Dynamic Energy Performance-Driven Approach for Renovation Assessment of the Danish Public School Ejerslykkeskolen

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Abstract:
An overall building energy modelling and simulation methodology is developed employing a holistic approach and using a dynamic energy performance model, representing various building specifications and characteristics including location and geometry, constructions, loads, occupancy activities and schedules, and various HVAC systems. The detailed model is implemented as a basis for a holistic energy renovation investigation and assessment. The overall building 3D model is developed in Sketchup Pro and the associated energy model is defined extensively in the OpenStudio tool, where the EnergyPlus simulation engine is employed to simulate the building dynamic energy performance. Ejerslykkeskolen, a public school in Odense, Denmark, is considered as a case study to implement the modelling and simulation methodology and assess energy renovation measures, aiming to improve the school energy performance to comply with the BR15 Danish Building Regulations. The school was built in the 1953 with around 8000 m² spanning across 12 blocks with an energy rating of ‘D’. Based on architectural drawings, design documents, systems inspections, field visits and interviews, the overall dynamic school energy performance model is developed and calibrated using actual measured energy consumption data. Using the model, a parametric analysis is implemented to investigate and assess the impact of various energy renovation measures in different school blocks from the technical, economic and environmental perspectives. It is shown that a deep energy renovation package, with a mix of physical envelope upgrade measures and measures to improve the intelligence of energy systems, could reduce the overall energy consumption by 62.1% along with 57.6% savings on the operational costs and reducing emissions by 63.7 tons of CO₂ annually. The deep energy renovation package allows Ejerslykkeskolen to comply with the BR15 Renovation Class 1. The overall assessment carried out will serve as a recommendation aiding the decision to renovate the school by 2018.

Keywords:

1. Introduction
Denmark is not an exception when it comes to the buildings sector large share in the overall energy consumption, where Danish buildings consume around 40% of the overall country energy consumption [1], mainly to fulfil heating and electricity demands. On the other hand, Denmark has set an ambitious goal to become fossil fuel-free county by 2050 [2] and to rely solely on renewable energy resources to satisfy energy needs in various applications. Thus, a clear roadmap has been highlighted [3] with major steps and frameworks being implemented in the last decades aiming to achieve the holistic ambitious energy and environmental objectives. Nevertheless, the ambitious 2050 Danish holistic energy plan highlights the potential of improving energy performance of both existing and newly built buildings, being a major milestone towards achieving the set energy and climate goals. Figure 1 [4] provides an overview of the drastic evolution in terms of the energy consumption in a standard 150 m² Danish building, considering different building regulations throughout the years. It is shown that the maximum allowed annual primary energy consumption in a new building has decreased majorly from around 350 kWh/m² in 1961 to only 20 kWh/m² in 2020. This highlights the large potential of improving the energy performance of existing buildings, considering that about 75% of current buildings in Denmark were built before the 1980’s. In
addition, the current Danish building regulation BR15 [5], set strict guidelines for existing buildings energy renovation, with two energy renovation classes, Renovation Class 1 and 2, setting strict limits on the annual primary energy consumption and physical envelope components specifications. The Danish Building and Urban Research Unit [6] has investigated Danish buildings which were built between 1960 and 2004, and highlighted exterior wall insulation, energy efficient windows and ventilation system upgrade as the three renovation measures to be implemented. Nielsen et al. [7] examined various factors affecting the decision making process in sustainable buildings energy renovation and stressed on the importance of carrying out an early comprehensive screening for different energy renovation measures and options considering the technical and economic impacts. In addition to the large number of projects implemented all across the country targeting residential houses and buildings energy renovation [8,9], different municipalities in Denmark have recently developed large-scale energy renovation programs for public and administrative buildings. Considering administrative buildings, Rose et al. [10] has reported the deep energy renovation processes of two office buildings, a cultural centre and a kindergarten with an estimated savings between 45% and 85% on the overall energy consumption. The energy renovation measures implemented include walls and roofs insulation, energy efficient windows, ventilation system upgrade, heat recovery units implementation, LED lights, efficient heat pumps, photovoltaic units and solar water heaters. Moreover, the energy renovation process of Vester Voldgade 123 office building has resulted into an energy efficient building being one of the world largest certified passive houses with energy savings reaching 76% after renovation [11]. In a recent study, Jradi et al. [12] reported the overall energy modelling, simulation and renovation process of four daycare centers in Aarhus, recommending a deep energy retrofit package comprising energy supply systems operation improvement, buildings envelope upgrade and PV system implementation, with estimated primary energy savings of 71%.

