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# Building Performance Simulation tools for planning of energy efficiency retrofits

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**KEYWORDS:** *Retrofitting, energy efficiency, building performance simulation, information flow*

## **SUMMARY:**

*Designing energy efficiency retrofits for existing buildings will bring environmental, economic, social, and health benefits. However, selecting specific retrofit strategies is complex and requires careful planning. In this study, we describe a methodology for adopting Building Performance Simulation (BPS) tools as energy and environmentally conscious decision-making aids. The methodology has been developed to screen buildings for potential improvements and to support the development of retrofit strategies. We present a case study of a Danish renovation project, implementing BPS approaches to energy efficiency retrofits in social housing. To generate energy savings, we focus on optimizing the building envelope. We evaluate alternative building envelope actions using procedural solar radiation and daylight simulations. In addition, we identify the digital information flow and the information exchange structures for each simulation.*

## **1. Introduction**

### **1.1 Background to study**

The impetus to energy efficiency comes from a variety of sources. In the European Union (EU), the Commission has adopted an action plan aimed at achieving 20% reduction in primary energy consumption by 2020, the *20-20-20 goal*. This reduction will require major improvements in the energy efficiency of buildings, which represent around 40% of the EU's total consumption (European Union, 2009). Recently, the EU's drive to reduce consumption mainly focused on new buildings. However, considering that the average lifetime of a building is over 50 years, and a complete renewal of the existing European building stock would take more than 100 years (Kaderják et al., 2012), a substantial reduction in total consumption will not occur if no energy is saved through retrofitting existing buildings (Verbeeck & Hens, 2005).

Selecting specific retrofit strategies is a complex endeavor with many actions to be considered. A decision support approach is therefore needed (Kolokotsa et al., 2009). Here, Building Performance Simulation (BPS) tools have an important role to play (Peltormäki, 2009). With the evolution of Information Technology (IT), BPS tools have been developed to simulate the performance of a building (Doukas et al., 2009). Consequently, today's BPS tools allow any aspect of a building retrofit strategy to be simulated and assessed before it is implemented, helping project participants to understand the implications of their choices and to make informed decisions (Beaven, 2011).

### **1.2 Multifaceted study**

Based on the above, this study has two goals. The first is to explore the current approaches to energy efficiency retrofits in the Architecture, Engineering, and Construction (AEC) industry. The second is

to describe a methodology to facilitate BPS tools as energy and environmentally conscious decision-making aids.

Using an integrated and experience-based approach (Towns, 2001), the study goals are addressed by: (1) a review of trends in the field of energy efficiency retrofits to establish a knowledge base, and (2) a case study of a Danish renovation project to explore the effect of BPS tools to support building design decision-making.

## **2. Methodology**

### **2.1 Review of current approaches**

A review of current approaches to energy efficiency retrofits has been conducted and included articles and research conducted by academic institutes; industry work practice; and guidelines generated by government institutions. The review was carried out to understand and identify current trends in energy efficiency retrofits, and specifically focused on the uptake of integrating BPS tools as aids for building design decision-making.

### **2.2 Qualitative case study research**

A qualitative case study of energy efficiency retrofits in Danish social housing has been conducted. The case study approach facilitates “in-depth, multi-faceted explorations of complex issues in their real-life settings” (Crowe et al., 2011). In the present case study, multiple context-specific retrofit actions were compared to identify and evaluate trade-offs and post-retrofit benefits, which were defined as reduced energy consumption and improved indoor environmental quality. To achieve improvements, the case study retrofit actions focused on optimizing the building envelope.

A key feature of this case study was that BPS tools was used to predict the influence of the investigated retrofits. In particular, the researchers used a comprehensive suite of solar radiation and daylight simulations to show how building performance is affected by specific retrofit choices. Solar radiation simulations were performed using Autodesk Ecotect Analysis (Autodesk, 2014); daylight simulations were performed using IES Virtual Environment (IES, 2014). Both Ecotect and IESVE use data interpolation from the EPW weather file. As part of the simulation process, the case study identified the task/tool-specific information exchange structures for each simulation, in the present case study the required data input for each solar radiation [Ecotect] and daylight simulation [IESVE]. Based on these simulations, knowledge was provided prior to the decision-making/retrofit planning, thereby facilitating a predictive, informative decision approach (Attia, 2012).

