creation of a BIM model for the project.

The progressive simulation framework presented here aims at reducing the redundancy, time and effort in collecting the required data by sub-dividing the data collection phase into three modes of operation (Basic, Advanced and Premium). Each mode is different in terms of the type and the extensivity of the data required. This division of the data complexity, in turn, has a direct influence on the quantity and quality of the outputs each mode delivers. The decision makers can select which of the three modes to use (Basic or Advanced or Premium) depending on the aim of the simulation and the available resources. Table 1 provides an overview on the type of information, the simulation scope and the most suitable project phase at which each mode could be better applied.

In Basic mode, the building geometry is to fulfil the requirements of a CityGML LOD2 [9] and other related building information has to be equal a BIM model of AIA LOD200[10]. However, as CityGML LOD2 [9] doesn’t include information on openings, opening areas are added to the model as an approximation of their percentage area per exterior wall area. Non-geometry related data such as technical systems, structure, thermal and physical specification can be derived from the regulations and building statistics. This can be done based on the building use and the year of construction or the last known year of renovation. Given the limited amount of information required by the mode it is best suited to create a rough estimation of the energy performance of the project, usually done in the early design phase of the project. It can be also used to decide if a project should be implemented at all based on its feasibility for retrofitting. The accuracy of the results of the Basic mode can be increased significantly with the use of sensitivity analysis as we will in chapter 4.

In comparison to the Basic mode, the Advanced mode is more demanding in terms of data requirements as it offers a wider range of simulation outputs with a greater accuracy. In the Advanced
mode, the building geometry has to meet the requirements of CityGML LOD4 [9] and the building information reliability is to be equal to a LOD300 BIM model [10]. Non-geometry data such as technical systems efficiencies, structural, thermal and physical properties, and occupant behaviour can be obtained from on-site measurements, site visits and questionnaires. In the Advanced mode the use of statistical data can only be tolerated in case the results of the sensitivity analysis revealed that such data have little or no influence on the results. Hence, the Advanced mode is best suited for a design development phase of the project to create a more accurate estimation of the energy use as well as to find the most suitable retrofitting strategy for the project. Nonetheless, if such information is readily available, the design team is advised to start with the Advanced mode and use the Basic mode to model other neighbouring buildings that might influence the use of a district energy system.

In the Premium mode, the building geometry requirements are similar to those of the Advanced mode, but the related building information reliability has to be equal to AIA’s BIM LOD500 [10]. This means that the information has to be verified on the site. Other non-geometry related data need to be derived from real time measured data.

The design team is free to choose which one of the three modes is best suited for their needs. In practice however, the Premium mode might be best suited for an in-use phase after the completion of the retrofitting. In this way the obtain results complement the facility management aspects, such as the documentation and the optimization of the technical system as it requires real-time measurements and the actual data from the building drawings.

Table 1: Overview of the Progressive Simulation Framework Modes

|                              | Basic                                           | Advanced                                      | Premium                        |
|------------------------------|-------------------------------------------------|-----------------------------------------------|--------------------------------|
| Geometry model               | CityGML LoD 2 or higher (opening areas approximated) | CityGML LoD 4                               | CityGML LoD 4                  |
| Extensivity of the model information | BIM LOD200 (AIA specification) or higher | BIM LOD300 (AIA specification) or higher | BIM LOD500 (AIA specification) |
| Main semantic information source | Default values from regulations and statistics | Working drawings, reports, user and owner questionnaires | Real time measured values       |
| Analysis scope/objectives    | Estimate the energy performance of one or more buildings before retrofitting | Estimate the building energy performance and occupant comfort before or after retrofitting | Assess the actual energy performance and occupant comfort after retrofitting |
| Most suitable Phase of application | Early design phase | Design development | In use                        |

3. The Progressive Simulation Framework Process Flow

Given the wide range of possible use cases of the progressive simulation framework, the following process flow is provided in order to guide the planners through the selection of the most suitable retrofitting option of the project in the early design phases. Hence, the applications of the framework in other phases such as design development and construction are not described here. Moreover, the Premium mode is excluded from this flow chart as it is recommended for the in-use phase of the project. The following section explains in detail the simulation process for the Basic and Advanced modes.
3.1. The process flow in Basic mode
In Basic mode the process flow is divided into three operation steps and corresponding decision steps (D1, D2 and D3) see (Figure 1). The goal of the first step “Identification” is to identify the building or a group of buildings that are most suitable for retrofitting based on their energy performance, life cycle cost and synergies potential. Thus, the process in the first step starts with creating Basic level BIM models of all the district buildings. Hence, at this stage the internal layout is not needed, the creation of the LOD 200 BIM [10] models is relatively fast with the help of an online mapping service, such as Google Maps or OpenStreetMaps and the openings areas are added to the model as an approximation based on their share of each outer wall. Once the Basic mode BIM model is ready, it can be populated with other energy related parameters such as the building HVAC system, usage hours and the envelope thermal properties. The input parameters can be taken from regulations and building stock statistics and specified based on the building type, construction year and last year of renovation in case no other information sources is available. After adding all required input parameters the project team can make the first simulation run to identify the buildings that are most suitable for retrofitting based on their energy performance estimation.

