Simulation-based optimization for Energy- and Cost-Efficient Refurbishment of an Educational Building

Levente Szatmári – Budapest University of Technology and Economics, Hungary – szatmari.levente@edu.bme.hu
Balázs Nagy – Budapest University of Technology and Economics, Hungary – nagy.balazs@emk.bme.hu

Abstract

This study aims to enhance the energy performance and user comfort of educational buildings, focusing on the BME Building ST as a case study. Using a comprehensive approach that combines dynamic energy simulations and genetic algorithms, we explored optimal renovation alternatives for the building envelope. Various thermal insulation materials and configurations were assessed, leading to improved user comfort and reduced energy demand in all simulated versions. Notably, models with greater thermal insulation exhibited higher comfort levels. Additionally, natural-based materials like wood fibre showed significant potential in reducing embodied carbon emissions, particularly in continental climates such as Hungary. The methodology involved creating a BIM model of the building in Autodesk Revit 2023, followed by advanced energy simulations using the EnergyPlus engine. We generated 160 different building versions with varying insulation materials and thicknesses. These simulations were processed in a Python environment utilizing the Eppy package for managing IDF files and the Pymoo package for implementing the NSGA-II optimization algorithm. The energy performance and user comfort of each version were evaluated to identify the best-performing models. The most energy-efficient model featured 12.5 cm vacuum insulation panels on facades and 25 cm mineral wool on roofs. Financial analysis indicated acquisition costs ranging from 1 to 3.5 million EUR, with estimated global costs over a 20-year period between 6.75 to 9.2 million EUR, compared to the reference building's 7.4 million EUR. The project developed a versatile methodology for multi-objective building energy optimization in a Python environment, applicable to various building types, prioritizing versions with minimal environmental impact and maximal user comfort. The study underscores the potential of energy-efficient renovations to enhance user comfort, reduce energy consumption, and mitigate environmental impacts in educational buildings.

1. Introduction

One of the most urgent problems of our time is climate change and the environmental pollution that accelerates it. Over the last century, the Architecture, Engineering, and Construction (AEC) industry, like other indispensable modern industries, has undergone rapid technological development. Engineers have had tools such as Building Information Modelling & Management (BIM) and Life Cycle Assessment (LCA) for several decades. These tools significantly reduce the amount of building materials used in new constructions, thereby reducing the primary energy requirements. Recent improvements in methods and techniques have further optimized the environmental loads produced during the 60–100-year design lifespan of buildings, which stages (B1-B7 in LCA) have the greatest environmental impact in a traditional architectural environment (Jeong et al., 2015; Farooq & Sajid, 2021). This optimization extends the lifespan and usability of buildings while reducing their long-term carbon footprint. To understand the field, literature research on energetic optimization was conducted. In 2013, Hamdy et al. used the Non-dominated Sorting Genetic Algorithm II (NSGA-II) (Deb et al., 2002) to set up a multi-stage optimization method for Life Cycle Cost (LCC) estimation in a Matlab environment. In 2019, Asdrubali et al. performed a case study on the thermophysical optimization of Italian schools from the 1960s. In 2020, Kiss and Szalay used NSGA-II to optimize the energy performance of dwellings through a modular approach. In 2021, Ghaderian et al. optimized the energy efficiency of educational buildings using similar algorithms in a Matlab. Franco et al. developed a methodology to optimize HVAC operation and user comfort in educational buildings in 2021. D'Agostino et al., in 2021, proposed an automated

Part of
Pernigotto, G., Ballarini, I., Patuzzi, F., Prada, A., Corrado, V., & Gasparella, A. (Eds.). 2025. Building simulation applications BSA 2024. bu,press.
https://doi.org/10.13124/9788860462022

workflow to optimize buildings' energy demand and construction cost. In 2022, Nagy et al. examined the Global Warming Potential (GWP) of buildings by analysing heat and moisture transport. Colarossi et al. also performed multi-objective optimization of school buildings focusing on thermo-acoustics in 2022.

Based on this research, using NSGA-II in a Python environment for building energy demand optimization provided a novel approach worth examining. This paper attempts to find the best possible thermal insulation solutions for BME Building ST, adhering to Hungary's building energy regulations (MCT, 2023). The aim is to reduce the building's carbon footprint over a 20-year period (EU, 2012) after the installation of the thermal insulation system, which inherently reduces operational costs during the examined period, while also improving user thermal comfort.

