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Renovation Measures for Reduction of Primary Energy Consumption and CO_2 Emissions of Hospital Building

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Abstract: Hospitals, as highly energy-intensive buildings, significantly contribute to a country's energy consumption and CO_2 emissions. The study focuses on a hospital building in Sarajevo, Bosnia and Herzegovina, and investigates the impact of selected energy renovation measures on hospital primary energy consumption and CO_2 emissions. The main goal of this paper is to develop a mathematical model for establishing relationship between primary energy consumption and CO_2 emissions (responses), and the three renovation measures (factors). The research uses dynamic simulation of the building's energy performance in Design Builder, validated with the actual energy consumption. Three energy renovation measures were considered in the study: installation of thermal insulation on external walls and flat roof, and the installation of a photovoltaic power plant. The Analysis of Variance and regression analysis were used to estimate factor effects, and to develop mathematical models. The analysis revealed that the installation of photovoltaic power plant on the roof and thermal insulation on the external walls had the most significant impact on reducing the building's primary energy consumption and CO_2 emissions. Installation of insulation on the roof did not significantly affect these performances compared to the other two measures. Developed models are suitable for evaluation of potential for energy and CO_2 savings through the implementation of energy efficiency measures. Study results can be extrapolated to all buildings within the same category, providing a valuable tool for energy efficiency planning in the healthcare sector.

Keywords: CO_2 emissions; design of experiments; energy renovation; hospital building; primary energy

1 INTRODUCTION

The healthcare sector, particularly hospital buildings, represents a significant portion of countries energy consumption and CO_2 emissions [1]. Hospitals are highly energy-intensive buildings, requiring large amounts of energy for operations including energy consumption in buildings and from medical procedures, such as sterilisation, radiology, laboratories, operating rooms, ventilation, air conditioning, heating, kitchens and laundry rooms [1, 2]. High energy consumption and CO_2 emissions of hospital buildings provide opportunities for implementing solutions that can reduce energy consumption and CO_2 emissions, therefore increase energy efficiency. These solutions can range from energy renovation of building envelope, equipment upgrades and integration of renewable energy systems, to the implementation of energy management and the promotion of user behaviour change towards more efficient energy use. The benefits of increasing energy efficiency in hospital buildings are numerous. Besides reducing energy costs and CO_2 emissions, energy efficiency can also have positive consequences for both human and environmental health and can improve the quality of patient care. Also, hospitals can serve as influential models for other sectors in society, demonstrating the feasibility and benefits of energy efficiency measures and contributing to broader efforts to mitigate climate change. The study [3], conducted in hospital building located in Grece found that the implementation of energy-saving measures, such as replacing all luminaires with LED lights and installing photovoltaic panels, could significantly reduce annual electrical energy consumption. This could potentially bring the consumption close to or even below 45% of the current annual electrical energy consumption. Study [4] offers a comprehensive decision-making approach for implementation of energy-saving renovation strategies in hospital building. This approach provides valuable insights for investors in selecting the most suitable energy-saving renovation plan. The evaluation criteria for this approach includes three important indicators: energy, financial, and thermal comfort. The authors presented results of case study conducted in a selected hospital building to demonstrate applicability of the proposed method. A study [5], focused on various aspects of energy efficiency in healthcare buildings in Spain over a period of 8 years, where it is concluded that significant energy savings can be achieved through implementation of efficient energy-saving techniques.

The general findings from numerous studies indicate that hospitals can achieve considerable reductions in energy consumption by adopting energy-efficient technologies and strategies. These strategies not only reduce energy consumption, but also contribute to economic savings and improved thermal comfort in hospital buildings, which can be incorporated in the national renovation strategies [6, 7].

Healthcare buildings in Bosnia and Herzegovina (B&H) constitute 13% of the total heated area of public buildings and are characterized by high specific energy consumption compared to other public buildings [8]. These buildings, particularly hospital buildings, require careful analysis due to their specific purpose, usage duration, and design parameters related to internal temperature. A hospital building in Sarajevo, constructed in the 1980s, has been selected for analysis based on its typical characteristics common for given construction period, which include poor energy-related characteristics and energy supply system deficient in renewable energy sources. To reduce energy consumption and CO_2 emissions, energy renovation measures of the building envelope and the installation of a photovoltaic power plant are being analysed.

