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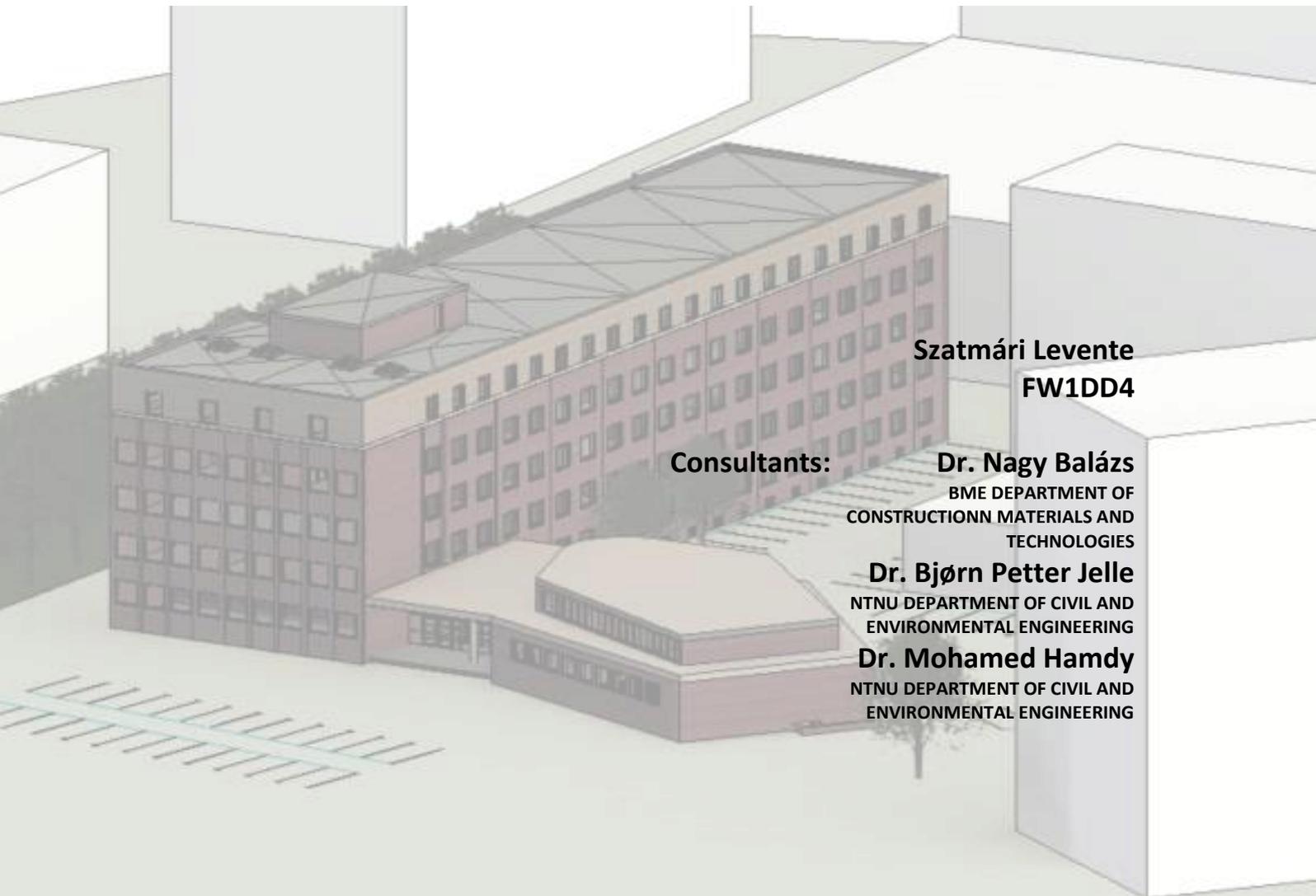
Faculty of Civil Engineering

Department of Construction Materials and Technologies

**BIM-BASED ENERGY AND ENVIRONMENTAL OPTIMIZATION
OF AN EDUCATIONAL BUILDING**

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BEVEZETÉS

Kulcsszavak: Dinamikus szimuláció, épületenergetika, fenntarthatóság, bim, épületszerkezetek, LCA

A véges energiaforrások és az általánosan fokozódó fogyasztás ellentétéből fakadóan építőmérnökként közösségi felelősségünk szem előtt tartani és a tőlünk telhető legnagyobb mértékben csökkenteni az építőipar környezetterhelését és elősegíteni az iparág dekarbonizációs törekvéseit, legyen szó akár újonnan megvalósuló projektekről, akár meglévő építmények korszerűsítésének feladatairól.

Általánosan elmondható, hogy az oktatási épületek túlnyomó többsége sem energetikailag, sem felhasználói komfort szempontjából nem felel meg a jelenkor követelményeinek, mely problémák jellemzően kéz a kézben járnak, így megoldásuk is szükségszerűen többfókuszú.

Dolgozatomban első részében szakirodalmi kutatást végeztem az épületek energetikai követelményeknek való megfelelésének, környezetterhelési tényezők és legfőképpen a CO₂-egyenérték potenciális csökkentése szempontjából, valamint a felhasználói komfort témakörében, illetve a modern és innovatív hőszigetelő rendszerek kialakításainak módszereiről a témához kapcsolódóan.

Dolgozatom tárgyául a BME ST épületét választottam, mely az egyetemi kampusz épületei közül az egyik legmagasabb a fajlagos energiaigénnyel rendelkezik. Az épületről BIM modellt készítettem a fellelhető tervdokumentációk és helyszíni szemlék alapján, majd a modell felhasználásával dinamikus energetikai szimulációt futtattam az épület jelenlegi energetikai teljesítőképességének megértése céljából.

Ezután genetikus algoritmusok Python környezetben történő implementálásával vizsgáltam a felújítandó épületburok optimális kialakítási alternatíváit annak érdekében, hogy a potenciális energiahatékonysági-célú felújítási javaslat mind CO₂-egyenérték, mind pedig felhasználói komfort szempontjából a lehető legkedvezőbb kialakítású lehessen.