2. Methodology

2.1 The Studied Building

Building ST was designed and constructed by Budapest University of Technology and Economics (BME) in 1950 (see Fig. 1). The site is part or the BME Campus, having in the area numerous buildings with protection due to their historical value. The ST building itself is not under protection, but the site is under historical, archaeological and world heritage protection (OENY, 2024). The building has a basement level with laboratories, mechanical and building operation premises, and additional shelters underground. Above that, the ground floor and three levels extend in a longitudinal orientation of NW-SE. Connected to this Basement-Ground floor-3 Levels (B-G-3L) structure, another wing has been built, containing the main entrance, the main Auditorium, and the hall.

Fig. 1 – ST building in 2024 at BME campus

In 1985, a 4th storey was built upon the existing structure, giving extra space for enlarging the available capacity in the building. These days the building is being used for educational and administrative purposes including classrooms, labs and offices, and the gross area of cc. 6400 m^2.

The construction of the existing building envelope is shown in Table 1.

Table 1 – Construction structure of the existing envelope

Construction		$U_{current}$ [W/m²K]
3 lys Bit. Sheet w.p. 5 cm sub. Concrete 2-25 cm slope slag 10 cm polysterene 11 cm RFC slate Steel strucure	Roof	0.29
38 cm brick, or 4 cm mineral wool 26 cm RFC beam 8 cm paving brick	Façade (up to 3rd floor)	1.43 0.75
25 cm brick 8 cm mineral wool 4 cm air gap 2*4 mm shale paving	Façade (4th floor)	0.40

On Fig. 2 a schematic representation of the Ground floor is shown. Similar colours represent similar functions of rooms, providing the basis of the thermal zones for the initial building energy simulations detailed later (see Section 2.3).

Fig. 2 – Floor plan and zones of the ST building's ground floor

A known problem of the building is the general summer overheating, which drastically decreases the usability of the facility in the summer period. Thermal images have been made checking the building envelope (Fig. 3) and were used to provide useful information about the structure of the building for improving the building model.

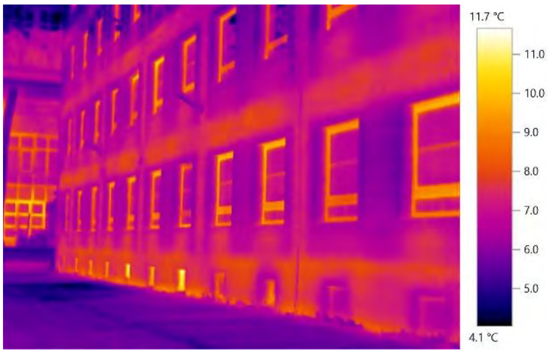

Fig. 3 – Thermal picture of the façade of the ST building

2.2 Applied Thermal Insulation Materials & Building Elements

Requirements for the energy performance of buildings are usually set by national authorities, applying rules and regulations established by international conventions and agreements. The following energy performance requirements needed to be met as minima for the designed building elements and constructions for building envelope elements within the project, with values in Table 2 or lower. As a model simplification, technological insulation applied to make plastering possible in case of vacuum panel or aerogel insulations and the fire propagation barriers were not considered. Based on literature research, a palette of possibly applicable thermal insulation materials was collected (Jelle, 2011; Lakatos, 2022), supplemented by applicable window and curtain wall systems, with available Environmental Product Declarations (EPD) fitting EN ISO 14025:2010 and EN ISO 15804:2012+A2:2019 standards that collected the products' environmental loads during their estimated lifespan of 50 years. The applied thermal insulation materials and thicknesses served as variables for optimization and as a basis of comparison in cases of dynamic energy simulations. For windows and curtain walls, Schüco apertures with 3-layer glazing were selected, fitting the requirements in Table 2.

Table 2 – Thermal transmittance design requirements and applied thermal insulation material thicknesses

Construction	**U_{design} [W/m²K]**	**Applied thickness range (increment) [cm]**
Façade	0.24	Mineral wool 14-20 (2), Woodfibre 16-22 (2), Aerogel 1-5 (1), VIP 2.5-12.5 (2.5),
Roofs	0.17	Mineral wool 15-25 (5), XPS 12-18 (3)
Windows	1.10	-
Curtainwalls	1.40	-

2.3 Building Energy Simulations

The basis of the building energy model (BEM) was a BIM model built in Autodesk Revit 2023 (see Fig. 4). The model was based on the documentation of the building and on-site diagnostics and surveying.