This step is followed by the decision step “D1 Data check” in which the project team is to decide if the available information is sufficient in terms of quality and quantity to create a number of retrofitting alternatives or not. In case it is not sufficient, the project team is to conduct a sensitivity analysis. The results of the sensitivity analysis will rank the most important input variables that generate the variation in the output[11]. Thus, the sensitivity analysis would indicate to the project team for which parameters they need to gather more accurate information. This process is followed by a decision step “D2” in which the project team needs to decide if the BIM model is to be updated based on the newly gathered information and if a new simulation run is required.

In the third step “Creation of retrofitting alternatives” the project team is to create a number of retrofitting alternatives i.e., changing the HVAC system, adding an insulation layer, etc. and to assess the applicability of each retrofitting variant based on the life cycle cost analysis (LCC) and the overall energy performance of the created variant. At this stage the project team needs to decide (D3) whether the retrofitting is feasible or not. In case the retrofitting seems to be feasible the project team is to proceed to the more detailed Advanced mode in order to create and select the best retrofitting alternative for the project.

3.2. The process flow in Advanced mode
Since the feasibility of the project is established, the goal here is to guide the users into finding the most suitable retrofitting alternative. This goal can be accomplished within the series of operations done in the 4th step “Advanced mode”. Firstly, the project team is to create a BIM model that satisfies the Advanced mode requirements, hence more detailed information about the building and its internal layout is to be gathered. This newly added information would require that the initial BIM model and the energy simulation results are updated based on the new information.

In the following stage, the project team is to conduct a sensitivity analysis in order to find the most suitable retrofitting alternative. The operations of the sensitivity analysis in this step are similar to those done in the second step. However, and in comparison to the ranking made in the 2nd step, the ranking of the sensitivity analysis in advanced mode would depend on those input variables that have the highest impact on the project retrofitting objective (i.e. reducing energy consumption, Return on investment (ROI), etc). Thus, the obtained results of the sensitivity analysis will guide the project team into developing the best combination of retrofitting measures that fulfil the project objectives.
Figure 1: The Process Flow of the Progressive Simulation Framework
4. Piloting the Progressive Simulation Framework Process Flow

The progressive simulation framework is piloted on the Alppila high school (Alppilan lukio) complex located in Helsinki, Finland. The school complex was built in 1957 and consists of four main sections with an interior courtyard in the middle. The school is attended by approximately 750 students. Most of the buildings’ spaces are supplied with the exhaust ventilation. Several spaces (kitchen, gymnasium and ball room) have the mechanical ventilation, but without a heat recovery unit. The school complex is connected to Helsinki’s district heating network. The objective of the retrofitting is to reduce the current primary energy demand of 187 kWh/m².a below the 130 kWh/m².a. mark in order to comply with the Finnish energy regulations for educational buildings [12].

4.1. Creation of the BIM Model

As the building to be retrofitted is pre-determined, only the process for creating and populating the BIM model are performed. For the creation of the initial geometry model of the buildings as per Basic mode requirements (i.e. CityGML LoD 2 [9]) we used Google Maps and SketchUp. The geometry model is then imported into MagiCAD, to create a BIM LOD200 [10] IFC file with the information about the number of floors and approximate areas of the four main sections that make up the school and the openings. The IFC model is then imported into the DOE-2.1E based simulation software RIUSKA to populate it with the necessary information to run the energy simulation. At this stage no information about the building thermal properties, HVAC systems existed, therefore, we used building values of a typical finish school found in the regulation and building statistics. (See [13, 14]). The first simulation run showed a heating energy demand of 212 kWh/m².a and an electrical energy demand of 43 kWh/m².a.