Munkám során cél volt a felújítási munkálatokat követő 20 éves ciklus lehető legkisebb környezetterheléssel járó változatának megállapítása a lehető legnagyobb felhasználói komforttal párosítva. A BIM alapokon végzett dinamikus szimulációval támogatott többcélú optimalizációs eljárások alkalmazása az energiahatékonysági felújítások terén lehetővé teszi, hogy az épületek tervezett innovatív és megvalósítható kialakítása a lehető legkisebb környezeti lábnyom mellett érje el a legnagyobb felhasználói komfortnövekedést, illetve energiafogyasztásbéli megtakarítást, hozzájárulva ezzel az egyetem fenntarthatósági törekvéseihez is.

(A dolgozatot a konzulensekkel való együttműködés érdekében angol nyelven készítettem el.)

ABSTRACT

Keywords: Dynamic simulation, building energy, sustainability, BIM, building structures, LCA

Due to the conflict between finite energy sources and generally increasing consumption, as civil engineers we have a social responsibility to keep in mind and to reduce the environmental impact of the construction industry as much as possible and to promote the decarbonization efforts of the industry, whether it is about newly constructed projects or the tasks of refurbish existing structures.

In general, it can be said that most educational buildings do not meet the requirements of the present, neither energetically nor in terms of user comfort, which problems typically go hand in hand, so their solution is necessarily multi-focused.

In the first part of my work, I carried out literature research on the compliance of energy performance requirements of buildings, environmental impact factors and, above all, the potential reduction of CO₂ equivalents, as well as about user comfort and on the methods of designing modern and innovative thermal insulation systems related to the topic.

As the subject of my paper, I chose BME Building ST, which has one of the highest specific energy demands among the buildings on the university campus. I made a BIM model of the building based on the available design documentation and on-site inspection, then using the model I ran a dynamic energy simulation to understand the current energy performance of the building.

Then, by implementing genetic algorithms in a Python environment, I investigated the optimal design alternatives of the building envelope to be renovated to ensure that the potential renovation proposal for the purpose of energy efficiency can be designed as favourably as possible in terms of both CO₂ equivalent and user comfort.

During my work, the goal was to determine the version with the lowest possible environmental impact of the 20-year cycle following the renovation works, combined with the greatest possible user comfort. The application of multi-purpose optimization procedures supported by dynamic BIM simulation in the area of energy efficiency renovations enables the planned innovative and feasible design of the buildings to achieve the greatest increase in user comfort and savings in energy consumption with the smallest possible environmental footprint, thereby also contributing to the university's sustainability efforts.

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1. INTRODUCTION

One of the most urgent problems of our time is climate change and the environmental pollution that accelerates it. In the last century, the AEC industry, similarly to industries indispensable to modern society, has undergone rapid technological development. As a result of this development, the industry's global annual CO₂ emissions now account for 39% of the Earth's total annual GWP (Global Warming Potential) value, considering the production of building materials, construction, and the operation of the existing building stock on the planet [1]. Today, the construction industry is the industry with the greatest environmental burden in the world.

Due to the global dimensions of the industry, the changes implemented in modern design solutions and processes, with favourable environmental effects can represent a significant improvement on a way to a feasible global environment and future. Engineers since a few decades back have had already tools such as BIM (Building Information Modelling & Management) and LCA (Life Cycle Assessment), which can be used to significantly reduce the amount of building materials used in the construction of each newly constructed building, thereby reducing the primary energy requirements of the building, while recent years, with the constant improvement of methods and techniques, having the ability to optimize the environmental loads produced during the 60-100 year long design lifespan of buildings became a common tool, which stages (B1-B7 in LCA) are the ones with the greatest environmental impact, making it possible to, with optimization processes and targeted refurbishments, extend the lifespan and the usability of buildings, while having the ability to reduce the carbon footprint of the building on a long-term.

This paper attempts to find the best possible thermal insulation solutions for BME Building St ([see 3.1.](#)), fitting for rules and requirements regarding building energetics in Hungary, 2023 [2], with an aim to reduce the carbon footprint of the building on a 20-year-long period after the installation of the thermal insulation system, which by its nature comes hand-in-hand with reduced operation costs on the examined period, while focusing also on the improvement of thermal comfort of users.

1.1. GOALS OF THE PROJECT

Within this work I want to examine the possible scenarios for the different applications of thermal insulation materials in various thicknesses on the external surfaces of the BME Building ST ([see 3.1.](#)), while searching for correlations between the specific and total energy demand of the building on an annual and on a 20-year-long scale [3], and the comfort level of people within the building through a year-long period, and also with the embodied GWP (Global Warming Potential) of the applied thermal insulation materials. During my work I apply the multi-objective optimization algorithm (MOOA) NSGA-II (Non-dominated Sorting Genetic Algorithm II) ([3]) to try and find Pareto-optimal [4] solutions for the applied thermal insulation solutions ([see 3.3.](#)). The aimed impact of the paper is to try and search for optimal long-term viable thermal insulation solutions of the subject building using considerable amount of reliable building energy simulation results and optimization algorithms, providing a workflow for further CIT (Construction Information Technology) building energy optimization projects.

1.2 LIMITATIONS

The scope of this paper focuses on the examination of possible solutions for application of different thermal insulation materials and thicknesses on BME building ST ([see 3.1.](#)) in order to optimize the building's energy demand and shrink the carbon footprint, while improving user comfort. Other aspects with an effect on these factors have not been examined, such as the possible changes in the habit of users or the change of schedule of usage. Application of smart building solutions, such as presence sensors or building automation solutions have not been involved into the field of study. The HVAC system of the building has been left at the current state from the aspect of examination, the whole mechanical and electricity system has been applied as its current state of operation in 2023. Nor active, nor passive shading solutions have been applied to examine the effect of these on user comfort. The effect of using fire propagation barriers to improve fire resistance limit for certain thermal insulation solutions on the building's energy performance is not considered in this current study. The moisture transfer performance and hygrothermal effect is not considered during the

simulations due to the limitations of the used energy performance modelling algorithms. The effect of thermal bridges were taken into account using simplified methods.