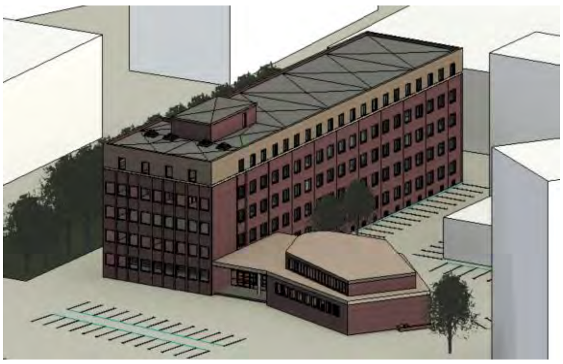

Fig. 4 – REVIT model of the ST building

Within Revit, Advanced Energy Settings were manipulated to provide a realistic basis for simulation.

Export Complexity was set to Complex with Mullions and Shading Surfaces to ensure these elements were included in the IDF file (Input Data File for EnergyPlus simulations), which is automatically created based on the BIM model when running the first System Analysis in Revit. This method uses the EnergyPlus engine and creates the file in Windows' Temporary folder, making it possible to use and reuse the model in later simulations within EnergyPlus. Building Type was set as "School or University," and Building Operation Schedule was set as 24/7 Facility. For Conceptual Types of constructions of the external envelope, High Mass Construction – No Insulation type was selected. While setting HVAC Systems, we faced the challenge that Revit does not have district heating as an option for HVAC systems, so after some consideration, a Central VAV system was chosen as the basis, which was later manually modified in the IDF files. As limitations, we must mention that modified HVAC systems and electrical and lighting systems or building automation solutions were considered out of scope. With the IDF file, which is the EnergyPlus input text file containing all the relevant data of the examined building, the next step was to prepare all the IDF files with the required thermal insulation materials and thicknesses applied to the necessary surfaces. For this, the Eppy (Santosh, 2023) package was used within a Python 3.10 Environment. This way, 160 different versions of the building in separate IDF files were created based on variables in Table 2. Due to the used package, moisture transfer performance and hygrothermal effects were not considered. Also, the effects of thermal bridges were considered using simplified methods.

Meteonorm 8 was used to create the EnergyPlus Weather file (EPW) for the location of the building, to ensure simulations were as realistic as possible, regarding daylighting and outside weather data.

Lastly, EnergyPlus' v23.1 IDD file was necessary, which is a dictionary file providing accessibility of data in IDF files for different versions of EnergyPlus. To run all the 160 building energy simulations, a multiprocessing code was used – and modified as necessary – from the Eppy documentation, to enable parallel processing on multiple cores of computers, significantly reducing runtime. Using the Pandas data manager toolkit in Python, the results of simulations were handled together. After examining these results and noticing major trends, a second round of energy simulations was run for the construction versions which fulfilled the requirements (see Table 1), supplemented by the new set of windows and curtain walls. This way, 72 versions from the original 160 remained for further examination.

2.4 Thermal Comfort

Thermal comfort analysis were based on the simple ASHRAE 55-2004 standard, when running building energy simulations in EnergyPlus (U.S. Dept. of Energy, 2023), the program provides a summary of the "Time Not Comfortable Based on Simple ASHRAE 55-2004" expressed in hours, which sums up the time during the simulation period when thermal conditions in each zone of the building are not comfortable for people wearing summer or winter clothes (EnergyPlus Input/Output References, 2023). To have a comparable result of thermal comfort in every examined building version, we subtracted this value from the 8760 hours of a year (the same as the simulation period), obtaining a value of "Comfortable hours" meaning the amount of time within a year when people do not experience any thermal discomfort in any thermal zones of the building based on simulation results. We must mention that various factors affecting thermal comfort in buildings, such as changes in the usage schedule, were left out of scope. Nor were active or passive shading solutions applied to examine their effect on user comfort.