Impact of each measure on energy consumption and CO_2 emission is assessed using Design of Experiments (DOE) methodology. DOE is statistical method widely used in identification of key factors and evaluation of effectiveness of different renovation strategies for reduction of buildings energy consumption. It allows researchers to identify most influential factors, such as energy renovation measures and to evaluate their individual or combined impact on energy consumption. While numerous studies have applied DOE to analyse residential and public building renovation measures [9, 10], there is limited research using this method to improve energy efficiency, specifically in the healthcare sector. Previous healthcare applications of DOE have focused on enhancing patient flow, scheduling efficiency, and information management [11, 12] rather than energy savings. This represents an opportunity to use DOE for assessing and optimizing the energy performance of healthcare facilities through building renovations.

Therefore, in presented study, a DOE method, Full Factorial Design (FFD) is used to establish relationships between primary energy consumption and CO_2 emissions and energy renovation measures of hospital building. The regression models developed in this study enable quantification of primary energy and CO_2 emissions considering implementation of energy renovation measures. This study aims to model the energy consumption and CO_2 emissions of hospital building, focusing on implementation of energy efficiency measures and the integration of renewable energy sources.

2 METHODOLOGY

2.1 Representative Building within the Hospital Complex

The hospital building analysed in this study is component of a large hospital complex (Fig. 1), constructed during the 1980 with 35800 m^2 of heated area. The analysed hospital building has 4883 m^2 of gross heated area, which represents 13.6% of gross heated area of hospital complex. The representative hospital building, shown in Fig. 1, is a multi-level building with basement, a ground floor, and four additional floors, and flat roof on top. Hospital operates continuously, providing services 24 hours a day, every day of the year.

Figure 1 (a) Satellite view of hospital complex, and (b) visual representation of selected hospital building

The building envelope consists of brick blocks, without thermal insulation and wooden windows, with triple glazing filled with argon. During 2017-2018, the building was renovated and the old windows, with aluminium profiles, were replaced with the new wooden frame windows. The heat transfer coefficient of the new windows is 1.0 W/m^2K. However, heat energy losses are present, due to the low energy characteristics of building external wall. The flat roof is constructed as reinforced concrete slab with 4 cm of thermal insulation.

Table 1 Basic data on building geometry and heat transfer coefficients for key construction elements

Construction element	External wall	Roof	Ground floor	Windows
Total surface area / m^2	2260	923	923	1216
Heat transfer coeff. / W/m^2K	1.698	0.602	0.256	1.0
Net heated surface area / m^2	4698			
Net heated volume / m^3	16787			
Building compactness ratio	0.28			

The heat transfer coefficients for key construction elements, as well as basic data on building geometry, are shown in Tab. 1. According to the provisions of the Rulebook on technical requirements for thermal insulation of buildings and rational use of energy, it is determined that heat transfer coefficient of external wall, ground floor and flat roof do not comply with the requirements set by national regulations [13].

The hospital building is supplied with energy from highly efficient industrial steam boilers, located in the central boiler room, which uses natural gas as fuel. Energy for heating and domestic water heating (DWH) is supplied to the buildings via heating substations (Fig. 2). Two water tanks are installed in heating substation for the preparation of DWH. The overall efficiency of the system, including the boiler room, distribution and internal installations and components, is 93.1%. The hospital building has a radiator heating system for building heating and a central cooling system that serves only a small part of the building.

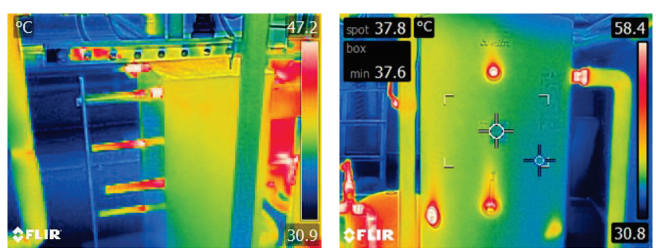

Figure 2 Thermal image of heating substation and DWH storage tank

2.2 Modelling the Energy Performance of the Representative Hospital Building

Design Builder is a software that incorporates the EnergyPlus simulation tool, and it was used for modelling building energy performance in this study. It provides dynamic simulations of building energy performance, including the analysis of heating, cooling, DWH, ventilation, lighting, and other systems [14, 15].