2. RESEARCH WORK

2.1 Building energy performance

Requirements for energy performance of buildings are always set up by national authorities in every country, applying also rules and regulations established by international conventions and agreements.

Therefore, as the first part of this paper research had been done in order to understand up to date and upcoming energetic requirements in Hungary [2], country of this paper's subject building (see 3.1).

As a basic goal of this paper, synchronized with national regulations [2], the following energy performance requirements need to be passed as minima for applied materials and constructions (see 3.) for building envelope elements within the project (see 3.1), where minima means values in Table 1 or lower:

Construction	Heat Transfer Coefficient (U) [W/m ² K]
Façade walls	0,24
Flat roofs	0,17

Table 1 Applied minima Heat Transfer Coefficient requirements.

Which Heat Transfer Coefficient values are coming from the simplified calculation method in [2], expressed by the following formula:

$$U = \frac{1}{R_{tot}} [W/m^2K]$$

Where:

U = Thermal Transmittance (U) [W/m²K]

R_{tot} = Total Thermal Resistance[m²K/W].

Where R_{tot} in the case of n number of homogeneous layers of structure being perpendicular to heat flow through the structure:

$$R_{tot} = R_{si} + \sum_{i=1}^n R_i + R_{se} \text{ [m}^2\text{K/W]}$$

Where:

R_i = Heat Conduction Resistance of each layer of the construction

R_{si} = Internal Surface Resistance

R_{se} = External Surface Resistance

For Heat Transfer Resistance of surfaces, the following values were applied, based on national rules and regulations [2] :

Surface Resistance [m ² K/W]	Direction of heat flow		
	Upwards	Horizontal	Downwards
R_{si}	0,10	0,13	0,17
R_{se}	0,04	0,04	0,04

Table 2 Applied Surface Heat Transfer Resistance values

Within the framework of the project envelope apertures, such as windows and doors, have not been modified. These building elements have been modelled and simulated based on the available design documentation and on-site inspection ([see 2.](#)).

The yearly energy demand and consumption, including weather and other environmental effects on the building had been examined by results dynamic energy simulations and measured data for electricity and heating demand from 2021 ([see 2.](#)).

2.2 Environmental loads

Through past centuries, due to rapidly increasing environmental pollution and expansion of general human activity on all fields of life called up the necessity of rules and regulations aiming for measuring and controlling the environmental loads caused by mankind. One of nowadays' biggest polluter regarding GWP (Global Warming Potential) with a ratio of cc. 40% of all CO₂ emission in the EU is the AEC Industry (Architecture, Engineering, Construction) [1].

To measure these loads, many calculating methods and theories had been set up, of which one of the most widely used and internationally accepted is the LCA [5] (Life cycle assessment) which since its early-stage use in the 1960s, have already been internationally standardized (ISO 14040:2006) and accepted, and it is constantly developed with new approaches [6] [7] [8]. The main idea behind the method that it follows through all the main stages of the evaluated product' or system's expected lifespan. The method gives a summary as result for the subject of evaluation, which causes measurability of the environmental load through the lifespan of the evaluated product and, and most importantly comparability of environmental loads of competing or technologically incomparable products.

When it comes to examining construction materials from the aspect of LCA, the usual format is the EPD (Environmental Product Declaration) which is a document provided by manufacturers via independent experts or by the manufacturers themselves applying for standard format of content and form requirements (EN 15804). EPDs are following the shape of LCA, summing on the environmental impacts of the examined product through stages of lifespan of the examined product.

Without the need of completeness, see below a few types of impact-summarizing values called impact categories used commonly in the framework of LCA and EPDs [9] [10] with the most important characteristics:

- **GWP** – Global Warming Potential
 - Unit of measurement: kgCO₂eq.
 - Most important reason behind the climate change
 - Involves all activities with greenhouse gas emissions
- **ODP** - Depletion Potential of the stratospheric Ozone layer
 - Unit of measurement: kgCFC-11eq.
 - The stratospheric ozone layer guards the planet from noxious UV-B rays, its depletion is harmful for both flora and fauna
- **AP** – Acidification Potential of land and water
 - Unit of measurement: mol H⁺eq., or kgSO₂eq.
 - The emission of transportation and energy production
 - Mainly affect the environment regionally in the form of acid rain
- **EP** – Eutrophication potential
 - Unit of measurement: kg(PO₄)³eq.
 - The natural ecosystem of the planet is being inhibited by algae

- Experts differ earth, sweet- and saltwater versions

Within the framework of this paper the GWP values, such as kgCO₂ values were handled as main environmental load indicators for the possible thermal insulation materials and sources of energy being used in the building ([see 3.](#)).

2.3 User comfort

In nowadays human society, in developed countries we spend approximately 90% of our lifetime indoors [11]. This means that indoor environment in general has a huge impact on our lives, influencing our general wellbeing and health, which makes developing a healthy and sound indoor environment a vital task.

