FINAL METHOD FOR SELECTION OF THE OPTIMAL SOLUTION FOR DEEP ENERGY RENOVATION OF A BUILDING

by

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The great potential for reduction of CO_2 emissions lies in the deep energy renovation of buildings that exploits the full potential of improving energy efficiency in buildings to maximize energy savings and minimize energy costs. However, in addition to the technical parameters, it is necessary to analyze the willingness of the client to pay for deep energy renovation. This paper presents a methodology applicable to all types of buildings that in a relatively short time provides an optimal solution that meets both parameters – technical and economic, while satisfying the legal requirements. The method was tested by simultaneous use of DESIGNBUILDER software package (which uses ENERGYPLUS as its dynamic simulation engine), PYTHON and SQL programming languages on an office building in the city of Zagreb, where a total of 720 combinations of building deep energy renovation were analyzed. In the analyzed case, it was proved that the application of this methodology results in obtaining the output values 20.51 times faster than the classical input of all combinations of deep energy renovation of the building in software tools. In addition, the probability of human error is much lower by applying this methodology given large amount of input data.

Key words: *deep energy building renovation, energy efficiency measures, optimal combination*

Introduction

In the EU, buildings are responsible for approximately 40% of final energy consumption and 36% of CO_2 emissions, making them a significant untapped potential for energy savings and reduction of greenhouse gas emissions [1]. Increasing energy efficiency in the building sector is being promoted through various policies to reduce energy consumption and costs making buildings more energy efficient and less dependent on fossil fuels. Thus, from 2020, all newly built buildings in the EU must meet Nearly zero energy building (nZEB) standards [2]. Further policy developments will likely prescribe that, as of 2030, all new buildings must be zero-emission buildings [3]. All of the mentioned shows that significant efforts are being made in the building sector for its decarbonization, so it is necessary to keep pace with new policies and to increase the rate and stage or degree of buildings renovations.

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Energy consumption in buildings, and consequently the CO_2 emission can be significantly reduced by improving the building envelope by reducing the heat transfer coefficient, which can be achieved by increasing envelope insulation and replacing windows. Thus, increasing the thickness of the thermal insulation results in a cumulative drop in the annual heat load and an increase in the cooling load. But due to the small range of cooling load increase, this effect can be neglected [4]. Based on research on 672 representative residential models of EU-28 buildings, it was shown that only improving the vertical envelope could reduce environmental impacts on the residential sector by about 6-19% in all analyzed environmental impact categories accounted, where some of those categories are climate change, ozone depletion, human toxicity, *etc.* [5]. Furthermore, research results on commercial buildings in the UK show that replacing single-glazed windows with double-glazed windows or alternative new glass can result in energy savings ranging from 39% to 53% [6]. When it comes to HVAC systems, numerous studies show methods of selecting the optimal solution. Thus, [7] shows how to choose the best HVAC system in a set of 11 alternative solutions for industrial buildings, while [8] uses a well-tested building simulation model to evaluate the effectiveness of 12 existing HVAC cooling strategies to reduce overall cooling energy consumption. However, it is not enough to focus exclusively on individual renovation measures (renovation related to the building envelope or the technical building system), it is necessary to implement an integrated strategy of deep renovation that exploits the full potential of improving energy efficiency in buildings to achieve maximum energy savings [9].

Over the last decades, many papers have been presented dealing with the research of deep energy renovation of buildings, where most research is focused exclusively on specific types of buildings, mostly the residential buildings, and less the non-residential buildings (public and commercial) [10-13]. Deep energy renovation of buildings includes various energy efficiency measures (architectural, construction, mechanical, electrical) as energy conservation measures in existing buildings that lead to an overall improvement in building performance, *i.e.*, on-site energy use minimization in a building. It was investigated in [14] that deep renovation of buildings together with a holistic approach can result in a reduction of final energy consumption by 60-90%, depending on the type of building, the year of construction and the climatic zone in which the building is located. In addition to technical parameters, it is necessary to analyze the willingness of the client to pay for deep renovation, given that focusing exclusively on energy efficiency optimization does not meet the overall requirements [15]. Thus, in [16] an approach was developed to assess and differentiate the cost-effectiveness of deep renovation within a portfolio of buildings using equivalent annual costs and change in the estimated value of the building. Furthermore, in research [17] the selected project solutions for energy saving up to the nZEB level were considered, as well as the consequent costs in the selected residential building representative of the Bologna housing stock. However, the cost-effectiveness of deep renovation should be assessed from building to building, not for the area or neighborhood [16], since building descriptions based on representative buildings lose accuracy [18]. In addition, one of the essential requirements when implementing deep renovation of buildings is compliance with the requirements of the existing legal framework. Thus, the question arises: how to choose the right integrated strategy that includes the synergy of technical and economic parameters while meeting the legal requirements during the deep energy renovation of an individual building (whether residential or non-residential)? One way to solve the described problem can be a heuristic solution based on the knowledge and experience of experts. Such an approach is characterized by a small number of alternatives, investing too much time, as well as the closeness of the optimal solution [19]. Another solution may be various optimization techniques using advanced software tools since today there are numerous computer programs for analyzing the dynamic behavior of buildings and the performance of technical building systems [20-22]. This solution has been applied in this paper but has been upgraded with process automation thus making a new methodology for selecting optimal solution among huge number of solutions in a relatively short time. In addition, the methodology applies to all types of buildings – residential and non-residential, and the result of the methodology applied is an optimal solution that meets two criteria: the minimum value of primary energy and the minimum value of building life cycle cost of implementing the deep energy renovation measures (all the costs that will be incurred during the lifetime of the product, work or service), while satisfying the legal requirements.