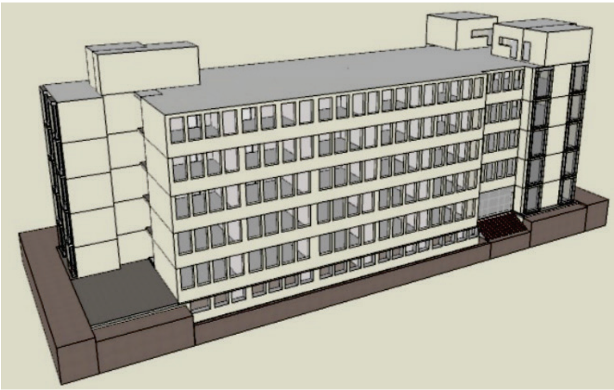

Figure 3 3D model of hospital building designed in Design Builder

The 3D model of hospital building designed in Design Builder is shown in Fig. 3. For building energy performance simulation, EnergyPlus utilizes hourly data to define external conditions in the calculations. These data, monitored by the National Meteorological Service, include parameters such as air temperature, atmospheric conditions, solar radiation, wind speed and direction, and are specific for the building location [14].

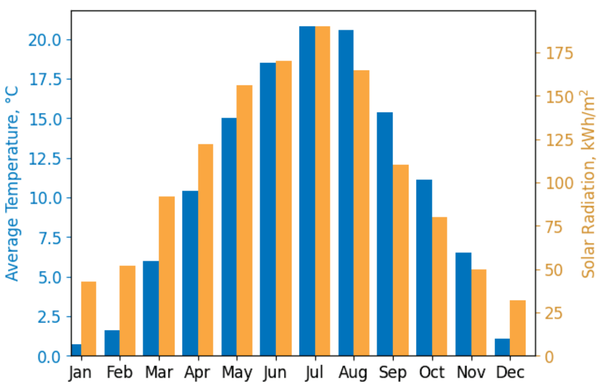

Figure 4 Climatic data for Sarajevo

The hospital building is located in Sarajevo (Capital of B&H), in a northern climate zone, 43.85 latitude and 18.14 longitude. Sarajevo climate is characterized by warm summers, cold and snowy winters, and partial cloudiness throughout the year. The official Heating Degree Days (HDD) for Sarajevo is 3077 [16]. The warmest month is typically July, with an average temperature of 20.8 °C, while the coldest month is January with an average lowest daily temperature of 0.7, as shown in Fig. 4. In terms of solar radiation, July is the brightest month in Sarajevo, while December is the darkest [17].

The zoning of the interior space of the hospital building is performed out according to the hospital layout, where internal design temperature of each zone was specified by the standard BAS EN 12831.

The total primary energy E_{prim}, which includes energy needs for heating, DWH and electrical energy, is calculated using following equation [13]:

$$E_{prim} = \frac{Q_{H,nd} + Q_{DWH}}{\eta_{sist}} f_{p,gas} + E_{el} f_{p,el} \tag{1}$$

where E_{prim} is the annual primary energy consumption in kWh/ann., $Q_{H,nd}$ is annual energy need for heating in kWh/ann., Q_{DWH} is annual energy need for DWH in kWh/ann., η_{sist} is overall system efficiency in %, E_{el} is annual consumption of electricity from the electrical grid in kWh/ann., f_p is fuel primary energy factor (1.1 for natural gas, and 3.0 for electricity) [13].

Annual CO_2 emission, is calculated according to the following equation [13]:

$$m_{CO_2} = \frac{Q_{H,nd} + Q_{DWH}}{\eta_{sist}} c_{p,gas} + E_{el} c_{p,el} \tag{2}$$

where m_{CO2} is annual CO_2 emission in kg/ann., c_p is CO_2 fuel coefficient per unit of energy (0.2 kg/kWh of natural gas, and 0.745 kg/kWh of electricity) [13].

Electricity E_{el} is calculated as total electricity needed, reduced by electricity produced from photovoltaic power plant, which also affect the reduction of CO_2 emissions.