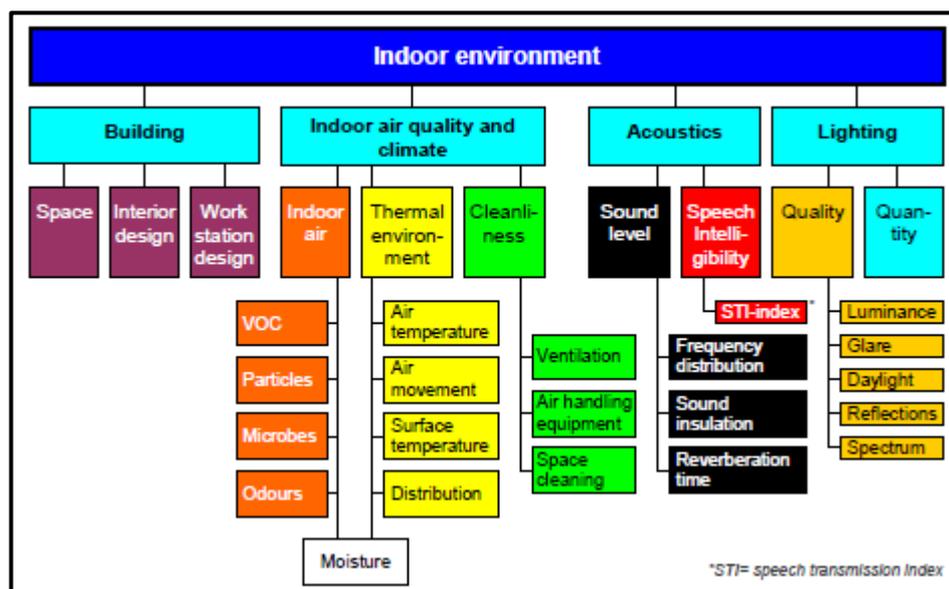


Figure 1 Parameters included in the definition of indoor environmental quality (IEQ) [12]

By WHO's (World Health Organization) definition of Health [12]: "Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity." Usefulness and general quality of buildings are measurable, hand in hand with many other crucial factors by comfort level of the people staying inside, regardless of time spent in the building but strictly connected to the purpose of usage. While talking about user comfort of a building, in general terms we mean the wellness of staying inside, or just even be in the neighbouring area of the building, regarding aesthetics and fitting into its environment. But, just as many other characteristics of buildings, this property can also be

divided into more smaller variables which together and affecting each other provide the user comfort as a result. These variables and connections between them can be seen at Figure 1 Parameters included in the definition of indoor environmental quality (IEQ) [12], summing up the parameters or indoor environmental quality (IEQ) [11].

As user comfort of buildings is an important question worldwide, multiple organizations and institutes are working on standardizing requirements and methods aiming to improve characteristics of building user comfort and energy efficiency of buildings, such as:

- **ISO** - International Organisation for Standardisation
- **ASHRAE** - American Society of Heating, Refrigerating and Air-Conditioning Engineers
- **CEN** - European Standardisation Organisation
- **WHO** - World Health Organisation
- **IEA** - International Energy Agency
- **EUROVENT** - European Industry Association for Indoor Climate, Process Cooling, and Food Cold Chain Technologies

Within the framework of this paper the focus is on thermal comfort which is, defined by the ANSI/ASHRAE Standard 55:” That condition of mind which expresses satisfaction with the thermal environment.”

Perceptions of this environment are affected by:

- Air temperature
- Radiant temperature
- Relative humidity
- Air velocity and turbulence

Human body and its heat generating characteristics also have parameters effecting thermal comfort [11], for metabolic rates on activities, see Figure 2 Metabolic rates of human body, varied by activity [11]:

- Met
 - A unit used to describe the energy generated inside the body due to metabolic activity. It is defined as 58.2 W/m^2 which is equal to the energy produced per unit surface area of an average person, seated at rest. The surface area of an average person is 1.8 m^2 .
- Metabolic rate [Met]

- Rate of energy production of the human body by metabolism, which varies with activity. It is expressed as Met units in the ISO and CEN standards.

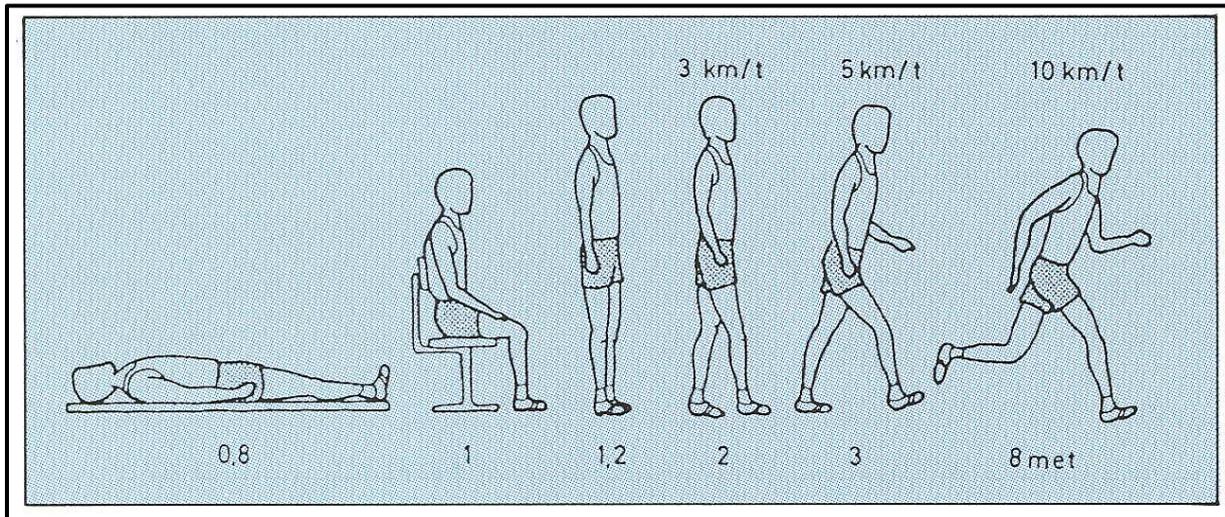


Figure 2 Metabolic rates of human body, varied by activity [11]

- Insulation (clothing) [clo]
 - The resistance to sensible heat transfer provided by clothing ensemble. Expressed in clo-units. $1 \text{ clo} = 0,155 \text{ m}^2\text{K/W}$.
 - 1 clo is the heat resistance in the clothing that will provide a sitting person with a comfortable state provided that the metabolic rate equals to $58,2 \text{ W/m}^2$, the room with drybulb temperature of $21 \text{ }^\circ\text{C}$, relative humidity of 50%, and a $0,1 \text{ m/s}$ wind speed.

