Residential building retrofit through numerical simulation: a case study

Ermanno Lo Cascioa  
*University of Genova*

Zhenjun Ma  
*University of Wollongong*, zhenjun@uow.edu.au

Davide Borelli  
*University of Genova*

Corrado Schenone  
*University of Genova*

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Residential building retrofit through numerical simulation: a case study

Ermanno Lo Cascio\textsuperscript{a,}\textsuperscript{*}, Zhenjun Ma\textsuperscript{b}, Davide Borelli\textsuperscript{a}, Corrado Schenone\textsuperscript{a}

\textsuperscript{a}DIME – Department of Mechanical Engineering, Energy, Management and Transports, University of Genova, Via All’Opera Pia 15/A, 16145, Genova, Italy
\textsuperscript{b}Sustainable Buildings Research Centre (SBRC), Faculty of Engineering and Information Sciences, University of Wollongong, New South Wales, 2522, Australia

Abstract

This paper presents an energy conservation measures prioritization process of a residential Australian building. For this purpose, a simulation model of the building has been implemented and validated based on the information from the energy audit report. Further, a preliminary set of potential energy conservation measures has been identified according to specific information collected during the building survey phase. DesignBuilder software has been used as the simulation tool and yearly energy benefits have been quantified for each intervention. Finally, an economic assessment is conducted based on the most common economic tools (net present value, internal rate of return, profitability index and discounted payback period). As a consequence, a final building performance simulation has been conducted in order to properly quantify the potential energy benefit of the whole retrofit intervention. As results, this study highlights how arduous could be, in certain cases, to achieve a cost-effective retrofit intervention and how economic indexes could bring users to exclude a priori certain energy conservation measures during decision-making process even when these interventions are necessary to improve thermal comfort and energy efficiency.

Keywords: Energy Conservation Measures; Building Simulation; Building Retrofit; Dynamic Model; Economic Assessment

* Corresponding author. Tel.: +390103532574.
E-mail address: ermanno.locascio@edu.unige.it
1. Introduction

Retrofitting of existing buildings offers a great opportunity for energy savings and greenhouse gas emissions reduction [1–3]. Over the last two decades, many efforts have been made on the development of decision support systems and methodologies for appropriate building retrofits. For instance, Tupper et al. [4] employed nine key steps for retrofitting an existing building. A systematic approach to proper selection and identification of the optimal retrofit options for existing buildings was presented by Ma et al. [5], in which overall building retrofit process was divided into five phases, including project setup and pre-retrofit survey, energy auditing and performance assessment, identification of retrofit options, site implementation and commissioning, and validation and verification.

For an effective building retrofit project, appropriate numerical simulations and economic analysis with an acceptable degree of uncertainty are essential in order to identify and determine the best retrofit strategies among a wide range of candidate options. A multi-objective optimization model was developed by Asadi et al. [6] for quantitatively evaluating the performance of different retrofit options in a building retrofit project. Pappas et al. [7] highlighted that developing a streamlined and cost-effective energy modeling process is critical for existing building energy retrofits. Ascione et al. [8] proposed a multi-criteria approach for the energy refurbishment of a historical building. Rysanek et al [9] presented a case study of a mid-size office building constructed in the early 1960s in Cambridge with minimal renovations. It can be a useful example since almost eighty percent of buildings in the UK have the same conditions. Westphal et al [10] proposed a satisfactory case study of energy performance modeling. This work proposed a methodology based on sensitive analysis for the calibration process of the numerical model. It took six iterations before the model could be considered properly calibrated. Pedrini et al [11] proposed a methodology for building calibration and modeling in warm climates. This methodology was based on three main stages with determinate tasks to be accomplished to achieve a reliable model calibration. The simulation accuracy is increased at each simulation step ranging respectively from 19.1 percent to 9.2 percent with respect to the real consumption data. Chidiac et al. [12] propose an interesting study which highlight the effectiveness of multiple retrofits upon their interaction.