Methodology

The methodology for selecting the optimal combination of deep energy renovation measures for of a building is graphically shown in fig. 1. The first step is to enter the existing condition of the building (hereinafter referred to as the reference building) in one of the advanced software packages. The reference building includes building construction data, technical data, occupancy, and operation schedules data obtained based on actual data on consumption and behavior of building users, as well as climatic data. After correctly entering the reference building data into the software tool and verifying the software tool used, it is possible to implement an almost infinite number of combinations of building reconstruction measures through energy simulations. This step is the core of the whole research methodology, so it is elaborated in more detail in the following chapter.

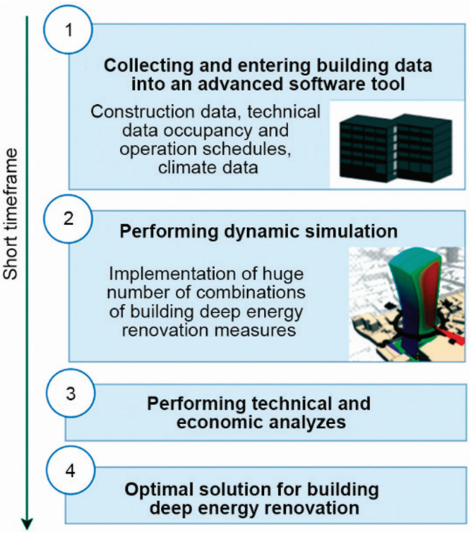

Figure 1. A schematic view of methodology

Automation of dynamic simulations

The flow chart of the process automation is shown in fig. 2 and each of the steps is described in more detail in separate subchapters.

Relevant data collection

The first step in automating the implementation of dynamic simulations is the collection of relevant technical data from manufacturers that include nominal heating/cooling capacities as well as COP and energy efficiency ratios (EER) at different source temperatures and flow temperatures of the heating/cooling medium. In addition, technical data on heating/cooling bodies or emitters (radiators and fan coil units) were also obtained from the manufacturer. Furthermore, the prices of heat/cooling energy sources, as well as heating/cooling bodies were obtained, which were used in the evaluation of the selection of the optimal solution, which is described in the chapters later. Data collection is followed by data processing and analysis using multiple linear regression to obtain biquadratic curves