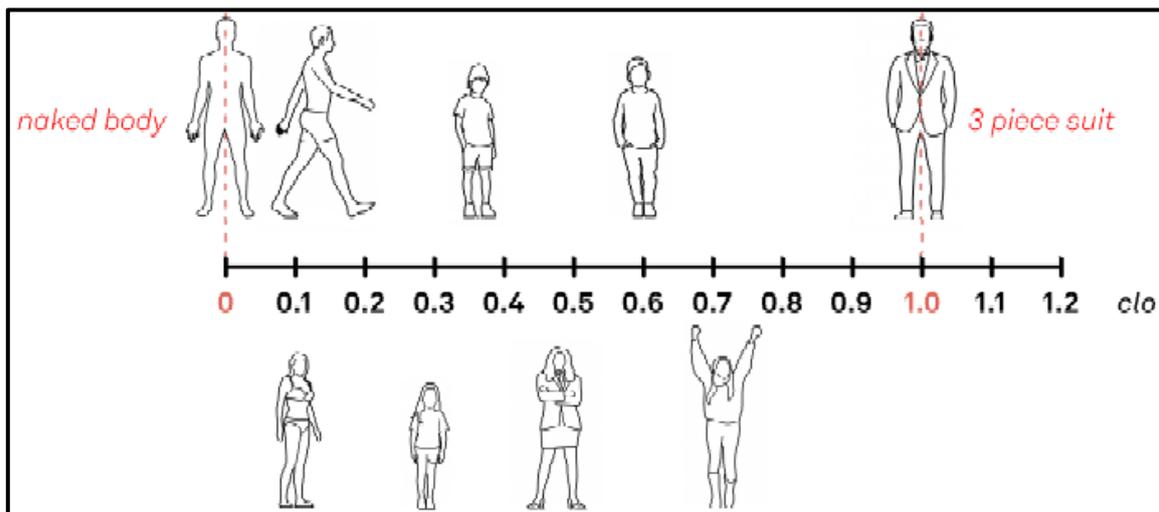


Figure 3 clo units by clothing [13]

While working on this project, building energy simulations were made in EnergyPlus 23.1.0 [14] software, which applies clo and met units dynamically based on the simple ASHRAE-55-

2004 standard ([see 3.4.](#)). These parameters are applied in the PMV and PDD calculations ([see 2.3.1](#)).

2.3.1 Thermal comfort parameters PMV and PPD

When calculating thermal comfort in buildings, one of the most widely used method is the PMV (Predicted Mean Vote) and the PDD (Predicted Percentage of Dissatisfied) method developed by Fanger in the 1970's [15] and has been outlined in the ISO 7730 standard [16].

The PMV is a numerical index which predicts the thermal comfort a large group of people in the same, mechanically heated and cooled inside environment calculated by self-declared values. PMV uses a scale between -3 and +3 with categories of “cold”, “cool”, “slightly cool”, “neutral”, “slightly warm”, “warm”, “hot” accordingly [17]. PPD is a percentage of dissatisfied people in the same environment, determining the ratio of dissatisfied people in the whole population of measurement. As the absolute value of PMV increases, the PPD increases [11], shown on Figure 4 value of PPD by PMV [11]Figure 4, and can be calculated by the following formula [11]:

$$PPD = 100 - 95 * e^{-(0,03353*PMV^4+0,2179*PMV^2)}$$

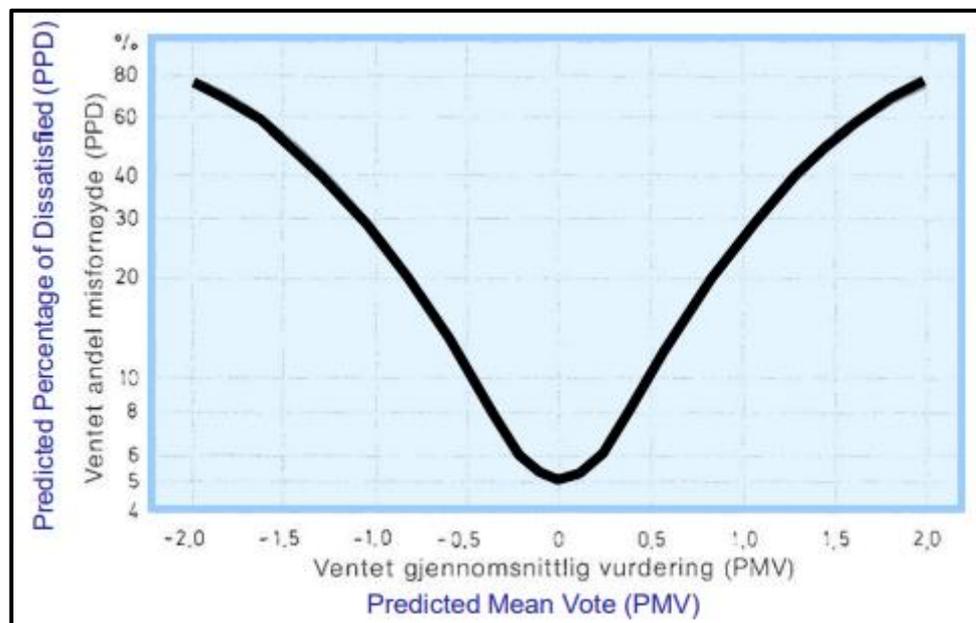


Figure 4 value of PPD by PMV [11]

For all the typical types of activities, a range of optimal operative temperature is ordered. These temperature ranges are dependent on the clothing, activity level [16]. Operative temperatures for office buildings are applied for the winter period within the range of 19-24

°C, typically 20°C, and for the summer period in the range of 23-26°C, typically 26°C [16] . Outside this range we are talking about non comfortable time to be in the building in the given moment. Based on Simple ASHRAE 55-2004 standard [17], when running building energy simulations in the EnergyPlus [14] software, the program provides a summary on the “Time Not Comfortable Based on Simple ASHRAE 55-2004” expressed in hours, summed up for the whole simulated time range, which is the main index used to express user comfort in this paper ([see 3.4.](#)).