2.3 Energy Renovation Measures

The renovation measures analysed in this study aim to reduce building envelope energy losses and provide electricity from renewable energy sources. Three measures are considered: installation of thermal insulation on the external wall (M1) and on the flat roof (M2), and installation of a photovoltaic power plant on the flat roof (M3). These measures will ensure that energy consumption for heating and electricity is reduced, and according to Eq. (2) and (3), will result in a reduction of primary energy and CO_2 emissions [18-20].

In the current state, the hospital external wall has no thermal insulation. To examine the impact of adding thermal insulation on primary energy consumption and CO_2 emissions, rock wool with a thermal conductivity of 0.033 W/mK is selected as the insulation material. Rock wool offers benefits such as improved acoustics, indoor comfort, and fire safety [21, 22]. Implementing this measure will reduce the external wall heat transfer coefficient U_{wall}, as presented in the next section. The maximum wall thermal insulation thickness analysed in this study is 20 cm. The hospital flat roof has a layer of 4 cm thermal insulation. This helps in reduction of energy losses through this envelope element. To analyse energy and CO_2 saving potential by installing additional thermal insulation on flat roof, installation of perlite board with thermal conductivity of 0.052 W/mK was analysed. Implementing this measure will reduce the roof wall heat transfer coefficient U_{roof}, as presented in the next section. The maximum roof thermal insulation thickness analysed in this study is 25 cm. Installation of photovoltaic power plant on the flat roof will ensure that a portion of the electricity consumed in the hospital is provided from renewable energy sources. The surface area available for the installation of the photovoltaic power plant is a crucial factor in determining the power output. The total area of the roof available for installation of photovoltaic panels is 566 m^2 that is 60% of the roof surface area. Therefore, the maximum installed power of photovoltaic power plant is estimated to be 80 kW.

Selected measures are represented by factors considered in this study, as shown in the following section.

2.4 Design of Experiments

Design of Experiments (DOE) is a multipurpose methodology used in various fields for identification of important input factors and their influence on the output variables or responses. In DOE, several key steps are involved as follows: determination of input variables (factors) and their levels, selection of output variables (responses), selection of the appropriate experimental design, conducting experiments or simulations, analysis of the obtained results and drawing objective conclusions.

In this study, FFD was used to establish relationships between primary energy consumption and CO_2 emissions, and the three renovation measures (M1, M2, M3), representing three factors. The considered factors are the wall heat transfer coefficient (U_{wall}), heat transfer coefficient of flat roof (U_{roof}) and the power of the photovoltaic power plant installed on the roof (P_{pv}). Factors are considered at two levels, low level (–1) and high level (+1). For the wall heat transfer coefficient (U_{wall}), levels -1 and +1 represent wall without insulation and wall with 20 cm of insulation, respectively. Similarly, for the heat transfer coefficient of a flat roof (U_{roof}), levels -1 and +1 represent roof in its baseline state and roof with 25 cm of thermal insulation, respectively. Finally, for the photovoltaic power plant installation on the roof (P_{pv}), level -1 represents no electricity production from renewable energy sources and a plant power of 0 kW, while level +1 represents plant with installed power of 80 kW. Factors considered in this study and their levels are shown in Tab. 2.

Table 2 Considered factors and their levels

Factor/Related measure	Level	
	–1	1
	Baseline	After renovation
U_{wall} / W/m^{2}K (M1)	1.698	0.272
U_{roof} / W/m^{2}K (M2)	0.602	0.218
P_{pv} / kW (M3)	0	80

For FFD with three factors, each on two levels, appropriate experimental design is 2^3 full factorial design. The experimental matrix contains 8 simulations, with each simulation run representing specific combination of factor levels and corresponding primary energy and CO_2 emissions estimates, as shown in Section 3.2.

The investment costs for each renovation measure are estimated when measures are implemented at their high level (+1). The investment cost for Measure 1 (M1) is 101000 Euros, for Measure 2 (M2) it is 63800 Euros, and for Measure 3 (M3) it is 57900 Euros. However, it is not possible to evaluate the simple payback period for these three renovation measures using DOE methodology at different renovation levels ranging from (–1) to (+1). As highlighted in the study [23], the total costs of renovation measures show sharp increase at level (–0.99) and higher, due to incurring fixed costs associated with the implementation of measures. The total cost of renovation measures is the sum of fixed costs and variable costs, which increase as the level of renovation increases. Consequently, it's not possible to establish a linear mathematical relationship between renovation costs and renovation measures levels ranging from (–1) to (+1). Nevertheless, cost analysis remains crucial and can be utilized in conjunction with modelled energy savings for renovation optimization, as demonstrated in [24]. This aspect is considered for future studies on this topic.