Despite the fact that the majority of the public schools in Denmark were built before 1970, offering very large potential for energy performance improvement, very few energy renovation investigations and applications are reported. In this study, the process of modelling, performance simulation and energy renovation assessment of Ejerslykkeskolen public school in Odense is described and reported. A holistic and systematic approach is developed and implemented, employing a detailed dynamic energy performance model allowing multi-objective energy renovation process evaluation and assessment from the technical, economic and environmental perspectives. Using a package of Sketchup Pro, OpenStudio and EnergyPlus tools, a holistic energy performance model is developed for the 8000 m² school representing the different blocks and considering various components and specifications including physical envelope and energy systems. Moreover, multiple field visits, envelope and systems inspections and interviews with the school users and managers were carried out to identify feasible energy renovation measures to be implemented. Various energy renovation measures and packages are investigated, targeting the school envelope and energy supply systems and reporting the overall technical, economic and environmental impacts. The work is carried out under the international research project COORDICY [13] in collaboration with Odense Municipality.
2. Holistic Modelling and Simulation Approach

In an overall perspective, the majority of the renovation projects carried out in Denmark in the recent years were driven by the passive need to change and modify considering the age of the targeted buildings [14]. This trend has resulted into large performance gap between the expected building performance before implementing the renovation process and the actual reported energy performance in the subsequent years after renovation. This is mainly due to the fact that there is no systematic and methodical approach driving the decision-making for the overall renovation project, with the absence of a holistic assessment and evaluation considering the technical, economic and environmental impacts of undergoing different renovation measures. From a regulatory perspective, BE15 [15] is the official building energy modelling, simulation and certification tool used in Denmark in accordance with the building regulation BR15. However, this tool uses a simplified and static energy modelling and simulation approach to predict the monthly energy consumption of buildings with a large number of assumptions and uncertainties including considering the whole building as one large thermal zone, simplified energy systems representation, neglecting the impact of occupancy behaviour and activity, using default schedules and fixed average ambient conditions. In terms of energy renovation assessment, the tool is able to provide feedback on some modifications in the building envelope but with no capability of assessing and simulating the impact of various renovation measures and combinations. Considering the ‘reactive’ approach as the trend for recent energy renovation projects along with the limitations and uncertainties associated with the BE15 software, this study aims to adopt and implement a holistic dynamic energy performance-driven approach for building energy modelling, performance simulation and energy renovation evaluation and assessment. This dynamic approach allows representing the different integrations and interdependences between various components and systems in the building while considering the impact of occupancy behaviour and weather conditions.

An overview of the holistic energy modelling, simulation and renovation assessment approach adopted in this work is presented in Fig. 2. Three tools are used to aid the overall implementation of the methodology. Sketchup Pro is employed to draw the 3D architectural model of the building using collected information on the geometry, location, orientation and physical envelope. As this model is completed, it is used as an input in the OpenStudio tool where the holistic building energy model is developed considering various building characteristics and specifications including constructions and materials, energy supply systems layout and operation strategies, loads and schedules, occupancy behaviour and weather conditions. OpenStudio is used as it provides a user-friendly and detailed platform for energy model development. In addition, the well-established and validated simulation engine of EnergyPlus is used as a basis for building energy simulation where the holistic building dynamic performance over the year is reported. After model development and performance simulation, the holistic model is calibrated using actual energy consumption data collected onsite with the aid of the OpenStudio Parametric Analysis Tool [16]. The calibrated model will then be employed as a baseline to implement, simulate and assess various energy renovation measures and packages, reporting the technical, economic and environmental impacts.