Notably, the primary purpose of this case study was to demonstrate the benefits of adopting BPS tools as aids to facilitate informative pre-retrofit investigations, not to present specific building performance figures.

Based on a *triple helix* of university-industry-government interactions, an interdisciplinary project team of clients, project managers, contractors, architects, engineers, and manufacturers collaborated in the case study (Etzkowitz, 2003). Here, representing the university and engineering link, the corresponding author of this paper was involved in simulation and design activities.

## **3. Review**

### **3.1 Energy efficiency retrofits**

Retrofitting is “the process of modifying something after it has been manufactured” (City of Melbourne, 2013). For buildings, energy efficiency retrofits are defined as actions that allow an upgrade of the building’s energy and environmental performance to a higher standard than was

originally planned (Jaggs & Palmer., 1999). An overview of potential retrofit strategies, and retrofit actions which may improve performance figures, is shown in Figure 1.

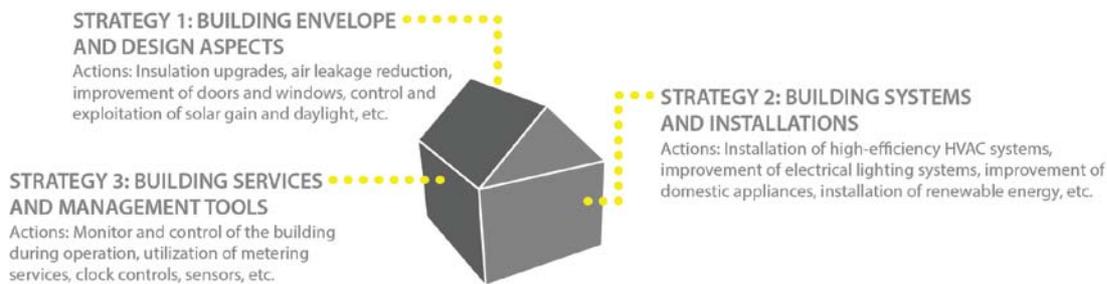


Figure 1. Retrofit strategies/actions [Inspired by (Kolokotsa et al., 2009)]

An example of a retrofitting action is the upgrading of insulation levels. Here, re-insulation of the building envelope – external walls, roofs, and floors – will improve the energy consumption of the building by reducing thermal losses through the fabric. Another example is the replacement of traditional single/double glazed windows with energy efficient triple glazed windows. As with the insulation upgrade, triple glazed windows will improve the building’s thermal performance. Replacing or changing the position, size, and shape of the windows may also result in improved solar gains, and better daylight exploitation, thereby reducing heat consumption and electrical lighting consumption, respectively (Bokel, 2007).

Furthermore, a key feature of retrofit is the objective of improved indoor environmental quality, usually measured by occupant comfort. Indoor environmental quality is determined by several factors, including air quality, acoustics, temperature, and lighting conditions. Consequently, some retrofit strategies integrate natural ventilation for better air quality, thermo-active building systems for thermal stability, and natural lighting for a better quality of illumination (Osso et al., 1996) (Paul & Taylor, 2008).

The green agenda is generally a powerful instrument in a retrofit argument. However, retrofits also allow an upgrade of functionality, architectural quality, and aesthetic value of the building (Kalc, 2012).

### 3.2 Retrofit performance criteria

The planning and evaluation of energy efficiency retrofits depend on well-defined project goals and carefully constructed criteria (Jaggs & Palmer, 1999). Accordingly, the main criteria for efficiency and sustainable performance in a retrofit include: (1) improvement of energy consumption, (2) limited impact on global environment, (3) improvement of indoor environmental quality, and (4) upgrading of functionality, architectural quality, and aesthetic value. Furthermore, the expected cost of a specific retrofit is key to its effective value. In this study, however, cost-effectiveness is not included as a criterion for retrofit evaluations.