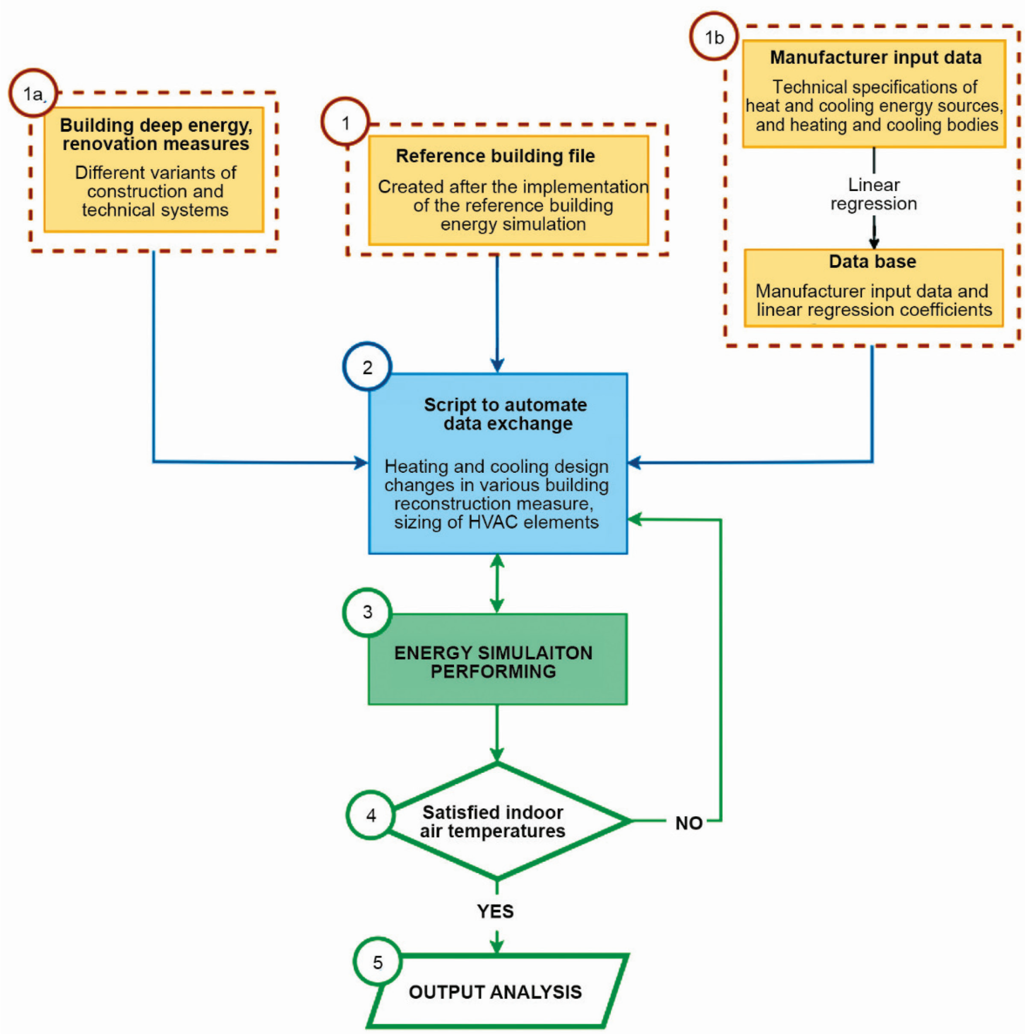

Figure 2. Flow chart of the process automation

describing changes in heating capacity, COP, cooling capacity and EER as a function of the outdoor air temperature and hot water temperature of the heating medium or cold water temperature of cooling medium. Biquadratic curve is given in eq. (1), where parameter x describes the external temperature of the heating/cooling source and y describes the hot water temperature of the heating medium or cold water temperature of cooling medium, while z describes the curve output, *i.e.*, heating/cooling capacity and heating/cooling power of energy source:

$$z = C_1 + C_2x + C_3x^2 + C_4y + C_5y^2 + C_6xy \tag{1}$$

The coefficients obtained by multiple linear regression, together with the nominal values of the operating characteristics of the heating/cooling energy source and the technical specifications of the heating and cooling bodies, were stored in a database according to manufacturer’s models.

Automation of data exchange from the database according to different variants of building deep energy renovation measures

Based on the building reference model, it is necessary to generate two files: a heating and cooling design file and simulation file. Using scripts that can be written in various programming languages, it is possible to analyze many changes in the files and generate input files for the next simulation run. Therefore, in this step, it is necessary to define different variants of deep energy renovation of the building that include construction, mechanical and electrical measures. Based on the reference file for heating and cooling design and using script, building construction elements and electrical systems are changed according to defined deep energy renovation variants to obtain the required heat and cooling loads for each zone of the building. Then the heating and cooling loads are stored in the database for all defined building deep energy renovation variants.

As already mentioned, the reference building model also generated a simulation file, where all analyzed HVAC systems were modelled with its input data to perform dynamic energy simulations in an external computer simulation environment. With the use of the script, two algorithms were performed to select appropriate heating/cooling bodies and heating and cooling capacities of the source based on the heating and cooling designs stored in a database for all deep energy renovation variants and a real number of cooling and heating bodies that could be installed in zones. Thus, the algorithm selects the first model of heating and cooling bodies for each zone of the building, where their capacity is higher than the heating/cooling design for the same zones. This algorithm is the input to the following algorithm for selecting the heating and cooling energy sources from the database where their capacity is greater than the total capacity of heating/cooling bodies, required capacity for domestic hot water preparation and total capacity of air conditioner heaters and coolers.

Performing and control of dynamic energy simulation

Using the described algorithms, it is possible to prepare input data for energy simulations in DESIGNBUILDER software package of many possible combinations of building deep energy renovation solutions limited only by computer storage space. To further reduce the duration of the run simulation time, folders with algorithm scripts, databases, and heating and cooling design files, as well as simulation input data files had been transferred to several virtual machines, a computer files that behaves like an actual computer, where multiple simulation processes of all combinations started running simultaneously. The indoor air temperatures of zones were monitored after each simulation as the output of simulation, where an error tolerance limit needs to be set. If the indoor air temperature is within the set error, the output is considered satisfied, otherwise the simulation file is corrected so that the algorithm selects higher energy source capacity to meet temperatures and simulations are performed again so that the results are within the given limits.