Fig. 2. Overall building energy modelling, simulation and renovation assessment methodology.
3. Case Study

The Municipality of Odense, Denmark third largest city, has launched the ‘ENERGY LEAN’ project [17] with the aim to reduce the overall energy consumption of public schools in the city along with reducing the corresponding CO₂ emissions by 40% and enhancing the schools energy rating. An investment of 225 million DKK was allocated to implement a large-scale energy renovation process targeting different existing public schools around the city. Ejerslykkeskolen, which was built in 1953, is one of those schools considered for energy renovation, comprising of 12 building blocks spanning across 8000 m² interior area. The school provides primary education with a reported 525 students in 2017. The school energy rating is ‘D’ based on the Danish building regulations, highlighting the potential of improving the energy performance throughout an efficient and cost-effective energy renovation process. Under the international research project ‘COORDICY’ and in collaboration with the Municipality of Odense, this study will present the overall process of Ejerslykkeskolen energy modelling, performance simulation and energy renovation evaluation and assessment. The holistic and systematic methodology presented in the previous section will be implemented for Ejerslykkeskolen case study where various energy renovation measures and packages will be simulated and evaluated. Figure 3 shows the overall plan view of the different school blocks with their respective geometry. All the school blocks are shown in the plan, except blocks 7 and 8 which are respectively a garage and a storage depot with a very limited area and thus were not considered in this study. The 10 blocks investigated were built in 1953 and still preserve the geometry and space allocation, with some minor additional adjustments and modifications in 1990 including extension of the teachers residence and the lunch and meeting room. Blocks 1,2 and 3 are 2 gym halls and a large meeting and party room. The other blocks 4 to 6 and 9 to 11 are majorly teaching blocks with block 4 having meeting and lunch rooms and block 12 is an SFO block for after school services and activities. In addition, Fig. 4 depicts different school images for the (a) blocks 5 and 6, (b) roofs of blocks 1,2 and 3, (c) gym hall and (d) main library.

Fig. 3. Plan view of different Ejerslykkeskolen blocks.

Fig. 4. Ejerslykkeskolen a) blocks 5 and 6, b) roof of blocks 1,2 and 3, c) gym hall and d) main library.
Table 1 provides an overview of the school specifications and characteristics including physical envelope constructions and materials and different energy supply systems. In addition, Table 2 presents major information regarding the ventilation system components and operation in the different blocks.

### Table 1. Ejerslykkeskolen specifications and characteristics.

<table>
<thead>
<tr>
<th>Location</th>
<th>Rødegårdsvej 164, Odense, Denmark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor Heated Area</td>
<td>6851 m²</td>
</tr>
<tr>
<td>Energy Class</td>
<td>D</td>
</tr>
<tr>
<td>Building Use</td>
<td>Classes, meeting rooms, gyms and library</td>
</tr>
<tr>
<td>Blocks</td>
<td>12 blocks</td>
</tr>
<tr>
<td>Opening Hours</td>
<td>6:30 – 19:00</td>
</tr>
<tr>
<td>Roof</td>
<td>Roof is mainly brick with 170mm insulation with 0.2 W/m².K U-value. Flat roofs have 100mm insulation with U-value of 0.36 W/m².K, where roof in the SFO has 200mm insulation.</td>
</tr>
<tr>
<td>Exterior Walls</td>
<td>Original exterior walls from 1953 are massively built with 48cm bricks with an overall U-value of 1 W/m².K. Hollow walls at SFO are of 30cm brick with 75mm insulation and 0.42 W/m².K U-value. Light external walls in the teachers residence have 50mm insulation. Basement walls are made of 35cm light concrete.</td>
</tr>
<tr>
<td>Floor</td>
<td>Mainly uninsulated concrete. Floor in the basement are concrete with 50mm leca insulation.</td>
</tr>
<tr>
<td>Windows</td>
<td>In 2003, the school windows were replaced with double-glazed windows of U-value ranging from 2.2 to 3.1 W/m².K. The basement has single-glazed windows of 4.9 W/m².K U-value.</td>
</tr>
<tr>
<td>Heating System</td>
<td>Direct district heating loop for the overall heating supply with 3 160W UP 40-50 and 1 100W UPE 32-60 heating circulation pumps</td>
</tr>
<tr>
<td>Domestic Hot Water</td>
<td>Hot water is produced using a marked APV flow exchanger located in the basement. A 90W circulation pump UP 20-30 is installed with 400 liter buffer tank for hot water storage with 70mm mineral wool insulation.</td>
</tr>
<tr>
<td>Space Heating Radiators</td>
<td>Radiators in every heated room with thermostatic valves</td>
</tr>
<tr>
<td>Ventilation System</td>
<td>A mix of mechanical and natural ventilation</td>
</tr>
<tr>
<td>Lighting</td>
<td>Mainly conventional 1 pipe luminaires with manual operation. Some classrooms are provided with motion sensors.</td>
</tr>
<tr>
<td>Equipment</td>
<td>Computers, laptops, screens, printers, refrigerators, dishwasher</td>
</tr>
<tr>
<td>Control System</td>
<td>The heating system is controlled centrally using the TAC CTS system. The ventilation units are not regulated by the CTS.</td>
</tr>
</tbody>
</table>