2.4 Modern thermal insulation materials and systems

When talking about renovation of buildings for energy efficiency purposes, we can divide into three main categories. First, the renovation or change of apertures on the building envelope, such as windows and doors. This is, in connection with buildings under monumental protection, or in areas or neighbourhoods with protection due to their historical values, often complicated and requires special permits and investigation, which take usually more time and money than the investor originally would have liked to spend on the project.

The second opportunity is the renovation and update of the mechanical and electrical system of the building. This, hand in hand with smart building solutions, often has promising potential to reduce the building’s energy demand and collectable data for further adjustments and improvements of the system, to make the operation of the system more feasible and environmentally friendly. But renovating an existing HVAC and electrical system has always has drawbacks. Most importantly, applying any new members or elements within the chain of the buildings existing electric grid, can often cause unwanted results such as lack of power or short circuits. These are happening most likely due to the fact, that most of the time the original documentation of the building is not available, and ever since the freshly built state, usually many more, smaller, or larger adjustments have been done, what most of the time have not been attached to or overwritten the original documents. Secondly, when the goal is to construct a brand-new HVAC and or electrical system in an existing and currently used building, the works related to the construction often require the break of usage, which by its nature causes inconvenience and extra logistical problems to solve, not to

mention the loss on income of the operator for the time of works. Based on the above, it can be said that this type of renovation is the least common of the three mentioned in this article.

The third and most widely used method is the application or renovation of thermal insulation system of the building envelope, which provides a wide range of materials and methods to instantly improve the characteristics of the energy usage in the building and optimize thermal comfort, while also raising the value of the real estate. The works usually not require the break of usage of the building, but of course have temporary inconveniences just as every other type of repair works on buildings. The application of thermal insulation materials is usually a must by fresh builds by rules and regulations [2], but in the field of existing buildings is also a common solution. Of course, there are special cases with monumentally protected buildings, which require a special licensing procedure, regarding the modification of facades of protected buildings, but this topic is out of scope of this paper.

Thermal insulation materials went through a huge development in the past decades and it is easy to see that within the field of construction materials, this is the piece with the possibly highest industrial competition, caused by uncountable manufacturers worldwide and their special techniques and applications providing solutions for all possible scenarios regarding the installation of thermal insulation systems.

When talking about thermal insulation materials we must be aware of some main characteristics based on what we can call a material a thermal insulator. The key property of thermal insulation materials is the thermal conductivity [W/mK] [18], which needs to be a low value to give the material and the whole multilayer envelope structure a high thermal resistance [m²K/W] and a low thermal transmittance value of [W/m²K]. Low thermal conductivity also a crucial property when it comes to constriction thickness. With thermal insulations having low thermal conductivity and therefore low thermal transmittance, we can build thinner structures, which result more area to sell or to rent, since the maximal external size of buildings is regulated. Thermal conductivity of a material stands from several variables, of which every one of them must be possibly minimized, to make the material have a low thermal conductivity as a result [18]. The equation and the variables contributing to sum up the material's λ_{tot} total overall conductivity is shown in the following equation:

$$\lambda_{\text{tot}} = \lambda_{\text{solid}} + \lambda_{\text{gas}} + \lambda_{\text{rad}} + \lambda_{\text{conv}} + \lambda_{\text{coupling}} + \lambda_{\text{leak}}$$

Where λ_{solid} = solid state thermal conductivity, λ_{gas} = gas thermal conductivity, λ_{rad} = radiation thermal conductivity, λ_{conv} = convection thermal conductivity, $\lambda_{\text{coupling}}$ = thermal conductivity term accounting for second order effects between the various thermal conductivities in the equation λ_{leak} = leakage thermal conductivity [18]. Theoretically there are thermal insulation materials, e.g., VIP (Vacuum Insulation Panels) which by their characteristics make the coupling effect negligible [18]. There are also several other properties of thermal insulation materials regarding applicability and other technical requirements, which are out this papers scope.

In the followings, without the need for completeness, I try to collect nowadays' most up to date and the near future's possible thermal insulation materials [18] [19], aiming to find possible solution of thermal refurbishment of this paper's subject building ([see 2.1.](#))

2.4.1 Traditional thermal insulation materials

2.4.1.1 Mineral wool

Mineral wool encompasses both glass wool (fibreglass) and rock wool, typically manufactured in the form of mats and boards, occasionally serving as filling material. Light and pliable mineral wool products find application in frame houses and structures with cavities. Conversely, denser, and sturdier mineral wool boards with high mass densities are employed for



Figure 5 Mineral wool insulation - blocked [81]

thermal insulation in load-bearing scenarios, such as floors or roofs. Mineral wool can also function as a filler material for various cavities and spaces [18]. Mineral wool insulation materials are made from the melt of a combination of volcanic and sedimentary rocks, consisting of fibres with a minimal size of 3-5mm [20]. It is bound together with a heat-hardening, formaldehyde-based resin. This material is utilized as a fire-resistant substance; however, its thermal insulation properties significantly degrade upon contact with water. Due to its fibrous structure, it allows the passage of vapor. It is available in both blanket (roll) and

board forms, with various thickness options. It is employed for the insulation of various structures, except those exposed to groundwater, owing to its broad range of hardness, spanning from resistant to negligible. The thermal conductivity of mineral wool is subject to variations based on temperature, moisture content, and mass density. For instance, the thermal conductivity may shift from .0037 W/(mK) to 0.055 W/(mK) as the moisture content increases from 0 vol% to 10 vol%. Mineral wool products offer flexibility, allowing perforation, cutting, and adjustment on-site without compromising thermal resistance [18].