Economic analysis is another important issue that should be considered when prioritizing and ranking the candidate retrofit options. There are many tools such as Net Present Value (NPV), Internal Rate of Return (IRR), Overall Rate of Return (ORR), Benefit-Cost Ratio (BCR), Discounted Payback Period (DPP), and Life Cycle Cost Method [5], can be used to evaluate the economic feasibility of potential retrofit options. Rysanek et al. [9] illustrated an alternative methodology to achieve the optimum building energy retrofits under technical and economic uncertainty based on the classical decision theories to perform a non-probabilistic optimization. Kumbarouglu et al. [13] used a public administration building constructed in 1900 in Germany as a case study for developing an economic analysis methodology. TOBUS software was used for this work. In this study, the uncertainty of energy price was estimated with Monte Carlo simulation. The results of this case study showed how energy price volatility creates a substantial value of waiting, making more rational to postpone the investment. NIST Handbook 1353 [14] offered a satisfactory discussion about the sensitivity analysis and Pappas et al. [7] used this methodology in their study. Sensitivity analysis is the study of how the uncertainty in the outputs of a mathematical model or system (numerical or otherwise) can be influenced by different sources of uncertainty in its inputs [14]. Energy service companies may represent a great opportunity for energy savings but, unfortunately, the potential order of magnitude of the energy/money saving of a single multi-floor building may not be financially sustainable for these companies in the most cases. Moreover, there are many problems and barriers related to the Energy Performance Contracting (EPC). Yang et al [15] established a Decision-Making Model of Energy Service Company operating period based on the Game Theory. Smit et al [16] illustrated the use of real options valuation and game theory principles to analyze the prototypical investment opportunities involving important competitive/strategic decisions under uncertainty.

This paper presents a case study of identification and determination of potential retrofit options for an Australian student accommodation. A systematic approach is followed to determine the optimal retrofit options using DesignBuilder simulation. An economic assessment has been conducted to assisting in properly identifying the most cost-effective retrofit options.
2. Methodology

The overall methodology used for building retrofits is illustrated in Fig. 1, which follows a sequence of the steps. The first phase is to carry out an energy audit and select key performance indicators as well as evaluate building operational performance. The second phase of this study has been conducted with the support of DesignBuilder, a simulation tool which allows users to simulate the building energy performance under various scenarios. In this phase, the geometry model was created with the certain simplifications, boundary conditions and schedules defined, and calibrated using the data available in the energy audit report. Once the model was properly calibrated, it is then possible to proceed to the next phase to estimate the yearly energy benefits of each retrofit intervention considered. More precisely the primary energy benefits were calculated as the difference in terms of kWh/year between pre and post intervention while the boundary condition has been kept the same at each simulation except those values relative to the retrofit option considered. Once the potential annual primary energy saving of each simulated retrofit option is determined, an economic analysis is then carried out in order to prioritize and rank the retrofit options considered. Finally, it is necessary to simulate the set of retrofits that has been identified to further estimate the potential primary energy benefits to be achieved. A final economic simulation is also required.

3. Case study

The case study examined is a 7000 m² student accommodation at the University of Wollongong, Australia. The case building has five interconnected blocks along an east-west axis, with rooms facing either north or south. The building can accommodate maximum 180 people in 42 apartments. The building is located at 34.40° south and 150.89° east at 5 meters above sea level, and Australian climate zone 5. The highest recorded temperature in this region was 44.1°C in January 2006 and the lowest one was 0.8°C in July 2008. The building was completed in 2006 with further refurbishment. The detailed energy audit has been conducted by a consultant.

3.1. Model setup and validation

The building model (Fig. 2) has been developed based on a set of simplifications. Table 1 summaries the main building envelope characteristics used in the building simulation. The student accommodation is surrounded by some trees which provide a certain level of shading, which was not considered in the model simulation. For this study, 9 iterations have been conducted before the model could be considered as properly calibrated. The validation results are shown in Fig. 3. It can be seen that the simulation results generally matched well with the data provided in the energy audit report. Due to the building function, the most challenging part of the validation process for this
case study was related to the user behavior modeling. For this purpose, several schedules have been created to properly emulate user habits.

![Fig. 2. DesignBuilder model](image)

<table>
<thead>
<tr>
<th>Building data</th>
<th>Value</th>
<th>Main zones type</th>
<th>Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building number of zones</td>
<td>434</td>
<td>Corridors</td>
<td>1026</td>
</tr>
<tr>
<td>Building heated floor area (m²)</td>
<td>2970</td>
<td>Bedrooms</td>
<td>2074</td>
</tr>
<tr>
<td>Building volume (m³)</td>
<td>9060</td>
<td>Living rooms</td>
<td>1215</td>
</tr>
<tr>
<td>Building area-weighted average U-value (W/m²K)</td>
<td>3.2</td>
<td>Other</td>
<td>4315</td>
</tr>
</tbody>
</table>
3.2. Energy conservation measures