### Table 2. Ventilation system overview in different Ejerslykkeskolen blocks.

<table>
<thead>
<tr>
<th>Spaces</th>
<th>Ventilation System Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salon</td>
<td>Balanced mechanical ventilation unit of DanVent type TC12 with variable speed fans and rotary heat recovery unit</td>
</tr>
<tr>
<td>Library and Block 10</td>
<td>Balanced mechanical ventilation unit of DanVent type Spar13 with variable speed fans and rotary heat recovery unit</td>
</tr>
<tr>
<td>Toilets</td>
<td>Mechanical ventilation using exhaust fans-driven by motion sensors</td>
</tr>
<tr>
<td>Dressing Rooms</td>
<td>One dressing room is mechanically ventilated using exhaust fan and the other is naturally ventilated</td>
</tr>
<tr>
<td>Teacher’s Office and Administrative Offices</td>
<td>Mechanical ventilation using exhaust fans</td>
</tr>
<tr>
<td>Gyms</td>
<td>Natural ventilation through random leaks</td>
</tr>
<tr>
<td>Classrooms and Corridors</td>
<td>Mechanical ventilation using DFJ type AZ60 and Novenco type CL800 ventilation units with exhaust fans. Some classrooms are naturally ventilated.</td>
</tr>
<tr>
<td>SFO (block 12)</td>
<td>Mechanical ventilation using 4 Exhausto BESF exhaust fans</td>
</tr>
<tr>
<td>Basement</td>
<td>Natural ventilation through random leaks</td>
</tr>
</tbody>
</table>
In overall, all school blocks are connected and served by direct district heating loop to fulfil heating demands via radiators in different rooms. Domestic hot water is produced in the basement with a storage buffer tank. A CTS system is used to centrally control the overall heating system with heating setpoint of around 21°C in the majority of the blocks. The ventilation system in the school is not controlled and comprises a mix of mechanical ventilation units in addition to natural ventilation in some blocks and spaces as shown in Table 2.

4. Ejerslykkesholmen School Modelling and Simulation

To simplify the investigation, the 11 school blocks were grouped and divided into 4 sections; A, B, C and D as shown in Table 3.

<table>
<thead>
<tr>
<th>Section</th>
<th>Blocks</th>
<th>Area (m²)</th>
<th>Heated Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1,2,3</td>
<td>1795</td>
<td>1266</td>
</tr>
<tr>
<td>B</td>
<td>4</td>
<td>1352</td>
<td>1214</td>
</tr>
<tr>
<td>C</td>
<td>5,12</td>
<td>1752</td>
<td>1451</td>
</tr>
<tr>
<td>D</td>
<td>6,9,10,11</td>
<td>3166</td>
<td>2920</td>
</tr>
</tbody>
</table>

The working methodology illustrated in Fig. 2 will be implemented for the Ejerslykkesholmen case study. Taking into consideration that the school was inaugurated in 1953, the information and data collection phase took a relatively long time including information about blocks geometry, spaces allocation, physical envelope characteristics and energy systems specifications. In this context, architectural and technical drawings were reviewed and multiple field visits were planned allowing physical envelope and technical energy systems inspection along with interviews with the school users and managers. Using the information collected in terms of the school blocks location, geometry and orientation in addition to the spaces allocation and distribution, a detailed 3D architectural model was developed in Sketchup Pro for the 4 different sections (A, B, C and D) presented above, as shown in Fig. 5. The 3D architectural models for the 4 sections presented above were introduced in OpenStudio to develop the school overall holistic energy performance model with detailed information regarding the school physical envelope, constructions and materials, different energy supply systems layout and operation strategies, lights and equipment, occupancy behaviour and activity, loads and schedules. In addition, an updated weather file was created to be used throughout the simulations, harnessing actual weather conditions collected for Odense including solar radiation, ambient temperature and wind speed.