Output analysis for optimal deep energy renovation solution selection

After the implementation of energy simulations, the annual energy needs for space heating, domestic hot water (DHW) preparation, and space cooling, capacities of heat/cooling energy sources, energy consumption, energy production, CO_2 emissions are obtained as outputs for each deep energy renovation solution. All the mentioned is obtained for different energy sources like electricity, natural gas, district heating, *etc.*, depending on the heat/cooling energy generator that characterizes the analyzed solution of deep energy renovation measures. Based on these outputs, it is possible to obtain primary energy values and building life cycle cost for each combination of building deep energy renovation. Annual primary energy consumption is determined based on the product of the total amount of energy supplied to the building for each combination of measures and national factors for primary energy for individual energy sources. A primary energy factor describes the ratio between final energy consumption and primary energy consumption of a certain energy source. In recent times, the EU has implemented regulatory use of these factors in the energy policy framework, and each country has its own factors depending on the method of energy conversion. Building life cycle cost is the sum of the investment cost (thermal protection of the outer envelope, technical systems for heating, cooling, ventilation, domestic hot water and lighting) and operating costs for energy throughout buildings lifetime, as well as the cost of replacing the system or part the system after the end of their lifetime. Additionally, when calculating the building life cycle cost, the discount rate is considered, which is a measure of reducing future monetary amounts or receipts to the present value. The optimal combination of deep renovation of a building is one that has minimal building life cycle costs and primary energy. In addition, legal regulations are defined as restrictions, where those combinations that do not meet the prescribed legal restriction are not analyzed.

Model and input data description

Within this chapter, the building on which the previously described methodology was tested is described, as well as combinations of measures for the deep energy renovation of that building.

Description of reference building

The methodology described in the previous chapter was implemented on an office building located in the city of Zagreb, which is oriented in a north-south direction. In terms of floor plan, it consists of two squares interconnected by a rectangle, and contains 7 floors: basement, ground floor, 4 floors and attic (architectural plans in *Appendix A*, and 3-D model of reference building in *Appendix B*). On all floors there are mostly office spaces and rooms for conferences and meetings. The total occupied area of the building is 2232.2 m^2, while the total occupied volume is 6567.3 m^3. The building envelope constructions generally do not meet the requirements of current regulations [23] regarding maximum thermal transmittance, *i.e.*, U-value [$\text{Wm}^{-2}\text{K}^{-1}$]. Currently, the thickness of the thermal insulation of the external wall and flat roof is 10 cm, which corresponds to the U-value of the external wall of 0.39 $\text{W/m}^2\text{K}$, and the U-value of the flat roof of 0.29 $\text{W/m}^2\text{K}$. Window glazing consists of double-insulated glass with a low-emission coating, corresponding to a U-value of 1.40 $\text{W/m}^2\text{K}$. A building substation connected to the district heating system is used as a heat source for space heating and DHW preparation of the reference building with hot water as the primary medium supplied from the district heating system. Secondary medium is hot water with high temperature regime, the flow temperature is regulated depending on the outside temperature and at low outdoor temperatures reaches temperatures above 90 °C. Space cooling of the building is also solved centrally, where cold water is produced by an air-cooled chiller. The existing lighting system is dominated using fluorescent tubes and fluorescent lamps with the possibility of dimming the light flux depending on the natural lighting of the office space.

To conduct energy simulations and obtain the most accurate results, the building is divided into 10 zones. Table 1 shows all zones with the corresponding occupied areas, as well as heating/cooling bodies emitters located in them.

Table 1. Zones of the reference buildings with occupied area and corresponding heating/cooling bodies

Zone name	Floor area [m^2]	Heating	Cooling	Mechanical ventilation	Radiator	Fan coil unit	WMU*
Hallway	438.71	●	●	○	○	●	○
Toilettes	133.46	●	○	○	●	○	○
Offices – east part	597.10	●	●	○	○	●	○
Offices – west part	545.80	●	●	○	○	●	○
Meeting room	77.22	●	●	●	○	●	○
Server room	16.11	●	●	○	○	○	●
Machinery room	107.85	○	○	○	○	○	○
Showers	13.84	●	○	○	●	○	○
Conference room	160.01	●	●	●	○	●	○
Dining area	142.12	●	●	○	○	●	○

*WMU – wall-mounted unit

Deep energy renovation measures

In this chapter, different variants of alternative solutions for the deep renovation of the reference building are proposed. As shown in fig. 2, alternative solutions include:

- renovation of the building envelope (thermal insulation of building envelope, glazing),
- renovation of the technical building system,
    - energy sources for heating and cooling,
    - lighting system, and
    - installation of photovoltaic system.

The renovation of the building envelope is of prime importance to reduce the energy demand for space heating. During the analysis, variant solutions were made in the form of increasing the thermal insulation of the building envelope (primarily the external walls and ceiling to the attic) and replacing the glazing with more energy-efficient glazing. The material used as thermal insulation in all combinations is mineral wool with a thermal conductivity value of $\lambda = 0.036$ W/mK. As variants of glazing solutions, triple insulated glazing with low emission coating, ($U = 0.80$ W/m^{2}K), and triple insulated glazing with double low emission and reflective coating, ($U = 0.66$ W/m^{2}K), were analyzed.