Table 2: Overview of the Simulation Input Parameters for The First Step

| Parameter       | Unit   | Value | Parameter       | Unit   | Value |
|-----------------|--------|-------|-----------------|--------|-------|
| Exterior wall   | W/m²K  | 0.81  | Infiltration    | 1/h    | 6     |
| Floor           | W/m²K  | 0.43  | ventilation schedule | h | 7 – 16 (closed during vacations) |
| Roof            | W/m²K  | 0.47  | Specific Fan Power | kW/m³/s | 1.5 |
| Windows         | W/m²K  | 2.8   | schedules for loads | h | 8 – 16 (closed during vacations) |
| Doors           | W/m²K  | 2.2   | Utilization rate | %     | 75% (of the building floor area) |
| Lighting        | W/m²   | 18    | DHW             | W/m²   | 11    |
| Equipment       | W/m²   | 8     | Window are per wall | % | 20 |
| Num. People     | Pers./m² | 0.19 | Water temp. heating | °C | 55 |
| Airflow         | l/m²/s | 2.0   | Heating efficiency | % | 0.8 |
4.2. Data Check, Sensitivity Analysis and Updating the Model
Since all used data in the first step were either approximated or inferred from regulations a sensitivity analysis was necessary to identify the input parameters that have the greatest impact on the simulation results. Thus, more accurate information about them is needed. Over 1000 simulations were performed and the sensitivity analysis showed that the airflow rate, followed by the lighting load, the floor U-value and the heating system distribution efficiency have the highest impact on the energy consumption figures. The equipment load, infiltration value, external wall U-value and the window per floor space ratio showed moderate impact. The roof U-value and the specific fan power showed small influence on the energy consumption. Hence, it was decided that at this stage no further investigation is needed for the values that showed low impact.

For the parameters that showed a high to moderate impact on the energy performance more accurate data were collected either through examining the building documentation or through an on-site data collection. As a result, the BIM model has been updated with new input parameters (Table 3). Based on the new input parameters a second simulation run was done. The results showed a heating energy demand of 177 kWh/m².a. and an electrical energy demand of 38.6 kWh/m².a. These figures were marginally higher than measured heating and electricity energy demand of 159 kWh/m².a. and 37 kWh/m².a. respectively. Therefore, the simulation results were considered reliable enough to assess the feasibility of retrofitting.

Table 3: Overview of the updated input parameters

| Parameter             | Unit  | Value | Parameter          | Unit  | Value |
|-----------------------|-------|-------|--------------------|-------|-------|
| Exterior wall         | W/m²K | 0.54  | Heating efficiency | %     | 0.9   |
| Floor                 | W/m²K | 0.57  | Lighting           | W/m²  | 15    |
| Equipment             | W/m²  | 6     | Airflow            | 1/m²/s| 1.5   |
| Infiltration          | 1/h   | 6     | Window are per wall%| 15    |       |

4.3. Creation of Retrofitting Alternatives
The goal of this step is to create a number of retrofitting alternatives that meet the project objective of lowering the primary energy demand below the 130 kWh/m².a. mark. The following range of technically feasible input parameters were used for the creation of the retrofitting alternatives.

Table 4: Variables Used in the Retrofitting

| Parameter | Unit   | Range         | Construction                                      |
|-----------|--------|---------------|---------------------------------------------------|
| Exterior wall | W/m²K  | 0.33 - 012    | Base wall + Mineral wool (10 – 30 cm)             |
| Floor     | W/m²K  | 0.49-0.13     | Base floor + Mineral wool (5 – 25 cm)             |
| Roof      | W/m²K  | 0.41-0.13     | Base roof + Mineral wool (5 – 25 cm)              |
| Window    | W/m²   | 1 – 0.85      | Triple glazed                                     |
| Infiltration | 1/h    | 3             | As a result of new windows                        |

4.4. Feasibility Check
In order to conduct the feasibility assessment, more than 200 simulations of all possible combinations of the retrofiring measures proposed in the previous step were done. After discarding the results that showed a primary energy demand above the targeted 130 kWh/m².a., 126 possible combinations were left for the LCC analysis. The energy consumption costs were calculated based on the typical district heating and electricity prices for the city of Helsinki. Furthermore, the costs of demolishing, acquiring and the installation of the new isolation and windows are all taken to account. For the LCC analysis
the energy prices were adjusted to inflation and the cumulative costs of the building were investigated for a period of 25 years. The LCC results showed that there were 10 possible retrofitting alternatives that have a payback period of less than 12 years. Therefore, the retrofitting of the project is considered to be feasible and the project shall move to a higher level of detail and analysis to develop and choose the most suitable retrofitting measures out of the 10 possible alternatives.