![Fig. 5. Sketchup 3D architectural models for sections: a) A, b) B, c) C, d) D.](image-url)

After the development of the detailed energy model in OpenStudio, the well-established and validated simulation engine of EnergyPlus was used to run an annual dynamic energy performance simulation of the overall school energy consumption. In addition, the developed holistic energy performance model was calibrated using actual energy consumption data collected from different
energy meters onsite. The methodology developed by Hale et al. [18] was implemented to calibrate the model employing the Openstudio Parametric Analysis Tool and importing actual weather conditions, occupancy schedules and actual monthly heating and electricity consumption data collected. A holistic parametric approach is used in calibrating the school energy model where multiple parallel simulations were carried out employing different combinations of variable parameters including infiltration rates, air flow rates, lights and equipment schedules and devices efficiencies. Around 150 combinations were simulated and the combination which yielded the lowest deviation from the actual monthly heating and electricity consumption was selected to serve as a baseline model for renovation measures implementation and simulation. Figure 6 presents the monthly consumption for heating and electricity respectively as predicted by the calibrated energy performance model in addition to actual monthly consumption reported by the school energy meters. It was shown that the calibrated energy performance model is capable of predicting the school performance in terms of energy consumption with an acceptable error of -1.7% and 3.5% for annual heating and electricity consumption respectively.

In addition, a breakdown of the annual energy consumption in Ejerslykkeskolen school is provided in Fig. 7. Heating consumption has the ultimate largest share in the overall energy consumption with around 86.6% and about 906 MWh annually, where the rest is in the form of electricity consumption for ventilation (5.1%), equipment (4.3%) and lighting (4.0%). As shown in Table 4, the estimated Ejerslykkeskolen school annual primary energy consumption is around 166.9 kWh/m² of interior heated area, considering energy consumption for heating, ventilation, lighting and building services and excluding electricity consumption by equipment. Based on the BR15 building regulation, if the school undergoes an energy renovation process it should consume a maximum of 135.4 kWh/m² to comply with Renovation Class 2 and less than 71.5 kWh/m² to comply with the higher Renovation Class 1. In addition, a similar new modern school complying with the BR15 regulation shall consume an annual primary energy consumption less than 41.2 kWh/m². The primary energy consumption numbers presented in the table show clearly the large potential of improving the energy performance of Ejerslykkeskolen school and reducing its energy consumption through a systematic overall energy renovation process on different levels.

![Fig. 6. Ejerslykkeskolen energy consumption Act vs Sim: a) electricity, b) heating.](image)

![Fig. 7. Ejerslykkeskolen school overall energy consumption breakdown.](image)
Table 4. Ejerslykkeskolen primary energy consumption vs BR15 standards.

<table>
<thead>
<tr>
<th>School Section</th>
<th>Primary Energy Consumption (kWh/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ejerslykkeskolen School current state</td>
<td>166.9</td>
</tr>
<tr>
<td>BR15 Renovation Class 2</td>
<td>135.4</td>
</tr>
<tr>
<td>BR15 Renovation Class 1</td>
<td>71.5</td>
</tr>
<tr>
<td>BR15 standard for a similar new school</td>
<td>41.2</td>
</tr>
</tbody>
</table>

Considering the different school sections, Table 5 provides an overview of the individual energy performance of each section, in terms of annual heating, ventilation, lighting and equipment energy consumption. It is shown that Section D with blocks 6,9,10 and 11 has the highest heating and electricity consumption among the 4 sections due to the large area covered. In addition, block A has a minimal ventilation energy consumption due to the fact that the blocks 1,2 and 3 are served mainly by natural ventilation with a small mechanical ventilation unit implemented. Regarding lighting and equipment consumption, there is a reasonable even distribution of consumption for the 4 sections considering each section area covered. Table 5 also reports the annual primary energy consumption of each section with section D the highest with 174 kWh/m² and section B the lowest with 113.7 kWh/m² per year.

Table 5. Energy performance of different Ejerslykkeskolen sections.