As variants of HVAC systems solution, the following heating/cooling energy sources were analyzed:

- building substation connected to the district heating system for space heating and DHW preparation, air-cooled chiller for space cooling,
- micro cogeneration (micro CHP) with condensing boiler to cover peak load for space heating and DHW preparation, air-cooled chiller for space cooling,

- Air source heat pump (ASHP) for space heating, DHW preparation and space cooling, and and
- water source heat pump (WSHP) for space heating, DHW preparation and space cooling.

Types of heating/cooling bodies, as well as heated, cooled, and ventilated spaces are the same for all combinations of heat/cooling energy sources, while the capacity of the heating/cooling bodies differs according to the thermal protection variants of the building envelope and the lighting system.

As variants of the lighting system solutions, FC (fluorescent lamp), LED sources and LED lamps were analyzed. In addition, in all the above combinations, the analysis of the installation of the photovoltaic system on the available surfaces of the building is included. The photovoltaic system is not technologically dependent on other proposed measures, and since the installation of solar heat collectors on the roof surface of the building is not planned, it was not necessary to vary different technical solutions of the photovoltaic system depending on other proposed measures. In view of the above, the power of the photovoltaic system that can be installed on the available roof area of the office building, whose power is 65 kW, was selected. With this power of the photovoltaic system, it is possible to produce 60786 kWh of electricity.

Summary of analyzed measures is shown in fig. 3. In total, there are 720 possible combinations of the described measures. The previously described methodology (chapter *Methodolgy*) was applied to the measures, while the obtained results are presented and analyzed in the next chapter.

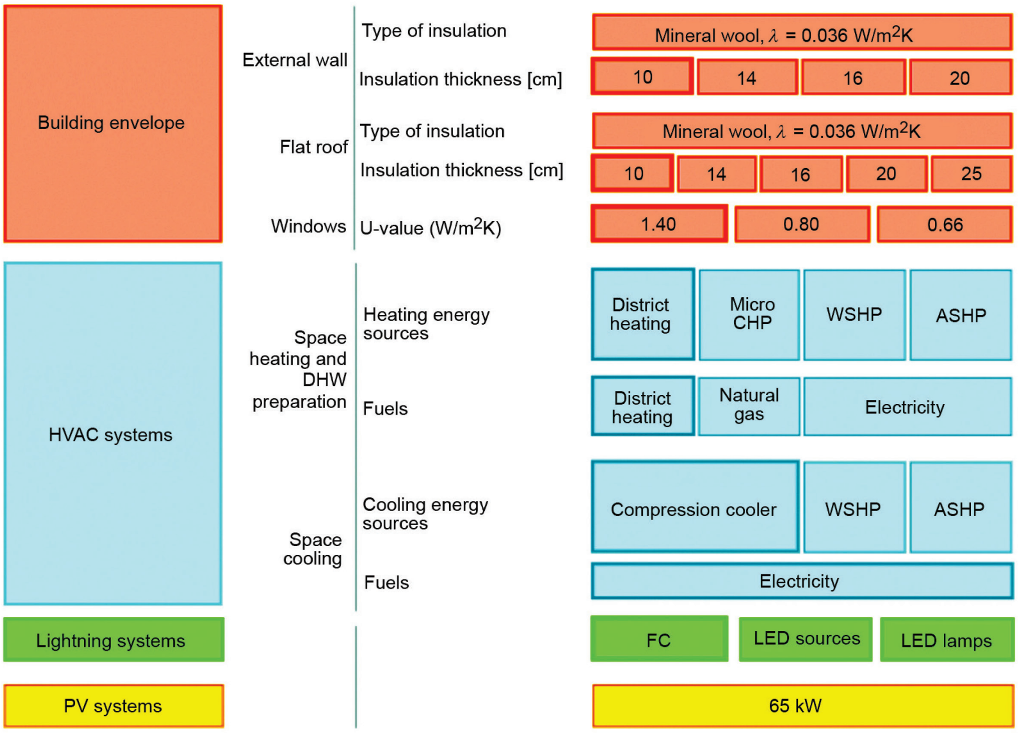

Figure 3. Summary of analyzed technical and construction solutions

Description of tools used to apply the methodology

All technical data (nominal heating/cooling capacities, COP, and EER at different source temperatures and flow temperatures of the heating/cooling medium, heating/cooling bodies or emitters), economic data (prices of heat/cooling energy sources, data on heating/cooling bodies), as well as coefficients obtained by linear regression using eq. (1) were stored in a database using SQL language. To generate the heating and cooling design files and simulation files, the DESIGNBUILDER software package [24], which uses ENERGYPLUS [20] as its dynamic simulation engine was used. According to [25], the heating and cooling loads modeled in ENERGYPLUS have acceptable deviations from the actual data and vary from 3% to 5%. The calculation of heating and cooling loads in ENERGYPLUS software is based on steady-state methods such as those offered by ASHRAE and CIBSE [26], where general simulation method and sizing methods are detailly described in ENERGYPLUS documentation, Engineering Reference [27]. Also ENERGYPLUS was tested with ANSI/ASHRAE Standard 140-2001 (BESTTEST) where it was compared with other whole building energy analysis programs and where it was shown how well ENERGYPLUS predicted thermal loads compared to the other programs, being with 58 out of 62 separate comparisons within the range of spread of results [28]. Furthermore, the simulation data obtained in the selected software tool significantly correspond to the actual data in the functioning of the building [29-31]. Therefore, by applying that software, it is possible to get quite accurate results.