Several of these criteria often appear to be in conflict, for example, energy consumption improvements versus architectural quality. Therefore, finding the optimum retrofit strategy is an optimization procedure. Here, the optimization involves iterative evaluations of proposed retrofit strategies/actions against selected criteria. Therefore, because optimization is complex, efforts for energy efficiency retrofits often focus on specific strategies/actions without the adoption of a holistic approach (Kolokotsa et al., 2009).

### 3.3 BPS-based decision-making methodology

Generally, decisions taken during the early stages of the design process, where the impact of design decisions on building performance is more significant than decisions made in later design stages, can

determine the success or failure of a retrofit. For this reason, ensuring informed decision-making in the design stages of both new builds and retrofitting is important (Shaviv et al., 1996).

Here, intelligent models and BPS approaches can be supportive. In the BPS-based process, a virtual model is developed to identify the most beneficial retrofit strategies/actions through predictive performance simulations. More specifically, a BPS tool is used to simulate the performance of a virtual model representing a specific retrofit strategy/action. Then, simulation results are evaluated against predefined performance criteria. If the results are not satisfactory, the retrofit strategy/action is modified and the simulation process is repeated (Attia, 2012). This iterative procedure is shown in Figure 2.



Figure 2. Iterative decision methodology [Inspired by (Kolokotsa et al., 2009)]

### 3.4 BPS-based retrofit design process

In contrast to design processes aimed at new-build, the retrofit design process is strongly influenced by the conditions of an existing building. The BPS-based retrofit design process is shown in Figure 3, here integrating the above mentioned BPS-based decision methodology. As shown, the BPS-based retrofit design process consists of three stages: (1) analysis of existing conditions, (2) development of retrofit strategies/actions, including evaluation against performance criteria, and (3) implementation of retrofit strategies/actions.

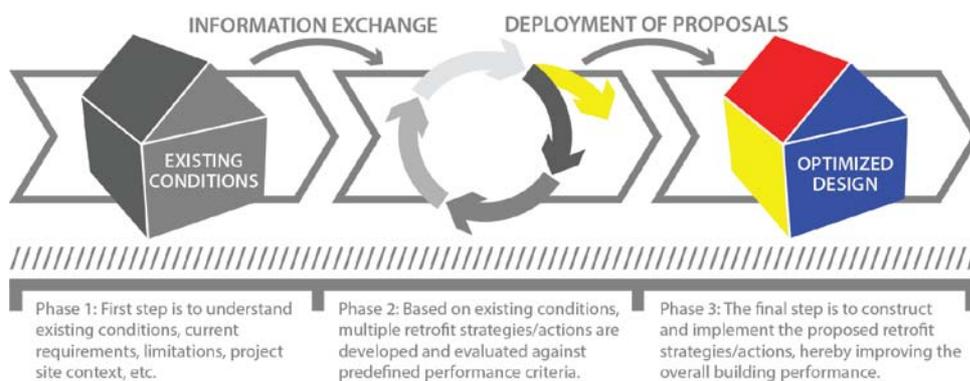


Figure 3. Retrofit design process

A key challenge to BPS-based retrofit design processes is the digital information flow between functional stages. In most cases, this information flow is defined by task/tool-specific information exchange structures, that is the required data input/output for specific BPS tasks/tools.

## 4. Case study

### 4.1 Analysis of existing conditions

The framework of this case study was directed toward the Gate 21 pilot project “Building Envelope Retrofits” (GATE 21, 2013). The aim of this project was to investigate the benefits of energy

efficiency building envelope retrofits in Danish social housing, referring to “Strategy 1”, implementing retrofit actions related to the building envelope and design aspects. In particular, Gate 21 was looking for creativity in developing multiple *exemplar* building envelope designs, with the aim of identifying successful actions that could be adopted into future building envelope retrofit projects. Another issue that was highlighted was that of developing building envelope designs optimized for solar radiation and daylight exploitation.



Figure 4. Pre-retrofit conditions of case study house

The dwelling used for the retrofit case study was a precast concrete construction, 1970s single storey house in Albertslund, Denmark (55.39°N 12.21°E). Pre-retrofit buildings typically have aging window units, poor insulation, air leakage, and mould growth due to surface condensation. These factors result in increased energy bills and poor indoor environmental quality. Figure 4 shows the house exterior and plan.