<table>
<thead>
<tr>
<th>School Section</th>
<th>A (MWh)</th>
<th>B (MWh)</th>
<th>C (MWh)</th>
<th>D (MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating Consumption</td>
<td>134.1</td>
<td>119.8</td>
<td>186.8</td>
<td>465.4</td>
</tr>
<tr>
<td>Ventilation Electricity Consumption</td>
<td>4.2</td>
<td>10.3</td>
<td>13.6</td>
<td>25.3</td>
</tr>
<tr>
<td>Lighting Electricity Consumption</td>
<td>7.9</td>
<td>7.4</td>
<td>9.3</td>
<td>16.9</td>
</tr>
<tr>
<td>Equipment Electricity Consumption</td>
<td>6.7</td>
<td>9.6</td>
<td>10.3</td>
<td>18.3</td>
</tr>
<tr>
<td>Primary Energy Consumption (kWh/m²)</td>
<td>115.8</td>
<td>113.7</td>
<td>144.9</td>
<td>174.2</td>
</tr>
</tbody>
</table>

5. Renovation Measures Implementation

The dynamic simulation of the Ejerslykkeskolen school energy performance has demonstrated the large potential to implement an energy renovation process to reduce the primary energy consumption by at least 31.5 kWh/m² to comply with the BR15 Renovation Class 2, and by 95.4 kWh/m² to comply with the Renovation Class 1. Thus, different energy renovation measures will be investigated in this section and implemented in the holistic dynamic energy model to simulate the technical, economic and environmental impacts on the school performance. A mix of physical envelope upgrade measures in addition to measures to improve the performance of the school energy supply systems are considered as presented in Table 6. The 12 renovation measures include: 1) wall insulation, 2) roof insulation, 3) triple-glazed windows, 4) LED lights, 5) daylight sensors, 6) motion sensors, 7) heating circulation pump upgrade, 8) ventilation system fans upgrade, 9) ventilation system heat exchanger implementation, 10) demand-controlled ventilation, 11) heating setpoint management and 12) installation of 10 kW PV units on the roof.

Table 6. Energy renovation measures implemented.

<table>
<thead>
<tr>
<th>Number</th>
<th>Renovation Measure</th>
<th>Number</th>
<th>Renovation Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>External Wall Insulation</td>
<td>7</td>
<td>Variable Speed Heating Circulation Pumps</td>
</tr>
<tr>
<td>2</td>
<td>Roof Insulation</td>
<td>8</td>
<td>Efficient Ventilation System Fan</td>
</tr>
<tr>
<td>3</td>
<td>Triple-Glazed Windows</td>
<td>9</td>
<td>Ventilation Heat Exchanger</td>
</tr>
<tr>
<td>4</td>
<td>LED lights</td>
<td>10</td>
<td>Demand-Controlled Ventilation</td>
</tr>
<tr>
<td>5</td>
<td>Daylight Sensors</td>
<td>11</td>
<td>Heating Setpoint Management</td>
</tr>
<tr>
<td>6</td>
<td>Motion Sensors</td>
<td>12</td>
<td>Photovoltaic System</td>
</tr>
</tbody>
</table>
The energy renovation measures were implemented for the 4 different school sections presented above. It shall be mentioned that some measures, particularly the HVAC systems measures, were not considered for specific school sections as it is regarded inapplicable. These measures include: measures 7, 8, 9 and 10 for Section A as it relies mainly on natural ventilation and there are already variable speed pumps for the heating loop, in addition to measure 7 for sections A and D. Moreover, measure 12 regarding implementing a PV unit on the roof was only applied on the whole school level and not for each section independently. In this context, Table 7 shows the impact of different renovation measures for the 4 sections from the technical, economic and environmental perspective.