By performing simulations of the reference model in DESIGNBUILDER software package [24], two IDF files were obtained: a heating and cooling design IDF file and simulation IDF file. With the use of PYTHON script and EPPY MODELEDITOR (ENERGYPLUS scripting language written in PYTHON), it is possible to analyze many changes in the IDF files and generate input files for the next simulation run. Based on the reference IDF file for heating and cooling design and using PYTHON script and EPPY MODELEDITOR, building construction elements and electrical systems are changed according to defined deep energy renovation variants (720 combinations) to obtain the required heat and cooling loads for each zone of the building. Then the heating and cooling loads are stored in the SQL database for all defined building deep energy renovation variants. Additionally, with the use of the PYTHON script, two algorithms were performed to select appropriate heating/cooling bodies and heating and cooling capacities of the source based on the heating and cooling designs stored in a database for all deep energy renovation variants and a real number of cooling and heating bodies that could be installed in zones. Thus, the algorithm selects the first model of heating and cooling bodies for each zone of the building, where their capacity is higher than the heating/cooling design for the same zones. This algorithm is the input to the following algorithm for selecting the heating and cooling energy sources from the database where their capacity is greater than the total capacity of heating/cooling bodies, required capacity for domestic hot water preparation and total capacity of air conditioner heaters and coolers.

Using the aforementioned algorithms, input data were prepared for a total of 720 combinations of deep energy renovation measures of a selected office building in Zagreb. The indoor air temperature was monitored after each simulation as the output of simulation and in the case that they were satisfying conditions with a 5% error, simulations were considered as valid and output results were stored in the database, otherwise, the corrected IDF file was generated to meet the conditions.

Results and discussion

The total time to obtain the IDF files of the heating and cooling design and the simulation IDF files for the 720 defined combinations of deep energy renovation of the building is 528.8 seconds (8.81 minutes). In the case of manually entering all combinations of measures and creating these IDF, this production time is estimated at 727.2 hours (4950.7 times slower than the proposed methodology), and it is highly dependent on the user experience. Thus, the probability of human error is much higher given the large number of inputs. After the creation of IDF files, the implementation of energy simulations and data processing for 720 combinations of deep energy renovation of the building, was carried out in 37.1 hours. In the case of using virtual machines, the time to obtain the results can be significantly reduced, depending on the number of available virtual machines (using four virtual machines means four times less time invested). Finally, the total time to obtain the final output values (excluding virtual machines) for all defined solutions using the proposed methodology is 37.25 hours, and the obtained output values are as:

- annual energy needs for space heating,
- annual energy needs for DHW preparation,
- annual energy needs for space cooling,
- heating and cooling capacity of heating/cooling energy sources,
- capacities of heating/cooling bodies for each zone,
- energy consumption,
- electricity generation - photovoltaic system and micro cogeneration, and
- the CO_2 emissions.

In terms of legal restrictions in Croatia for buildings located in continental part of the country (where the analyzed office building is located), all deep renovation combinations in which the annual specific primary energy has a value greater than 35 kWh/m^{2}a, the specific annual required energy for heating has a value greater than 22.21 kWh/m^{2}a, the heat transfer coefficient of the external wall has a value greater than 0.3 W/m^{2}K, the heat transfer coefficient of a flat roof has a value greater than 0.25 W/m^{2}K does not meet the requirements prescribed by applicable regulations in the Republic of Croatia [23]. The set of obtained deep renovation solutions is shown in fig. 4. All solutions represented by a point "●" meet the legal requirements in terms of the amount of annual energy required for space heating and the maximum values of heat transfer coefficients, while combinations marked with an "x" do not meet the legal requirements. Furthermore, the diagram shows the primary energy limit, where all combinations to the left of the primary energy limit meet the legal requirements of the total annual primary energy, while the combinations to the right of the primary energy limit do not meet these requirements. To determine the building life cycle cost, real data on investment and maintenance costs from the manufacturer, a discount rate of 5%, and a building lifetime of 20 years were used.