The pre-selection process has been driven by different specific considerations. More precisely, about 65 percent of the total electricity consumption is related to interior equipment i.e. personal appliances. Then, it would be quite difficult to identify a proper Energy Conservation Measure (ECM) for this part since the relative electricity consumption is strictly related to student personal needs and habits. On the other hand, the primary energy demand for the lighting covers about 13 percent of the total amount. In this case, a proper ECM with LED lights can be considered. After the implementation of this ECM, the current lumen rate would be kept the same with no alteration about the current indoor lighting levels. This retrofit practically consists in substituting almost 570 fluorescent lamps with LEDs lamps. The cost for this intervention has been estimated to be around 22 thousand dollars considering an average price of 39 $ per fixture. The average nominal power reduction would be about one-third of the actual T8 fluorescent tube.

Further, heating is controlled by the thermostat, staying on for a maximum of 3 hours and automatically switching off when the air temperature reaches a certain threshold which has been set around 23°C in the simulation. Then, the possibility to replace the current 400 W electric panels with a more efficient system has been excluded since the system is still reliable and the substitution would involve consistent initial investment which would surely overpass the budget availability with a modest final result in terms of energy savings. At this stage, in order to reduce the electricity consumed for the heating it would be necessary to intervene on the envelope characteristics rather than the HVAC system. It has to be considered the most appropriate strategy since the building air permeability is too high (approximately about 7 air change per hour at 50 Pa difference) and the average U-value (3.2 W/m²K) of the building are quite poor as compared with modern building standards which make it difficult to heat spaces. As a consequence, as possible ECMs, it would be interesting to analyze the possibility to reduce the air leakage, increase roof insulation and increase the glazing performance. To avoid thermal bypass and mitigate the risk of interstitial condensation, retrofit techniques might include the use of taped membranes or sheet materials, proprietary grommets and seals around service penetrations. For this case study, air leakage paths were in several typical areas: in partitions via door furniture, switches, sockets and directly through the external envelope via window frames and the patio doors. To properly simulate this ECM it has been considered that after this intervention the expected average air leakage reduction will be 41.17 percent lower with respect of the current state. The cost for this upgrade has been estimated to be around 15 thousand dollars. Considering the roof insulation option, it will be necessary to install 13 cm of expanded polystyrene. The roof area has been detected to be 1334 square meters. Considering a reference price of 9.68 $ per square meters for the insulation material easily the cost of this retrofit has been estimated to be around 15 thousand dollars. Finally, concerning the glazing upgrade, it would be replaced with a low emissivity single glaze (e2=2) Clr 6 mm. This retrofit option is actually easier to be implemented since there is no need to substitute the actual single glazing frame with a new one designed for a double glaze. The total glaze surface of the building is approximately about 1000 square meters. The estimated cost for the single glaze retrofit option has been calculated to be around 84 thousand dollars. More potential ECM would
concern the possibility to implement a solar-boosted DHW system in support of the current system made of two 35 kW gas-fired heaters. It would enable an exploitation of a renewable energy source decreasing consistently the current carbon emissions. The retrofit intervention would consist in the implementation of 45 square meter solar collectors. Each of them is made of 14 vacuum double glaze tubes. The panel details are shown in Table 2. The initial investment for this ECM has been estimated to be about 30 thousand dollars. Fig. 4 shows the cover factor calculated for the solar collectors taken into consideration while Table 3 shows an overview of the ECMs potential energy benefits.

Table 2. Solar collector characteristics.

<table>
<thead>
<tr>
<th>Panels</th>
<th>$a_1$ (W/m²K)</th>
<th>$a_2$ (W/m²K²)</th>
<th>$\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum collector</td>
<td>1.15</td>
<td>0.004</td>
<td>0.676</td>
</tr>
</tbody>
</table>

Table 3. Solar collector characteristics.