**Table 7. Technical, economic and environmental impacts of various energy renovation measures.**

<table>
<thead>
<tr>
<th>Measure</th>
<th>Electricity Savings (MWh)</th>
<th>Heating Savings (MWh)</th>
<th>Cost Savings (DKK)</th>
<th>Emission Savings (kg.CO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Section A</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.97</td>
<td>43.83</td>
<td>16139.8</td>
<td>3454.2</td>
</tr>
<tr>
<td>2</td>
<td>0.33</td>
<td>17.78</td>
<td>6426.9</td>
<td>1382.7</td>
</tr>
<tr>
<td>3</td>
<td>0.46</td>
<td>20.46</td>
<td>7547.8</td>
<td>1614.6</td>
</tr>
<tr>
<td>4</td>
<td>4.20</td>
<td>-1.56</td>
<td>7887.2</td>
<td>1180.1</td>
</tr>
<tr>
<td>5</td>
<td>3.56</td>
<td>-1.23</td>
<td>6712.8</td>
<td>1006.5</td>
</tr>
<tr>
<td>6</td>
<td>2.07</td>
<td>-1.04</td>
<td>3812.1</td>
<td>564.1</td>
</tr>
<tr>
<td>11</td>
<td>0.35</td>
<td>18.19</td>
<td>6599.1</td>
<td>1418.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measure</th>
<th>Electricity Savings (MWh)</th>
<th>Heating Savings (MWh)</th>
<th>Cost Savings (DKK)</th>
<th>Emission Savings (kg.CO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Section B</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.95</td>
<td>48.12</td>
<td>17486.5</td>
<td>3756.5</td>
</tr>
<tr>
<td>2</td>
<td>0.56</td>
<td>22.45</td>
<td>8393.0</td>
<td>1788.8</td>
</tr>
<tr>
<td>3</td>
<td>0.64</td>
<td>29.52</td>
<td>10845.2</td>
<td>2322.7</td>
</tr>
<tr>
<td>4</td>
<td>4.05</td>
<td>-1.72</td>
<td>7544.8</td>
<td>1123.9</td>
</tr>
<tr>
<td>5</td>
<td>4.54</td>
<td>-2.13</td>
<td>8383.9</td>
<td>1243.9</td>
</tr>
<tr>
<td>6</td>
<td>1.60</td>
<td>-0.79</td>
<td>2934.7</td>
<td>564.1</td>
</tr>
<tr>
<td>7</td>
<td>0.72</td>
<td>-0.71</td>
<td>1200.5</td>
<td>232.1</td>
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<th>Emission Savings (kg.CO₂)</th>
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<th>Heating Savings (MWh)</th>
<th>Cost Savings (DKK)</th>
<th>Emission Savings (kg.CO₂)</th>
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Based on the simulation results, it is shown that measures targeting the school blocks physical envelope (1 to 3) yield major savings on the heating energy consumption. Insulating the external wall is found to be the top priority for implementation in any energy renovation process allowing the largest savings for the 4 school sections in the range of 43.8 to 122.1 MWh per year. However, it was found that measures targeting the ventilation system are very profitable in decreasing heating consumption in sections B, C and D, including adding a ventilation heat exchanger unit and implementing demand-controlled ventilation to manage the ventilation system operation. In addition, the heating setpoint management was found an efficient and cost-effective measure to cut heating demands in the different blocks with no additional investments. On the other hand, it is shown that installing efficient LED lights and implementing daylight sensors are the two measures with the maximum savings on the electricity consumption in all the blocks, where motion sensors have a relatively lower impact. In addition, upgrading the ventilation system fans allows a major reduction on the ventilation system electricity consumption ranging from 3.2 to 7.1 MWh in sections B, C and D. From the economic perspective and as electricity is much more expensive than heat (2 DKK/kWh electricity compared to 90 DKK/GJ heat consumption), it is very profitable to target measures which allow electricity consumption savings, including LED lights, daylight sensors, and upgrading fans, although such measures increase heating consumption relatively due to less heat losses and internal heat gains from highly efficient components. In addition to external walls insulation which found to provide large savings on the operational costs, it was noted that daylight sensors, LED lights, ventilation heat exchanger addition and demand-controlled ventilation implementation allow significant operational cost savings. Correspondingly, these renovation measures will also yield major reduction on the school CO\textsubscript{2} emissions as presented in Table 7.

On the other hand, there is no single renovation measure of the 11 measures implemented above that could prove feasible alone to reduce the energy consumption of the Ejerslykkeskolen school to an acceptable level to comply with the BR15 building regulations for existing buildings. Taking this into consideration, in addition to the age and current status of the school along with the current situation of the physical envelope and energy supply systems, a deep energy renovation process is indispensable to improve the holistic performance. Based on the technical, economic and environmental assessment carried out above for various renovation measures implemented in the 4 school sections, a holistic deep energy renovation package is developed and implemented on the level of the whole school with a mix of physical envelope upgrade measures in addition to measures to improve the energy performance and management strategies of different energy supply systems. The deep energy renovation package is presented in Table 8 with the different energy measures implemented in each school section.

Table 8. Different energy measures included within the deep energy renovation package.