2.4.1.2 Expanded polystyrene (EPS)

Expanded polystyrene (EPS), derived from non-renewable energy sources, is a heat-insulating material crafted from small polystyrene spheres obtained from crude oil. These spheres, containing an expansion agent like pentane C_6H_{12} , expand when heated with water vapor, bonding at contact points [18]. The manufacturing process involves transforming these spheres into cubic-meter-sized blocks using a specialized block foaming device. Subsequently, hot steel wires cut these blocks into panels of varying widths. While EPS is primarily used above rafters for insulating roofing structures, its applications extend to walkable surfaces, ground-level floors, flat roofs, facades, and as an additive in lightweight concrete production. EPS has similar thermal conductivity characteristics as mineral wool, having the value in the range of 0.037-0.054 W/(mK) while increasing the moisture in the material from 0 to 10% respectively [18]. Despite its easy installation due to customizable sizing, EPS generates a significant amount of non-biodegradable waste, posing challenges for complete outdoor collection. Restricting its usage is strongly recommended in favour of eco-friendly insulation alternatives. Recycling is feasible in waste incinerators, and EPS exhibits a relatively high calorific value [20]. Due to its



Figure 6 EPS insulation while installation [82]

low fire resistivity characteristics, application of EPS thermal insulation material requires special fire safety engineering.

2.4.1.3 Extruded polystyrene (XPS)

Extruded Polystyrene (XPS) insulation is a high-performance material derived from melted polystyrene, featuring exceptional thermal insulation qualities. Produced by introducing expansion gases such as HFC, CO₂, or C₆H₁₂ during extrusion, XPS exhibits a closed pore structure. Typically manufactured as boards, its thermal conductivity ranges between 0.030 and 0.040 W/(mK) [18] [21] and varies with temperature, moisture content [22], and mass density. XPS is versatile, allowing perforation, cutting, and on-site adjustments without compromising thermal resistance [18]. While it excels in insulation applications, its elevated commercial cost reflects its superior qualities. Despite being non-biodegradable, it finds use in various settings, particularly where achieving high insulation values with minimal thickness is crucial. Specialized fire-resistant variations, such as PIR, exist. XPS possesses water repellence, low vapor permeability, and is commonly applied in prefabricated boards, sandwich panels, or on-site foamed, while being also used as roof or plinth wall insulation.



Figure 7 XPS roof insulation while installation [23]

2.4.1.4 Polyurethane (PUR)

Homogeneous, foamed plastic insulation possesses exceptional thermal insulation properties, justifying its high commercial price. Its strength varies and can be outstanding depending on the chemical composition. Typically applied in areas where achieving high thermal insulation values with minimal layer thickness is essential, such as in sandwich panels. This non-degradable material is fundamentally combustible, but specialized, fire-resistant variations, like PIR, exist. It exhibits water-repellent properties, and its vapor permeability is low. Application can occur in prefabricated boards, sandwich panels, or as on-site foamed, two-component installations [20]. Polyurethane (PUR) is a material derived from the reaction between isocyanates and polyols (alcohols containing multiple hydroxyl groups). During the expansion process, closed pores are filled with expansion gases such as HFC, CO₂, or C₆H₁₂. The insulation material is produced in the form of boards or continuously on production lines. PUR is also applied on-site in foam form, for example, for insulation around windows and doors and filling various cavities. Typical thermal conductivity values for PUR range between 0.020 and 0.030 W/(mK), considerably lower than mineral wool, polystyrene, and cellulose products. The thermal conductivity of PUR varies with temperature, moisture content, and mass density. For example, the thermal conductivity may increase from 0.025 W/(mK) to 0.046 W/(mK) with increasing moisture content from 0 vol% to 10 vol%, respectively. PUR products can be perforated, cut, and adjusted on-site without compromising thermal resistance [18]. It is important to note that while PUR is safe for its intended use, it raises serious health concerns and hazards in case of a fire. During a fire, the burning of PUR releases hydrogen cyanide (HCN) and isocyanates, which are highly poisonous. HCN toxicity results from the cyanide anion (CN⁻), which hinders cellular respiration. Hydrogen cyanide is generally found in the smoke from plastics containing nitrogen (N) [18].

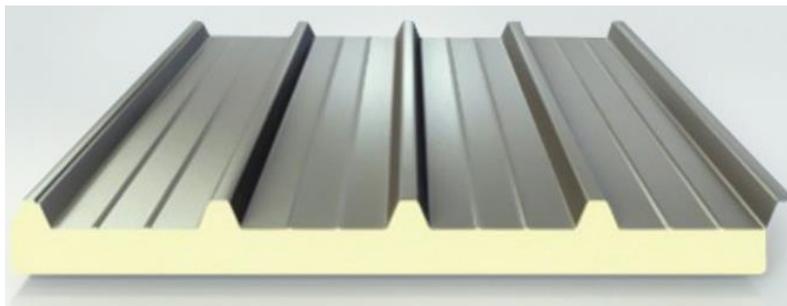


Figure 8 figure 8 PUR sandwich panel [25]

2.4.1.5 Wood fibre insulation

Wood fibre insulation, a notable alternative in the realm of thermal insulating materials, is crafted from natural wood fibres, often sourced from softwood species [24]. The production process involves mechanically refining the wood into fibres and then binding them with natural or synthetic binders. This method creates a material that combines excellent thermal insulation properties with sustainability. The thermal conductivity of wood fibre insulation typically ranges from 0.035 to 0.050 W/(mK) [25], showcasing its efficiency in hindering heat transfer. The variability in density and thickness allows for customization to specific insulation requirements. Notably, the fibrous structure enables moisture regulation, preventing the development of condensation within structures. Wood fibre insulation is employed in various applications, including roofs, walls, and floors. It serves well in both new constructions and retrofitting projects, contributing to energy efficiency, and reducing environmental impact. The material's fire resistance is achieved through additives, ensuring compliance with safety standards. One noteworthy aspect is its environmentally friendly nature, stemming from the renewable and biodegradable characteristics of wood. The manufacturing process often involves minimal energy consumption, contributing to its eco-friendly profile. In summary, wood fibre insulation stands as a technologically advanced and environmentally conscious choice for thermal insulation, offering a balance between performance, sustainability, and versatility in applications [24] [25] [26] [27].