2.5 Environmental Loads

To measure environmental loads of products or systems, many calculating methods and theories had been set up in the past decades, of which one of the most widely used and internationally accepted is the life-cycle assessment (LCA) which since its early-stage use in the 1960s, has already been internationally standardized in ISO 14040:2006 and accepted, and it is constantly developed with new approaches (Szalay et al., 2022). To determine the environmental loads of applied materials and elements, EPDs of applicable thermal insulation materials and viable summaries of environmental loads based on EN ISO 14025:2010 and online EPD catalogues were researched (Institut Bauen & Umwelt, 2023). Also, because of manufacturers' need for constant improvement and environmental consciousness, many of them now provide EPDs based on EN ISO 15804:2012+A2:2019 prepared for their specific products. In this paper the applied indicator for the examined thermal insulation materials and building elements was the Global Warming Potential (GWP), which summarizes all activities through the examined subject's estimated lifespan, summing them up into the unit of measurement as $kgCO_2eq$.

2.6 Financial Analysis

Financial analysis was conducted based on the fees and advised prices in the Guide for Construction Cost Estimation 2023 (Hunginvest, 2023), which is a generally accepted collection of core prices and fees in the Hungarian AEC industry, to estimate acquisition costs of the examined thermal insulation systems. Financial analysis was done only on the 72 building versions which, by their characteristics, fulfilled the requirements. Within the framework of this paper, when discussing operating costs, only the sum of costs for electricity and district heating were considered and other utilities, such as drinking water, sewage, or mandatory maintenance costs, were not involved in the calculations, as these are not strictly related to the building's energy demand and thermal comfort, which is the main scope of this work. Since the focus is on the operation of the building over a 20-year period after the application of the new thermal insulation systems and apertures. To apply the Global Cost method (EU, 2012), a yearly price increase factor of 5% and a yearly discount factor of 3% were applied in all examined cases. Initial utility costs of 0.40 EUR/kWh for electricity and 0.50 EUR/kWh for district heating were applied, which are considered usual for public institutions in Hungary as of May 2024.

2.7 Optimization

To search for the Pareto-optimal solutions for the thermal insulation system of the building, which means finding the solutions in the model space that are non-dominated by others, causing a frontier of equally good solutions from the perspective of the examined parameters, called the Pareto front, the Pymoo NSGA-II (Blank, 2023) Python package was used. NSGA-II provides a set of possible best solutions for decision-makers, allowing them to focus only on the solutions with the best trade-offs within the set and making the weak solutions fall out of scope. NSGA-II (Deb et al., 2002) is an extension of genetic algorithms, incorporating non-dominated sorting and crowding distance. During optimization, the population size was 72, involving all the examined construction versions. Other optimization parameters were used as Pymoo's default, such as the number of generations being 100, while a crossover and mutation rate of 0 was used due to no interest in creating theoretical constructions, ensuring that realistic model versions were used, and the actual Manhattan crowding distance (Brownlee, 2020) was applied when setting up the Pareto front.

3. Results

3.1 Energy Demand

All the examined model versions performed within the range of 490-503 MWh yearly energy demand, while the reference building's energy demand in its current state is 622 MWh per year. This means a rough 20% decrease in energy demand in all the examined construction versions compared to the reference model. In Fig. 5, a plot of the yearly site energy demands and the number of yearly comfort hours in the building versions is shown. There is a relatively straight inverse relationship between these two parameters in the examined construction versions: the lower the energy demand, the higher the number of comfort hours. This can be explained by the fact that thicker insulation reduces the effect of external climate on the building within the examined ranges of materials and thicknesses. The construction version performing best in this comparison is the one with 12.5 cm VIP on the facades and 25 cm Rockwool insulation on the roofs, while the following versions are all the thickest insulated ones.