3 RESULTS AND DISCUSSION

After determining the required input parameters, the building's energy performances are calculated using methodology presented in previous section. Also, simulated building energy consumption is validated with the actual annual energy consumption of hospital building. Following, the FFD is used to analyse the impact of selected factors on the building primary energy and CO_2 emissions.

3.1 Building Energy Performance and Validation of the Results

The building model was validated by comparison of the simulated energy consumption obtained by Design Builder with the actual annual energy consumption of the hospital building. The actual energy consumption was obtained based on gas and electricity bills, aggregated for the entire hospital complex. To determine the consumption only for the analysed building, total energy consumption was scaled in relation to the ratio of gross heating surface of analysed building and gross heating surface of the hospital complex. Comparison of actual and modelled annual energy consumptions are shown in Tab. 3.

Table 3 Comparison of actual and modelled annual energy consumption

	Annual electricity consumption / kWh	Annual heating and DWH energy consumption / kWh
Actual data	367359	993213
Model	348936	1056584
Relative error	5.01%	–6.38%

The validation results are very satisfactory and show a relative percentage error ranging from 5.01 to 6.38% of heating, DWH and electricity consumption. This error percentage could be reduced if there were installed heat meters and electricity consumption meters for each building of the hospital complex separately, showing actual consumption of each building in hospital complex. In any case, the obtained results confirm that the model created in the Design Builder provides reliable simulation of the real building.

Fig. 5 shows hourly diagram of fuel consumption, temperature changes and heat balance for January.

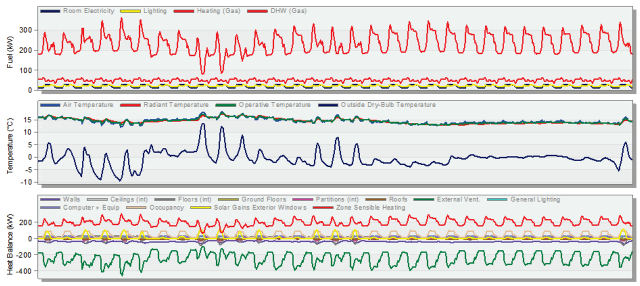

Figure 5 Hourly diagram of fuel consumption, temperature variation and heat balance for January

From Fig. 5, it is noticeable that variations in fuel consumption follow the variations of external temperature, so the highest fuel consumption is in the period of the lowest external temperatures. The heat balance diagram shows that heat losses through building envelope are compensated primarily by thermal energy supplied by the heating system, and by heat gains from the lighting, electrical devices, occupants, and solar gains.

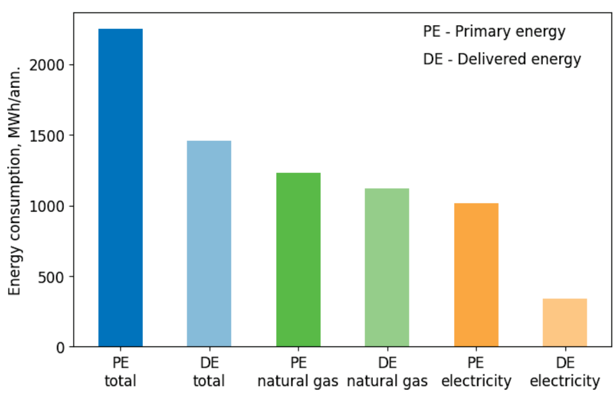

Figure 6 Annual building primary and delivered energy

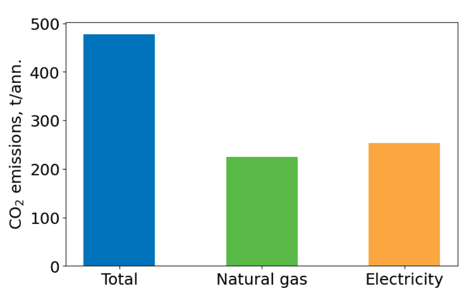

Figure 7 Annual building CO_2 emissions

Fig. 6 shows building annual primary and delivered energy. Natural gas share is 45.3% in total primary energy, while electricity share is 54.7%. Primary energy is greater than delivered energy by 35%, due to losses in the fuel processing, thermal conversion, and transmission and distribution to the hospital.