<table>
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<tr>
<th>Section</th>
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<tr>
<td>A</td>
<td>wall insulation, roof insulation, LED lights, daylight sensors, heating setpoint management</td>
</tr>
<tr>
<td>B</td>
<td>wall insulation, roof insulation, LED lights, daylight sensors, ventilation fans upgrade, ventilation heat exchanger unit, heating circulation pump upgrade, heating setpoint management</td>
</tr>
<tr>
<td>C</td>
<td>wall insulation, roof insulation, LED lights, daylight sensors, ventilation fans upgrade, ventilation heat exchanger unit, heating circulation pump upgrade, heating setpoint management</td>
</tr>
<tr>
<td>D</td>
<td>wall insulation, roof insulation, LED lights, daylight sensors, ventilation fans upgrade, ventilation heat exchanger unit, heating setpoint management</td>
</tr>
<tr>
<td>Whole School</td>
<td>10 kW PV system on the roof</td>
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</table>

Based on the dynamic energy simulations, it was shown that the deep energy renovation package allows reducing the overall energy consumption of Ejerslykkeskolen by 62.1%, with a corresponding reduction of 57.6% on the operational costs and around 63.7 tons of CO\textsubscript{2} emissions.
annually. In addition, the annual primary energy consumption of Ejerslykke skolen after implementing the deep energy renovation package is around 56.1 kWh/m² with a reduction of 111 kWh/m² compared to the current school situation. Thus, the school will comply after renovation with the highest Danish energy standard for existing buildings, Renovation Class 1. Although this renovation package provides significant savings on the energy consumption, operational costs and emissions, it is associated with a relatively high investment cost. If a pure economic perspective is considered in the assessment, then measures targeting the energy supply systems including LED lights, heat exchanger addition, and pumps and fans replacement are considered cost-effective with a relatively short payback periods compared to physical envelope and constructions upgrade measures. However, taking into account the importance of the school indoor thermal comfort and air quality and considering the need to upgrade the school envelope constructions to comply with the BR15 Danish building regulations, a holistic deep energy renovation package of both envelope upgrade and systems performance improvement is essential. Such package allows significant energy, operational costs and emissions savings in addition to allowing Ejerslykke skolen to comply with BR15 regulations in terms of energy consumption and physical envelope specifications.

6. Conclusion

The ambitious Danish 2050 energy plan has targeted improving the existing building energy performance as a major factor to eliminate the country reliance on conventional fossil-fuel resources and meet the strict energy and environmental objectives. In the recent decades, the majority of the energy renovation projects in Denmark were driven by the passive need to change, considering the building age and status. In addition, the approach implemented is mainly based on static technical and economic calculations and evaluations with large assumptions regarding the use of the building, and thus failing to capture the interactions and dynamic changes in the envelope behaviour and systems function. This has resulted into large performance gaps between the building expected performance before the renovation process and the actual reported energy performance in the subsequent years after renovation. To address these challenges, the current study aims to establish a new holistic and systematic methodology for buildings energy performance modelling, simulation and renovation assessment based on technical, economic and environmental perspectives. The holistic approach adopted employs a detailed dynamic energy performance model representing various building specifications and characteristics including physical envelope constructions and materials, energy supply systems layout and operation strategies, loads and schedules, occupancy behaviour and activity and weather conditions. A case study of a Danish public school, Ejerslykke skolen, is considered to implement the modelling and simulation methodology and assess energy renovation measures, aiming to improve the school energy performance to comply with the BR15 Danish Building Regulations. An overall 3D architectural school model was created and the detailed holistic energy performance model was developed in OpenStudio, where EnergyPlus simulation engine was used to simulate the annual dynamic energy performance of the school. In addition, the dynamic model developed was calibrated employing actual energy consumption data. A holistic technical, economic and environmental assessment was carried out to investigate the impact of 12 renovation measures on the different school blocks performance. Based on the energy simulations of different measures in the 4 individual school sections, a deep energy retrofit package was developed using a mix of physical envelope upgrade measures and measures to improve energy supply systems operation and management in addition to adding PV system on the school roof. Implementing this package has resulted into reducing the school overall energy consumption by 62.1% with around 57.6% reduction in the operational costs and 63.7 tons of CO2 emissions savings annually. The primary energy consumption of the school after renovation was evaluated to be around 56.1 kWh/m², allowing the school to comply with the BR15 Ren. Class 1. The results attained in this study will serve as an overall evaluation, assessment and recommendation to support the decision-making process for the school renovation by 2018. The energy performance and indoor thermal comfort and air quality in the school blocks will be monitored as a part of the energy renovation process post-assessment under COORDICY project.
Acknowledgments
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References