## 4.2 Development of building envelope retrofit actions

Based on review findings, the practice procedure for the development and evaluation of optimized building envelope retrofit actions followed five steps: (1) definition of performance criteria, (2) development of retrofit strategies/actions, (3) building performance simulations, (4) evaluation of simulation results, and (5) retrofit proposals.

### 4.2.1 Definition of performance criteria

Case study performance criteria were defined to establish a basis for evaluation. Performance criteria were generated with two main purposes: (1) to improve energy consumption by optimizing the exploitation of solar radiation and (2) to improve indoor environmental quality by optimizing the exploitation of daylight. In many cases, such performance criteria will be some combination of potential improvements. For example, optimizing the exploitation of solar radiation may not only improve energy consumption figures, but also indoor environmental quality levels by supporting occupants' thermal comfort. Equally, optimizing the exploitation of daylight may not only improve indoor environmental quality levels, but also energy consumption figures.

### 4.2.2 Development of retrofit strategies/actions

In collaboration with the case study project team, a list of retrofit actions was developed. Since the aim of this case study was to investigate the effects of multiple building envelope designs, basic retrofit actions included re-insulation of external walls and upgrading of existing windows. Specifically for this case study, the influence of selected building envelope design variables was investigated, particularly, that of alternative window positions, sizes, and shapes to investigate the resulting effects on solar gains and daylight conditions. The retrofit options consisted of nine building envelope designs/retrofit actions:

- Action 1: Energy efficient windows.
- Action 2: Energy efficient windows + increased window width.
- Action 3: Energy efficient windows + increased window height.

- Action 4: Energy efficient windows + extra window section at patio doors.
- Action 5: Energy efficient windows + double patio doors.
- Action 6: Energy efficient windows + small skylight in living room.
- Action 7: Energy efficient windows + large skylight in living room.
- Action 8: Energy efficient windows + extra window section in living room.
- Action 9: Energy efficient windows + extra window section in master bedroom.

#### 4.2.3 Building performance simulations

BPS tools were used to investigate the retrofit actions. Simulations were performed on two levels: (1) simulation of solar radiation striking exterior surfaces [Ecotect] and (2) simulation of interior solar gains and daylight distribution [IESVE]. Before simulating, specific information exchange/data input requirements for each simulation were identified:

- Site: Global coordinates, weather data, elevation, 3D geometry, context [Ecotect + IESVE].
- Building: Global coordinates, orientation, elevation, 3D geometry [Ecotect + IESVE].
- Spaces: Elevation, 3D geometry, space boundaries, [IESVE].
- External constructions: 3D geometry, U-values, [IESVE].
- Internal constructions: 3D geometry, U-values, surface reflectance values [IESVE].
- Windows: Orientation, 3D geometry, U-values, g-values, VT-values, shadings [IESVE].

In Figure 5, selected solar radiation simulations are shown. Here, average hourly solar radiation is mapped over existing conditions, hours in question 06-18, all year, summer, and winter, contour range 0-200 Wh/m<sup>2</sup>. The Ecotect case study models were kept simple, representing outer volumes/exterior surfaces only. As shown, surrounding vegetation was not included.

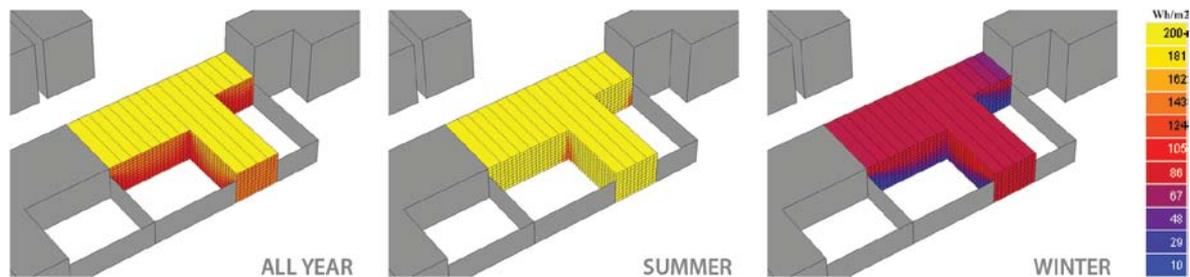


Figure 5. Incident solar radiation on exterior surfaces (south view)