<table>
<thead>
<tr>
<th>ECM</th>
<th>Energy Saving (MWh/year)</th>
<th>Energy Saving (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light replacement</td>
<td>25.8</td>
<td>6</td>
</tr>
<tr>
<td>Air leakage reduction</td>
<td>33.8</td>
<td>8</td>
</tr>
<tr>
<td>Roof insulation</td>
<td>9.5</td>
<td>2</td>
</tr>
<tr>
<td>Glazing upgrade</td>
<td>10.1</td>
<td>2</td>
</tr>
<tr>
<td>Solar boosted DHW</td>
<td>87.5</td>
<td>30</td>
</tr>
</tbody>
</table>

4. Economic analysis

4.1. Economic assessment of ECMs

A reasonable primary energy costs to be considered in the economic assessment have been set as following: electricity cost will be 0.13 dollars/kWh for the first year with an expected average annual increase of 7 percent. On the other hand, the average gas price is about 5.5 $/GJ which corresponds to 0.198 dollars per kWh with an expected average annual increase of 8 percent. No incentives eventually deriving from renewable retrofit measures have been taken into consideration. For the economic analysis, an Interest Rate (R) of 5.3 percent and an inflation rate (f) of 2.5 percent per annum were used and a time length of 21 years has been set for this study. Fig. 5 shows the average annual primary energy prices growth considered in the simulation. Obviously it might be very difficult to properly predict these kinds of retail costs especially for such extended time horizon. Then, probably sensible difference
between the estimated costs shown in Figure 5 and real future retail costs will be observed. However, these tools are still very helpful for comparing different ECMs economic performances. The annual energy saving deriving from each ECM considered has been set as constant during the whole simulation period (21 years) for the economic simulation. The equations used for the calculation of the economic indexes are as follows:

\[ NPV = CF \sum_{j=1}^{n} \frac{(1 + f)^j}{(1 + R)^j} - I_0 \]  

\[ PI = \frac{NPV}{I_0} \]

where \( I_0 \) is the initial investment and \( CF \) is the cash flow.

Table 4. Economic assessment overview.

<table>
<thead>
<tr>
<th>ECM</th>
<th>Investment (k$)</th>
<th>NPV (k$)</th>
<th>IRR (%)</th>
<th>PI</th>
<th>DPBP (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light replacement</td>
<td>22.1</td>
<td>16.6</td>
<td>2</td>
<td>0.75</td>
<td>6.4</td>
</tr>
<tr>
<td>Air leakage reduction</td>
<td>15</td>
<td>96</td>
<td>14</td>
<td>6.4</td>
<td>3</td>
</tr>
<tr>
<td>Roof insulation</td>
<td>15.4</td>
<td>-51</td>
<td>-</td>
<td>-3.3</td>
<td>9.2</td>
</tr>
<tr>
<td>Glazing upgrade</td>
<td>10.2</td>
<td>-3.4</td>
<td>-1</td>
<td>-0.3</td>
<td>7.1</td>
</tr>
<tr>
<td>Solar boosted DHW</td>
<td>30.6</td>
<td>-146</td>
<td>-</td>
<td>-4.7</td>
<td>11.2</td>
</tr>
</tbody>
</table>

Referring to Table 4, the investment prices have been calculated based on the reference prices declared on commercial catalogues of each ECM. Apparently just two intervention seems to be economically except for the solar boosted DHW since it has a negative NPV, PI, and IRR. Moreover, it has the longest Discounted Pay Back Period (almost 11.2 years). For this reason, it has been excluded from the prioritization process as a possible measure. Except the solar booster DHW, the glazing and roof insulation retrofit options seem to be not economically sustainable as well but they will be taken into consideration in the further whole energy assessment since profitability indexes have been considered to be in an acceptable range. Moreover, the ECM relative to glazes replacement will be necessary to increase the indoor environmental comfort especially in bedrooms where sensible
temperature gradients have been detected within the room volume after an infrared thermal inspection especially during winter period where temperature difference between the space nearby the window and middle of the room volume were observed. With this consideration, the total investment amount will be about 63 thousand dollars.

4.2. Whole economic assessment of ECMs

Based on the four selected energy conservation measures, a final numerical simulation was conducted in order to properly estimate the potential energy benefit that can be achieved by the implementation of the prioritized ECMs i.e. lighting replacement, roof insulation, glazing upgrade and air leakage reduction.

| Table 5. Whole energy benefits |
|-------------------|-------------------|
| ECM               | Energy Saving (MWh/year) | Energy Saving (%) |
| Whole ECMs        | 58.4               | 14                |

| Table 6. Whole economic assessment |
|-------------------------------|-------------------|-------------------|
| ECM               | Investment (k$) | NPV (k$) | IRR (%) | PI  | DPBP (years) |
| Solar boosted DHW | 63               | 28       | 1       | 0.44 | 6            |