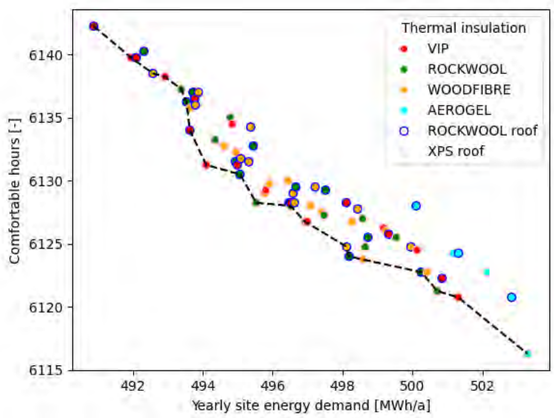

Fig. 5 – Yearly site energy demand – Comfortable hours

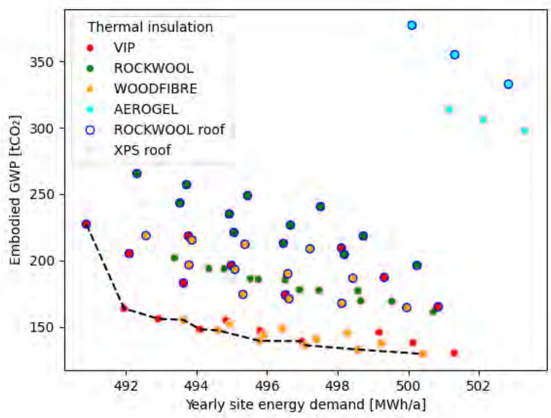

Fig. 6 – Yearly site energy demand – Embodied GWP

As a major trade-off, a decrease in yearly site energy demand is notable with the increase of embodied GWP, meaning generally, the more material we build into the system, the less the energy demand will be (see Fig. 6). The decrease in yearly energy demand is noticeable with the increase of embodied GWP, meaning the more material we install in the form of thermal insulation, the less the energy demand will be. Based on the results, it can be stated that XPS roof insulation versions (pink outline) have significantly lower embodied GWP values compared to Rockwool roof insulation versions (blue outline). This is due to the difference in specific embodied GWP values of XPS and Rockwool, 160 and 270 kgCO_2eq./m^3, respectively, and the difference in their design thermal conductivity values of 0.035 W/(m K) and 0.040 W/(m K), respectively, which allows for thinner roof insulations from XPS with similar thermal characteristics. The Pareto front consists of wood fibre and VIP façade insulation versions, which have the lowest specific embodied GWP values of the examined façade thermal insulation materials with values of 53 to 115 kgCO2eq./m^3, respectively. This makes wood fibre versions the most environmentally friendly façade thermal insulation solution, even though they need to be applied with the highest thicknesses of the examined materials.

It is worth mentioning that the aerogel insulations have the highest embodied GWP of the examined materials, which pairs with the highest yearly site energy demand, indicating that this material performs the worst in this comparison.

3.2 User Comfort

A comparison plot of the embodied GWP and the number of comfortable hours in the building with the Pareto front is shown in Fig. 7. A general trend of increasing comfortable hours parallel with the increase of embodied kgCO_2eq. of each version is noticed. All the elements of the Pareto front are within the range of 6222 to 6242 hours a year, which is a definitive step forward from the reference model's 5800 hours by approximately 430 hours a year, but too low to be called significant. To increase user comfort, other types of variables should be introduced, such as shaders, changes in the usage schedule of the building, or using more detailed analysing methods, such as PMV or PPD (Fanger, 1970), are advised.

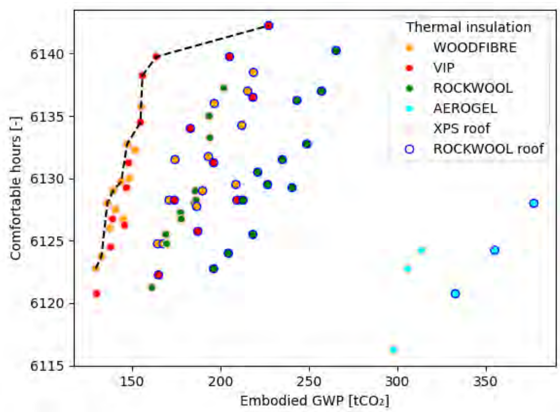

Fig. 7 – Embodied GWP – Comfortable hours

3.3 Environmental Loads

Fig. 8 shows the connection between specific site GWP, summed up for 20 years by a constant yearly energy demand, and embodied GWP. Since site

GWP and energy demand are closely related, the shape of the plot is naturally like Fig. 6. On a 20-year scale, all the examined versions have a specific site GWP between 770 to 790 tCO_2/m^2. The reference building has a predicted 956 tCO_2/m^2 for the next 20 years, meaning the examined model versions show a specific GWP decrease of approximately 20%.