For the sake of a clearer presentation, only solutions that meet the conditions prescribed by the applicable regulations have been singled out and shown in fig. 5. These requirements are met by 135 solutions for deep renovation of the building (18.75% of the total analyzed solutions), of which: 81 solutions that use a WSHP as a heat/cooling source, 45 solutions that use an ASHP as a heating/cooling source and 9 combinations that use district heating as a heat source and a compression cooler as a cooling source. A total of 27 solutions of deep renovation that meet legal restrictions make the selected office building a positive energy building, which means that in these solutions the amount of energy produced onsite from RES is greater than the energy consumed. In all these combinations, a water source heat pump is used as a source of heating/cooling energy.

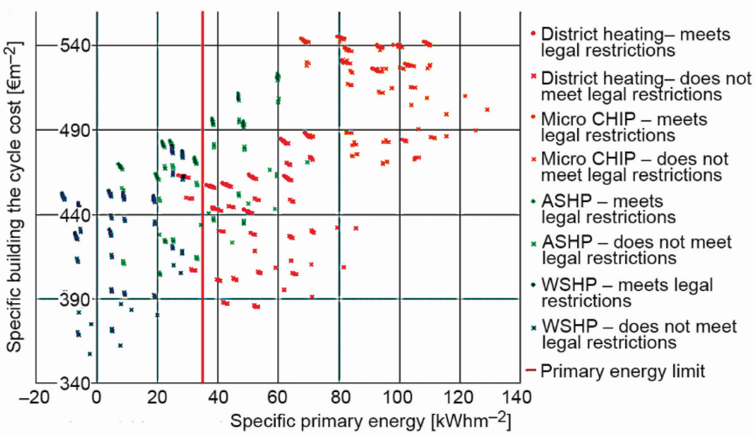

Figure 4. Dependence of specific primary energy and specific building life cycle cost for all building deep energy renovation solutions

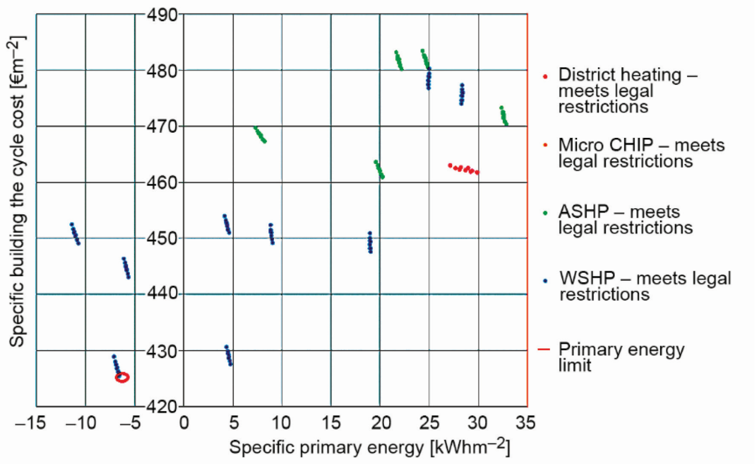

Figure 5. Dependence of specific primary energy and specific building life cycle cost for building deep energy renovation solutions that meet legal requirements

Considering the lowest specific building life cycle cost (425.5 €/m^2) and the corresponding amount of primary energy (–6 kWh/m^2), the optimal solution for deep energy renovation of the selected office building in Zagreb is the following solution: external wall insulation thickness of 14 cm, flat roof insulation thickness of 16 cm, window *U*-value of 1.40 W/m^{2}K, WSHP as a source of heating/cooling energy, LED lamps as a lighting system, and PV system of 65 kW, tab. 2. From the results shown, the windows will remain unchanged, which means that a satisfactory result can be achieved with the current windows.

Table 2. Optimal building deep energy renovation solutions according to specific building life cycle cost

Source of heating/cooling energy	E_{prim} [kWhm^{-2}a^{-1})]	Specific building life cycle cost [€m^{-2}]	Lighting system	External wall insulation thickness [cm]	Flat roof insulation thickness [cm]	Window U-value [Wm^{-2}K^{-1}]
WSHP	–6	425.5	LED lamps	14	16	1.40

In addition, tab. 3 presents the impact of each individual parameter on primary energy savings with respect to the reference state. It can be noticed that the greatest impact on the primary energy savings (75.38%) has the replacement of heat/cooling sources – the replacement of the existing building substation connected to district heating system and air-cooled chiller with a WSHP. Furthermore, increasing the insulation thickness of the external walls by 4 cm results in a primary energy saving of 20.31%, and increasing the flat roof insulation thickness by 6 cm results in a primary energy saving of 19.22%. And finally, replacing fluorescent lamps with LED lamps can result in primary energy savings of 23.99%. If the deep energy renovation of the building is performed (simultaneous replacement of all the above), more energy is produced at the location than is consumed, *i.e.*, energy savings of over 100%, or 107.96% to be exact, are achieved. In this context, by applying all the mentioned measures of deep energy renovation of the building, the office building in Zagreb would be called an positive energy building because it produces more energy than it consumes. By avoiding producing more energy than on-site consumption, it is possible to reduce the installed power of photovoltaic modules and reduce costs.