Fig. 7 presents total annual CO_2 emissions, as well as the share of natural gas and electricity in the total emissions. Natural gas and electricity have a total share in CO_2 emissions of 47.1% and 52.9%, respectively.

3.2 Design of experiments, ANOVA and regression analysis

Analysis of variance (ANOVA) and regression analysis were used for statistical analysis, with the aim of developing of regression models for predicting the building primary energy consumption and CO_2 emissions. The experimental matrix, with coded factor levels and calculated building primary energy consumption and CO_2 emissions, for each simulation, is presented in Tab. 4.

Table 4 Experimental matrix

Exp	M1	M2	M3	m_{CO2} / t/ann.	E_{prim} / MWh/ann.
1	–1	–1	–1	477.8	2250.2
2	1	–1	–1	438.9	2036.5
3	–1	1	–1	466.5	2188.7
4	1	1	–1	432.5	2000.0
5	–1	–1	1	413.2	1991.0
6	1	–1	1	374.3	1777.2
7	–1	1	1	402.0	1929.4
8	1	1	1	367.9	1740.7

ANOVA is used to determine statistical significance of all factors and their influence on the response variables, building primary energy consumption and CO_2 emissions. In this study, ANOVA was performed at a significance level of 0.05. The results of ANOVA, with only statistically significant terms and their corresponding *F* and *p*-values, are presented in Tab. 5 for building primary energy, and Tab. 6 for CO_2 emissions.

Table 5 ANOVA of the model for prediction of building primary energy consumption E_{prim}

Source	Degrees of Freedom	Sum of Squares	Mean Square	*F*-value	*p*-value
Model	3	220216	73405	933.31	0.000
A (U_{wall})	1	80968	80968	1029.46	0.000
B (U_{roof})	1	4809	4809	61.15	0.001
C (P_{PV})	1	134439	134439	1709.32	0.000
Error	4	315	79		
Total	7				

Table 6 ANOVA of the model for prediction of CO_2 emissions m_{CO2}

Source	Degrees of Freedom	Sum of Squares	Mean Square	*F*-value	*p*-value
Model	3	11157.0	3719.00	1298.97	0.000
A (U_{wall})	1	2661.8	2661.84	929.72	0.000
B (U_{roof})	1	156.9	156.85	54.79	0.002
C (P_{PV})	1	8338.3	8338.30	2912.39	0.000
Error	4	11.5	2.86		
Total	7				

The results of ANOVA presented in Tab. 5 and 6 show significantly large *F*-values and significantly small *p*-values. In both cases, primary energy and CO_2 emissions, the *p*-values of all factors are less than 0.05, indicating significant impact of all model terms on primary energy of building and CO_2 emissions. The greatest impacts on the building primary energy and CO_2 emissions result from implementation of measure M3, the installation of photovoltaic power plant on the roof of the building, and measure M1, the installation of thermal insulation on the external walls of the building. Given that there is already 4 cm of thermal insulation on the flat roof, it is shown that installation of an additional insulation layer of on the roof will not significantly affect primary energy and CO_2 emissions in comparison to the other two measures (M1 and M3). As a result, the implementation of measure M2 according to ANOVA is ranked as the measure with the least impact on primary consumption and CO_2 emissions.

The regression models for predicting building primary energy consumption and CO_2 emissions are given by the following expressions:

$$E_{\text{prim}} = 1989.21 - 100.60 U_{\text{wall}} - 24.52 U_{\text{roof}} - 129.63 P_{\text{pv}} \quad (3)$$

$$m_{CO_2} = 421.64 - 18.24 U_{\text{wall}} - 4.43 U_{\text{roof}} - 32.28 P_{\text{pv}} \quad (4)$$

The high values of the R^2 coefficients for model of building primary energy consumption (adjusted R^2 = 99.75 %, and predicted R^2= 99.43 %), and CO_2 emission (adjusted R^2 = 99.82 %, and predicted R^2= 99.59 %), indicate high accuracy in prediction of responses.