In Figure 6, selected daylight simulations are shown. Here, average annual solar gains and daylight distribution are mapped over existing conditions, retrofit *Action 1* with energy efficient windows, and retrofit *Action 7* with energy efficient windows and a large skylight in the living room, contour range 40-760 LUX. The base-case model was created to understand the existing conditions of the case study building. This model was used as a reference to estimate improvements from retrofit actions 1 to 9.

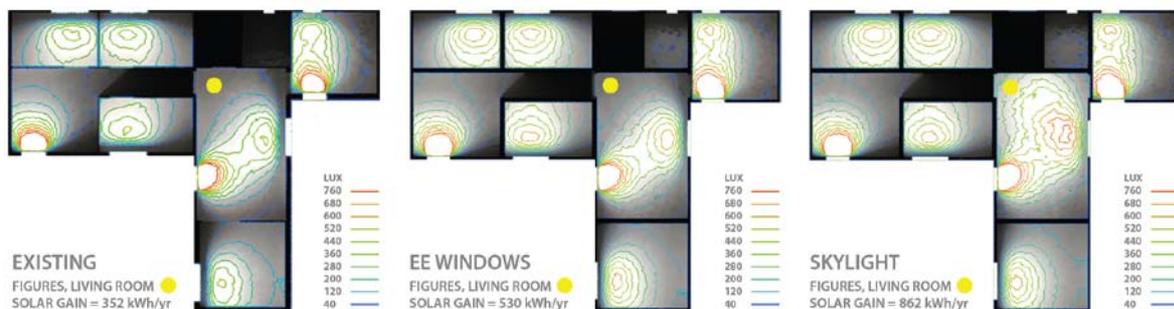


Figure 6. Correlation of interior solar gains and daylight distribution (top view)

#### 4.2.4 *Evaluation of simulation results*

Based on the BPSs, several kinds of correlations were demonstrated. For example, Figure 5 shows that an obstructed context greatly influences radiation values. As shown, the surrounding wooden fence causes overshadowing, particularly, during winter when the sun is low. Therefore, upper parts of the façades and freely exposed roofs should be prioritized when optimizing the exploitation of solar radiation.

Figure 6 shows that the replacement of existing windows with energy efficient windows brings significant improvements. Energy efficient windows have smaller frames, allowing more sunlight and daylight to penetrate. In addition, the installation of the large skylight further improves the solar gains and daylight distribution and is particularly effective at bringing solar radiation and daylight into deep spaces/darker areas of the case study building.

#### 4.2.5 *Retrofit proposals*

The evaluation of simulation results forms a solution space for potential building envelope retrofit actions. This solution space does not define any specific optimum retrofit, rather a wide range of applicable retrofit actions. Nevertheless, installing large window openings will improve solar radiation and daylight exploitation. Note, however, that high intensity solar radiation is the commonest cause of overheating in buildings and should therefore be controlled, for example, with adjustable external solar shading.

### **4.3 Implementation of retrofit strategies/actions**

The final step is to implement specific building envelope retrofit actions into the case study building. For implementation, the case study project participants should select specific retrofit actions within the developed solution space. This selection process is currently being conducted.

## **5. Conclusions**

In the decision-making process of selecting specific retrofit strategies, multiple actions are available. The decision maker has to take into consideration energy, environmental, functional, architectural, and financial aspects to develop a sustainable retrofit strategy. For this purpose, a decision support approach is needed.

In this study, the critical role of Building Performance Simulation (BPS) tools as energy and environmentally conscious decision-making aids was emphasized. In the case study, this was particularly shown by solar radiation and daylight simulations results. Based on this tendency, the BPS approach is generally evaluated as a useful methodology for planning of energy efficiency retrofits.

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