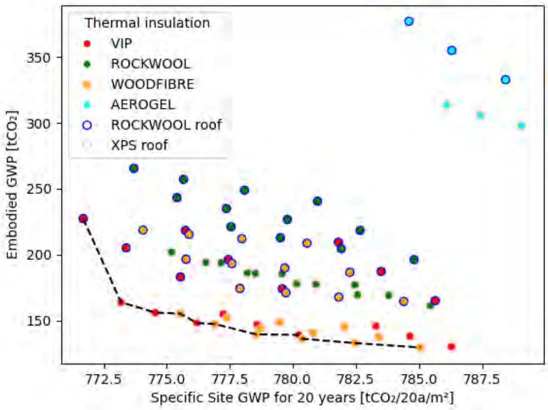

Fig. 8 – Specific Site GWP for 20 years – Embodied GWP

3.4 Financial Analysis

The financial analysis was two-fold. First, the estimation of acquisition cost of building versions was done, resulting in a range of 1 to 3.5 million EUR for acquisition costs for the 72 financially examined model versions. Secondly, the estimated global cost of model versions was performed, resulting in a range of 6.75 – 9.2 million EUR of global costs over the 20-year period after installation compared to the reference building's estimated 7.4 million EUR global cost for the same period, considering no acquisition cost. The financially best-performing model version turned out to be the one with 20 cm of mineral wool insulation uniformly on façades and roofs with an estimated global cost of 6.75 million EUR. Financial estimations could have considerable uncertainties, but with the side effects of comfort improvements and the reduced environmental footprint, these results prove the usefulness of the examination.

4. Conclusion

The application of several thermal insulation solutions on an educational building from an energetic optimization approach was examined. Numerous model versions provide feasible solutions to decrease the energy demand of the building, such as the application of mineral wool and wood fibre façade insulation systems. All the examined versions would reduce the environmental footprint of the building on a 20-year scale compared to the reference building, but user comfort could not increase significantly within this approach, since many interventions that would help with this was beyond the scope of the current research. Determining the best version of the examined constructions is challenging on an objective scale, but observable major trends and parameters can provide significant help in making decisions regarding energy-related refurbishment of buildings, which can lead to better quality and comfort of facilities in the long term. Shading solutions or schedule changes, among others, are variables that can be included in the scope in the long term, providing a significantly larger population size to optimize through with possibly lower global cost and reduced environmental footprint. The methodology is applicable to other buildings, while the goal of developing for districts or campus-scale buildings.

Acknowledgements

The research reported here was supported by TKP2021-NVA-02 project. Project no. TKP2021-NVA-02 has been implemented with the support provided by the Ministry of Innovation and Technology of Hungary from the National Research, Development and Innovation Fund, financed under the TKP2021-NVA funding scheme.

References

Asdrubali F., Evangelisti L., Fontana L., Guattari C., Montella I., Prestininzi P., Salerno G., Tonelli C., Vitale V. 2019. "On the Thermophysical performance Optimization of Italian Schools of the 60s: A Case Study in Ostia (RM)" Building Simulation Applications BSA 2019: 299-305.

Asdrubali, F.; Venanzi, D.; Evangelisti, L.; Guattari, C.; Grazieschi, G.; Matteucci, P.; Roncone, M. 2021. "An Evaluation of the Environmental Payback Times and Economic Convenience in an

Energy Requalification of a School". *Buildings* 11: 1-12. https://doi.org/10.3390/buildings11010012

Blank, Julian. 2023. Home page. https://pymoo.org/index.html

Brownlee, Jason. 2020. 4 Distance Measures for Machine Learning. Python Machine Learning. August 19. https://machinelearningmastery.com/distance-measures-for-machine-learning/

Colarossi D., Di Loreto S., Tagliolini E., Principi P., Serpilli F. 2022. "Multi-Objective Optimization of Thermo-Acoustic Comfort of School Buildings" Building Simulation Applications BSA 2022: 59-67.

EU Council. 2012. "COMMISSION DELEGATED REGULATION (EU) No 244/2012." Official Journal of the European Union 25.