The main effect plot in Fig. 8 and 9 shows the impact of wall heat transfer coefficient (A, U_{wall}), heat transfer coefficient of the flat roof (B, U_{roof}), and photovoltaic plant power (C, P_{pv}) on building primary energy consumption and CO_2 emissions, respectively. It is evident that the installation of a photovoltaic power plant has the most significant effect on the response, followed by installing thermal insulation on external wall. Installation of additional thermal insulation on the flat roof has the least effect on primary energy consumption and CO_2 emissions.

When examining the impact of installing a photovoltaic power plant on the primary energy consumption, it can be observed that primary energy consumption decreases from 2118 MWh annually (when the PV plant is not installed, denoted as $P_{\text{pv}} = -1$) to 1860 MWh annually (when the 80 kW PV plant is installed, denoted as $P_{\text{pv}} = +1$). Simultaneously, CO_2 emissions decreases from 454 tons annually ($P_{\text{pv}} = -1$) to 389 tons annually ($P_{\text{pv}} = +1$). The effect of installing thermal insulation on the external wall on the primary energy consumption and CO_2 emissions is less pronounced, but still significant. Primary energy consumption is reduced from 2089 MWh annually (when the wall is not insulated, denoted as $U_{\text{wall}} = -1$) to 1888 MWh annually (when the wall is insulated with 20 cm of thermal insulation, denoted as $U_{\text{wall}} = +1$). Similarly, CO_2 emissions decreases from 440 tons annually ($U_{\text{wall}} = -1$) to 403 tons annually ($U_{\text{wall}} = +1$). The effect of installing the additional thermal insulation on the flat roof on the primary energy consumption and CO_2 emissions is the lowest among the three measures. With additional roof insulation, primary energy consumption is reduced from 2014 MWh annually (when the roof is insulated with 4 cm of thermal insulation in the current state, denoted as $U_{\text{roof}} = -1$) to 1985 MWh annually (when the roof is insulated with 25 cm of thermal insulation, denoted as $U_{\text{roof}} = +1$). CO_2 emissions decreases from 426 tons annually ($U_{\text{roof}} = -1$) to 417 tons annually ($U_{\text{roof}} = +1$).

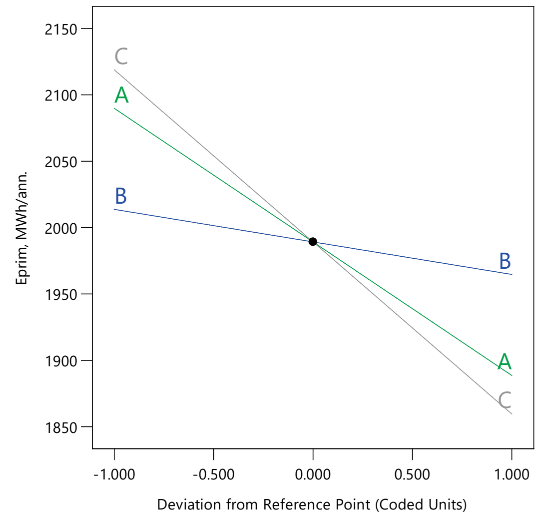

Figure 8 Main effects plot for E_{prim}

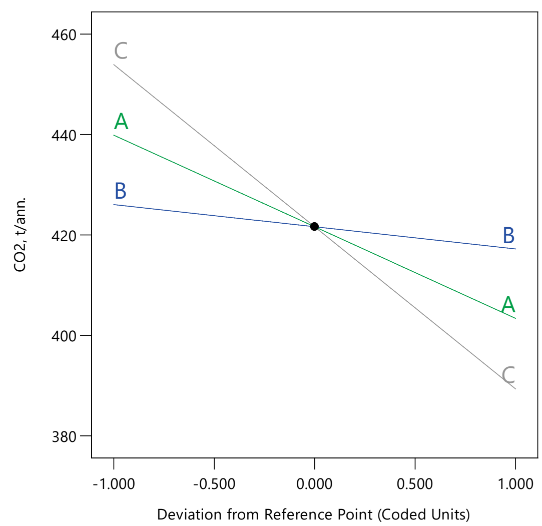

Figure 9 Main effects plot for m_{CO2}

All three energy renovation measures, installing a PV plant, installing thermal insulation on the external wall, and installing the additional thermal insulation on the flat roof contribute to reductions in both primary energy consumption and CO_2 emissions, whereby the installation of the photovoltaic power plant has the most significant impact.