Table 3. Individual influence of each analyzed parameter on primary energy savings with respect to the reference state

	External wall insulation thickness	Flat roof insulation thickness	Window U-value	Source of heat/cooling energy	Lighting system
Reference state	10 cm	10 [cm]	1.40 W/m^{2}K	DH/compression cooler	FC
Optimal solution (considering technical and economic parameters)	14 cm	16 [cm]	1.40 W/m^{2}K	WSHP	LED lamps
Primary energy savings	20.31%	19.22	0.00	75.38	23.99

The presented results were obtained by performing simulations in the DESIGNBUILDER software package, where given the current state of the building, the optimal combination of measures of deep renovation of the building results in primary energy savings of 88,01 kWh/m^{2}a (107,96%). In [30] the annual energy consumption obtained by simulations in the DESIGNBUILDER software package was compared with the actual consumption from the records of monthly consumption of electricity and natural gas, where the difference was found to be less than 1.6%. Therefore, it can be concluded that the presented results give acceptable approximate values when selecting the optimal combination of deep renovation measures.

Conclusion

This paper presents the methodology for selecting the optimal solution for deep energy renovation of buildings that applies to all types of buildings within the construction sector: residential and non-residential. The application of the methodology results in an optimal solution of building deep energy renovation that meets the technical, economic, and legal requirements in a short time frame. The main contribution of the presented methodology is significant time savings. To prove this methodology, it was implemented by simultaneous use of DESIGNBUILDER software package, PYTHON and SQL programming language on an office building in the city of Zagreb. A total of 720 building deep energy renovation measures were analyzed, with 37.25 hours invested in obtaining the optimal solution. The total time to obtain the IDF files of the heating and cooling design and the simulation IDF files for all analyzed combinations of deep energy renovation is 528.8 seconds (8.81 minutes), while in the case of manual entry of all these combinations and creation of these IDF, this production time is estimated at 727.2 hours (4950.7 times slower than the proposed method). Manual entry time is highly dependent on the user experience, so the estimated time may be slightly less or longer. Additionally, the probability of human error by manual input is much higher given the large amount of input data.

The optimal solution for deep energy renovation of the selected office building in Zagreb is the following solution: external wall insulation thickness of 14 cm, flat roof insulation thickness of 16 cm, window U-value of 1.40 W/m^{2}K, WSHP as a source of heating/cooling energy, LED lamps as a lighting system and PV system of 65 kW. However, in addition to technical and economic analysis with legal restrictions, in future research it is necessary to implement a multi-criteria analysis, where other parameters will be considered since the final decision is made by the investor and his ability and willingness to pay.

The large final as well as primary energy savings achievable under deep energy renovation measures implementation highlight the need for policies that provide economic incentives for building owners, to stimulate deep energy renovation of buildings. The application of the method and the presented techno-economic results with legal restrictions enable the selection of the optimal solution of deep energy renovation and represent the basis for the adoption of these policies and the final decision of the building owners.

The analyzed building in this paper plans to carry out a deep energy renovation soon, and in future research, it is necessary to verify the results obtained by the presented methodology based on measured values. Furthermore, the presented method can be applied to different purposes of buildings and based on the obtained results to functionally show the impact of different parameters (construction and technical) on the output values. In this way, equations can be created by applying which it is possible to define the impact of any parameter on energy consumption, depending on the purpose of the building.

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Appendix A – Floor plan of the characteristic floor of the reference building

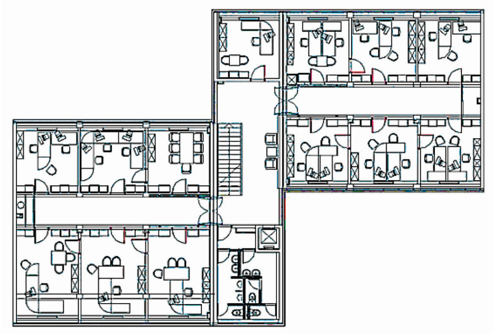

Figure A1. Floor plan of the characteristic floor

Appendix B – The 3-D model of the reference building in the DESIGNBUILDER software package

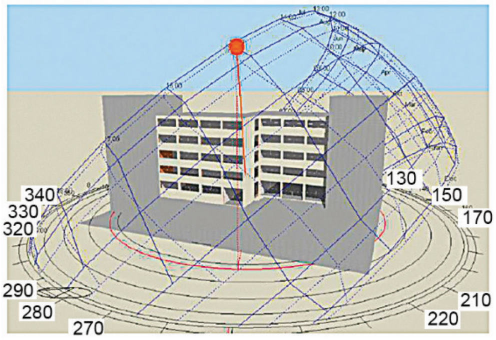

Figure A2. Rendered view of the reference building in DESIGNBUILDER software package

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