D'Agostino D., D'Agostino P., Minelli F., Minichiello F. 2021. "Proposal of a new automated workflow for the computational performance-driven design optimization of building energy need and construction cost" , *Energy and Buildings* 239. https://doi.org/10.1016/j.enbuild.2021.110857

Deb K., Pratap A., Agarwal S., Meyarivan T. 2002. "A fast and elitist multiobjective genetic algorithm: NSGA-II." *IEEE Transactions on Evolutionary Computation* 6 (2): 182-197. https://doi.org/10.1109/4235.996017

EnergyPlus Input/Output References: SummaryReports (2023) Available online: https://bigladdersoftware.com/epx/docs/23-1/input-output-reference/output-table-summaryreports.html#outputtablesummaryreports (accessed on 25th May 2024)

Franco, A., Bartoli, C., Conti, P., Miserocchi, L., Testi, D. 2021. "Multi-Objective Optimization of HVAC Operation for Balancing Energy Use and Occupant Comfort in Educational Buildings." *Energies* 14(10), 2847. https://doi.org/10.3390/en14102847

Fanger, P.O. 1970. "Thermal Comfort. Analysis and Applications in Environmental Engineering." (Danish Technical Press).

Ghaderian M., Veysi F.. 2021. "Multi-objective optimization of energy efficiency and thermal comfort in an existing office building using NSGA-II with fitness approximation: A case study." *Journal of Building Engineering* 41. https://doi.org/10.1016/j.jobe.2021.102440

Hamdy M., Hasan A., Siren K.. 2013. "A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010." *Energy and Buildings* 56: 189-203. https://doi.org/10.1016/j.enbuild.2012.08.023

Hollberg A., Kiss B, Röck M., Soust B. Verdaguer, Wiberg A.H., Lasvaux S., Galimshina A., Habert G.. 2021. "Review of visualising LCA results in the design process of buildings." *Building and Environment* 190. https://doi.org/10.1016/j.buildenv.2020.107530

Hunginvest Mérnöki Iroda Kft. Guide for Construction Cost Estimation 2023 in Hungarian 2023. Magyarország: ÉTK Kft.

Institut Bauen und Umwelt e.V. 2023. Published EPDs. https://ibu-epd.com/en/published-epds/

Jelle, Bjørn Petter. 2011. "Traditional, state-of-the-art and future thermal building insulation materials and solutions – Properties, requirements and possibilities." *Energy and Buildings* 43(10): 2549-63. https://doi.org/10.1016/j.enbuild.2011.05.015

Jeong K., Ji C., Koo C., Hong T., Park H. 2015 "A model for predicting the environmental impacts of educational facilities in the project planning phase" *Journal of Cleaner Production* 107: 538-549. https://doi.org/10.1016/j.jclepro.2014.01.027

Kiss B., Szalay Zs.. 2020. "Modular approach to multi-objective environmental optimization of buildings." *Automation in Construction* 111. https://doi.org/10.1016/j.autcon.2019.103044

Kiss B., Szalay Zs.. 2023. "Sensitivity of buildings' carbon footprint to electricity decarbonization: a life cycle–based multi-objective optimization approach." *The International Journal of Life Cycle Assessment* 28: 933-952

Lakatos, Ákos. 2022. "Novel Thermal Insulation Materials for Buildings" *Energies* 15(18). https://doi.org/10.3390/en15186713

Ministry of Construction and Transportation. 2023. 9/2023. (V. 25.) MCT decree. https://njt.hu/jogszabaly/2023-9-20-8X.1#SZ11@BE2

Nagy B., Marosvölgyi M., Szalay Zs. 2022. "Global

Warming Potential of building constructions based on heat and moisture transport analysis." THERMAL SCIENCE 26 (4B): 3285-96. https://doi.org/10.2298/TSCI210224278N

OENY 2024 – National Construction Registration System https://www.oeny.hu/oeny/veding/?telepules=Budapest%2011&hrsz=4110&keppel=false

Santosh, Philip. 2023. eppy documentation. https://eppy.readthedocs.io/en/master/index.html

Szalay Zs., Szagri D, Bihari Á, Nagy B, B Kiss, Horváth M, Medgyasszay P. 2022. "Development of a life cycle net zero carbon compact house concept." *Energy Reports* 8: 12987-13013. https://doi.org/10.1016/j.egyr.2022.09.197

U.S. Department of Energy's (DOE) Building Technologies Office. 2023. EnergyPlus. https://energyplus.net/