From Fig. 8 and 9, it can be clearly seen that the implementation of energy renovation measures (installation of thermal insulation on the external walls and flat roof, as well as installation of the photovoltaic power plant on the roof of the building) result in reduction of both, primary energy consumption and CO_2 emissions. This is also visible in 3D response surface plots of primary energy and CO_2 emissions, presented in Fig. 10 and 11.

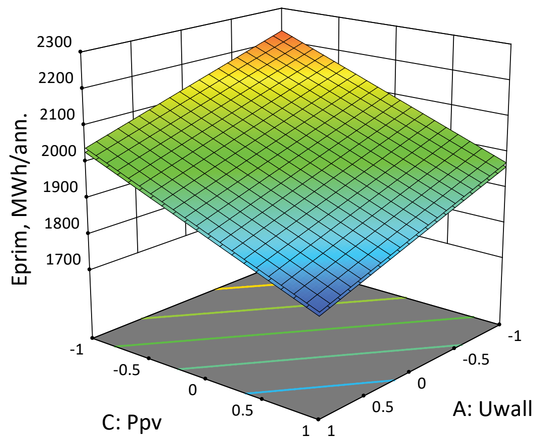

Figure 10 3D response surface plot of E_{prim} as a function of U_{wall} and P_{pv}

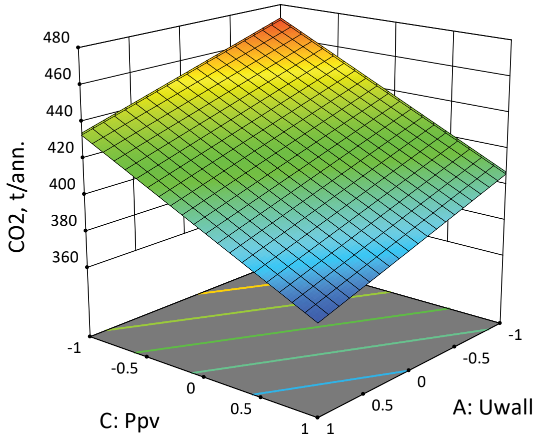

Figure 11 3D response surface plot of m_{CO2} as a function of U_{wall} and P_{pv}

4 CONCLUSIONS

This study demonstrates the benefits of dynamic simulations combined with DOE and regression analysis to model energy performance and identify optimal energy efficiency measures for hospital buildings. The effects of implementing various energy renovation measures on the primary energy consumption and CO_2 emissions of hospital building are analysed.

Hospitals are known to consume significant amount of energy, with energy use intensity being one of the highest among all building types, providing large energy saving potential. In this study, impact of three energy renovation measures on primary energy and CO_2 emission were considered: installing thermal insulation on the external walls and roof and installing photovoltaic power plant.

Hospital building model is designed in Design Builder software, following dynamic simulations of energy performances considering parameters such as climatic conditions, architectural and construction characteristics, installed technical systems, and fuel used. Modelled energy performances of the hospital building, in the current state, show a high agreement with actual energy consumption data, hence validating the accuracy of the building model.

Using Design of Experiments (DOE), followed by ANOVA and regression analysis, mathematical relationships between primary energy consumption and CO_2 emissions (responses) and the renovation measures (factors), were established. The regression models developed in this study enable estimation of primary energy and CO_2 emissions based on renovation measure levels. The analysis revealed that installing photovoltaic power plant and thermal insulation on external walls have the greatest impact on reducing building primary energy and CO_2 emissions. Therefore, study results show that it is possible to develop the mathematical model for prediction of energy performances as a function of various renovation measures, and to use statistical analysis to identify optimal energy renovation measures for hospital buildings.

The research presents a unique dataset of energy characteristics of hospital buildings for various renovation options and levels. Given the lack of studies related to energy renovation in hospital buildings, findings from this study are valuable and may be applicable to other buildings within the healthcare sector. Future research should focus on renovation optimization in healthcare buildings, considering energy and CO_2 emission savings, as well as cost analysis. Presented study results and related analysis will contribute to the broader goal of reducing energy consumption and CO_2 emissions in the built environment, particularly in the healthcare sector.

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