5. Discussion

A practical application of a state-of-art retrofitting methodology [5] has been followed for this case study with certain simplifications and adaptations in the retrofitting process. Results shows how difficult could be to achieve a cost-effective retrofit intervention in terms energy saving and how, in certain cases, economic indexes could bring users to exclude a priori certain energy conservation measures during the decision-making process even when these interventions are necessary to improve thermal comfort of the occupants and energy efficiency. In fact, it's clear how the use of the most common economic indexes, NPV, IRR etc, generally speaking, is fundamental for the decision making process but, while conducting the ECMs economic assessment, necessarily results have to be properly interpreted and contextualized for each case considered. As a consequences, this specific case study, aims to highlights this issue showing how just two of the five selected ECMs seems to be economically sustainable. But, the implementation of just two ECMs would bring to very low energy savings and it doesn't makes really sense considering the purpose of the retrofitting. The most appropriate ECMs configuration instead would involve the implementation of all the retrofit intervention except the solar boosted DHW which payback period has been considered too long (11 years). Then, during the economic assessment phase, it would be important to evaluate both ECMs economic and energy benefits rather than just the economic performance estimated by using those tools. Moreover, this study aims to reinforce the consideration about a fundamental issue previously analyzed by Chidiac et al [12]. This issue refers to the effectiveness of a single retrofit intervention which differs from the case where the same retrofit is considered in conjunction with other retrofit interventions on the same envelope: the total energy saving for a given time length, has not to be considered as the sum the potential energy savings achievable by each single retrofit intervention. That is important to be highlighted since it might easily bring non-expert users to commit calculation errors during the energy saving estimation process thought dynamic simulations. For this study, it has been possible to observe how the whole energy saving deriving from the implementation of all the retrofit options identified has been estimated to be about 58.4 MWh per year. Instead the sum of the potential energy saving of each intervention is about 62.7 MWh per year which means an overestimation of 7.36 percent. This difference would be even more significant for larger buildings of course, depending from boundary condition and envelope characteristics.

Finally, it would important to consider that today research efforts concerning the energy saving in residential and tertiary buildings have been focused on a wide range of energy saving opportunities which mostly refers to technical, engineering, economic and financial issues. Of course, it is fundamental to understand where and how it is
possible to achieve an efficient exploitation of primary energy by using proper technologies, methodologies and approach trying to find sustainable financial models to make hazardous interventions possible. But surely there is another "side of the medal" in the energy issue which is related to users’ behavior in buildings and their psychology. Generally speaking, considering the technical and economic efforts needed to achieve consistent energy savings specially in residential building sector, it might be interesting to focus on this key point of the energy consumption in building, investigating about which are the most effective KPIs or psychological approaches that increase users’ energy awareness bringing them to avoid energy waste. Further it would be fundamental do identify a proper "consciousness strategy" that may involve different opportunities and actors which varies, for instance, from energy monitoring and online feedback at residential level and media effective energy campaign strategy definition. Finally, in certain cases, it might be possible to achieve consistent energy savings just by correcting certain typical wrong users’ habits especially in residential sector where building energy management systems are not so used.

6. Conclusions

A 7000 square meters residential Australian building retrofit prioritization process has been presented following the state-of-art building retrofit methodologies with the objective to highlight common practical issues in retrofitting decision process. For this purpose, a simulation model of the building has been implemented and validated based on the information provided in the energy audit report. The calibration process required nine iterations for this study. Further, a preliminary set of potential energy conservation measures has been defined which include the possibility to replace the current lighting system with a LED system, reduce the building air leakage, insulate the roof to reduce thermal losses during cold seasons, reduce the U-Value of the openings by implementing low emissivity glazes and finally implement solar collector to support the domestic hot water production. Finally, an economic assessment has been conducted and just two retrofit options seemed to be economically sustainable by using the most common analysis tools: net present value, internal rate of return, profitability index and discounted payback period. Further a final building performance simulation has been conducted in order to properly quantify the potential energy benefits of the whole retrofit intervention excluding the solar booster DHW intervention since it does not present promising economic performances. The whole energy consumption for this building is about 426.5 MWh per year of electricity and 291.4 MWh per year of natural gas. The potential energy saving deriving from the implementation of the most cost-effective ECMs configuration has been estimated to be about 58.4 MWh per year concerning the electricity consumption and 19.6 MWh per year referring to the natural gas consumption. Finally, the intervention relative air leakage reduction seems to be the most cost-effective retrofit option to be implemented for this specific case study followed by LEDs technology.
References