4.5. Advanced Mode and Creation of Most Suitable Retrofitting Alternative
More recent and updated building technical documents and drawings were collected for the creation and population of the Advanced mode of the BIM model. Here the external walls, the positions and areas of windows and doors as well as the inner spaces layout were accurately modelled. The closer investigation of the building documents revealed that not all the exterior walls have the same construction and that the domestic hot water energy demand is almost half of what was estimated in Basic mode. Furthermore, it was noticed that the ventilation rate, the electrical loads and occupancy schedules of some zones such as the ballroom, the kitchen, the dining hall and the gymnasium are not matching the assumptions made in the Basic mode and needed to be corrected.

As a result the input parameters were updated and energy simulations were iteratively calculated to reach a model with the energy demand values close to the ones acquired from utility bills. The same procedure described in 4.3 was performed in relation to the selection, creation and assessment of the retrofitting alternatives. Similar to the case observed in the Basic mode, 10 retrofitting alternatives have shown a payback period of less than 12 years, thus the next step was to choose the most appropriate combination of retrofitting measures for the project.

| Consumption | Unit | Measured | Basic mode | Optimized Basic mode | Advanced mode |
|-------------|------|----------|------------|----------------------|---------------|
| Heating     | kWh/m².a | 159      | 212        | 177                  | 169           |
| Electricity | kWh/m².a | 37       | 43         | 38.6                 | 38.9          |

4.6. Selection and Development of the Most Suitable Retrofitting Measure
The final decision on the most suitable retrofitting alternative to be implemented in the project is a complex task that involves multiple stakeholders and would usually involve other factors than the LCC analysis results of the retrofitting variants. However, for the sake of simplification, we based our decision on the LCC results in order to give an example of how the progressive framework can be used in guiding the decision making process. As previously mentioned, about 10 retrofitting alternatives have showed a payback period of less than 12 years. The following combination of retrofitting measures has showed the lowest initial investment cost (34.6 €/m²) and shortest payback period (11 years).
Table 6: Variables of the most suitable retrofitting option

| Parameter   | Unit       | Value | Construction                      |
|-------------|------------|-------|-----------------------------------|
| Exterior wall | W/m²K      | 0.33  | Base wall + 10cm Mineral wool      |
| Floor       | W/m²K      | 0.3   | Base floor + 10cm Mineral wool     |
| Roof        | W/m²K      | 0.19  | Base roof + 15 cm Mineral wool     |
| Window      | W/m²      | 1     | Triple glazed                      |
| Infiltration | 1/h        | 3     | As a result of new windows         |

5. Conclusions and Discussion

In this paper a progressive building energy modelling framework coupled with BIM level of development for predicting the energy performance of the existing building stock has been described and piloted at the real case study in Finland.

The developed framework provides the planners with a systematic and structured process framework for the creation of the BIM model of the existing building stock throughout the building project phases. The framework is based on three progressive modes: Basic, Advanced and Premium. The accuracy and depth of the output of each mode differs as per the nature and extensivity of the input data.

In this paper the framework for applying both Basic and Advanced mode has been presented and tested on a real case study. The results of conducting an energy simulation using Basic mode requirements have demonstrated that good simulation results can be obtained by using a simplified 3D building model with targeted input parameters. Thus, the use of the Basic mode permits us to predict the energy consumption of the existing building stock with a fair accuracy and minimal effort. The accuracy of the results can be vastly improved by using a sensitivity analysis to collect more accurate data on high impact input parameters. These findings are in line with those of other researchers who have applied a similar approach [15, 16]. The relative high accuracy of the simple model used in the Basic mode can be attributed to the very good documentation of the existing building stock in Finland, the high degree of compliance with the building regulations in construction and that fact that the case study was a school building, which made it relatively easy for us to predict accurately the occupant behaviour and operation times.

The use of more detailed and accurate data in the Advanced mode has proven to be essential for finding the most suitable retrofitting solution because a fair number of the assumed parameters used in the Basic mode required amendment in the Advanced mode. Thus, the Basic mode results should not be used for making decisions on the type of retrofit, but rather as a guideline for estimating the feasibility of retrofitting a building or a group of building as suggested in the framework.

The results of this work have demonstrated clearly the importance of having a well maintained and updated digital 3D representation of the buildings in a city as well as an updated and detailed database for the typical national construction and HVAC systems used in the exiting building stock. Our case study showed that with the help of those two elements we were able to create a fairly simple but very accurate energy model. The widespread use of BIM models in future would facilitate the having a more accurate representation of the buildings and can therefore accelerate their retrofitting rate. Finally, it is important to test and validate the applications of the framework further on a larger number of buildings with different usage profiles and under different climatic conditions.
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