Figure 9 Steico Wood fibre thermal insulation elements in various thickness [28]

2.4.2 State-of-the-art thermal insulation materials

2.4.2.1 Vacuum Insulation Panels (VIP)



Figure 10 VIPs being installed [86]

Vacuum insulation panels (VIPs) stand at the forefront of contemporary thermal insulation technology. Comprising an open porous core of fumed silica encased in multiple metallized polymer laminate layers, VIPs boast unparalleled thermal conductivity, ranging from 0.003 to 0.004 W/(mK) when newly applied [18]. However, an inevitable drawback emerges over time, with conductivity typically escalating to 0.008 W/(mK) after 25 years due to water vapor and air diffusion through the VIP envelope and into the core [18]. Depending on the VIP envelope type, this conductivity may substantially increase after 50 and 100 years. One critical limitation is the vulnerability of VIPs to puncturing, resulting in a drastic rise in thermal conductivity to around 0.020 W/(mK). Consequently, adjusting VIPs at the construction site or perforating them leads to a significant loss in thermal insulation performance, marking a major disadvantage [18]. Despite these drawbacks, VIPs currently emerge as one of the most efficient solutions for thermal building envelopes, offering substantial energy savings and economic benefits. While VIPs might not represent the ultimate future solution, their current relevance and efficiency make them a pragmatic choice for numerous thermal insulation applications today, most importantly due to its low thermal conductivity, which provides a relative high thermal resistivity even in significantly thinner constructions compared to traditional thermal insulation materials such as mineral wool or EPS [29] [30] [31].

2.4.2.2 Aerogels

Aerogels are easily considered as nowadays' cutting-edge thermal insulation solutions, currently holding the highest potential among various contenders [18] [32]. Utilizing carbon black to mitigate radiative transfer allows for impressively low thermal conductivities, potentially reaching 0.004 W/(mK) at 50 mbar pressure. However, commercially available aerogels, considered state-of-the-art, typically



Figure 11 Aerogel as thermal insulation while renovating historical buildings [49]

exhibit thermal conductivities between 0.013 and 0.014 W/(mK) at ambient pressure [18] [33]. Despite their relative high compression strength, aerogels possess fragility due to exceptionally low tensile strength, a challenge addressed through the incorporation of a carbon fibre matrix. While the production costs remain high, aerogels offer intriguing versatility by being producible in opaque, translucent, or transparent forms, expanding their applicability across a diverse range of building scenarios. To position aerogels as a widespread thermal insulation choice for opaque applications, substantial cost reduction is imperative. Their potential, particularly in achieving ultra-low thermal conductivities, makes them an area of intensive study and a technology with promising prospects for the future [18]. For widespread use, substantial cost reduction is needed.

2.4.2.3 Gas filled panels (GFP)

Closely aligned with Vacuum Insulation Panels (VIPs) is the technology of Gas-Filled Panels (GFP). GFPs leverage gases with lower thermal conductivity than air, such as argon (Ar), krypton (Kr), and xenon (Xe), in contrast to the vacuum employed by VIPs [18]. Maintaining a concentration of low-conductive gas and preventing air and moisture infiltration are pivotal for optimizing the thermal performance of GFPs. While vacuum proves to be a superior

thermal insulator compared to the gases utilized in GFPs, the latter's grid structure doesn't need to contend with an internal vacuum, a requirement for VIPs [18]. Internal low emissivity surfaces in GFPs act to reduce radiative heat transfer. Prototype GFPs, however, exhibit relatively high thermal conductivities, around 0.040 W/(mK), despite lower theoretical values [18]. Consequently, GFPs inherit many advantages and disadvantages from VIPs. The outlook for GFPs as thermal building insulation raises questions and uncertainties. In comparison, VIPs appear to be a more favourable choice for both current and future applications, considering their superior performance attributes. The balance of advantages and drawbacks underscores the ongoing need for advancements in GFP technology to compete with the efficiency of VIPs [18] [34] [35].



Figure 12 Cross-section of GFP [18]

3.MATERIALS AND METHODS

In this chapter a summary on the workflow of the project and applied materials and methods can be found.

3.1 The studied building

To understand the framework of the project, it is important to know the subject of this paper,

BME Building ST.

Address: Budapest, Stoczek
József u. 6,
(HRSZ.:4110)
1111 Hungary

Architect: Zoltán Farkasdy [37]

Year of
construction: 1950



Figure 13 BME Building ST on Google Maps [36]

The building was designed and constructed by the order of Budapesti Műszaki Egyetem (BME) in 1949-50, by the plans of KÖZTI – the official national architectural and design office for public buildings of the era in Hungary, with the supervision of architect Zoltán Farkasdy [37]. The name ST comes from respect to József Stoczek, famous Hungarian engineer and professor of the 19th century, and by also the main entrance of the buildings is approachable from the Stoczek street. 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 (HRSZ.: 4110) is under historical, archaeological and world heritage protection [38]. The main idea behind the core usage units of the building was to have a basement level of laboratories, mechanical and building operation premise and additional shelters underground, above that the ground floor and 3 levels in a longitudinal orientation of NW-SE, having lecture rooms and offices on every level, supplemented with a water block on each of these levels. These levels are connected by 2 set of concrete stairs, one on the SE end of the building, operating as a technical stair, having an emergency exit at the ground floor, and one in the centre operating as the main stairway, running around the elevator, having a secondary entrance, with a curtainwall (Figure 14) giving the building a unique

appearance. Connected to this B-G-3L (Basement - Ground floor - 3 Levels) structure, another wing has been built, containing the main entrance, the main Auditorium, and the hall.



Figure 14 the secondary entrance and the curtainwall in different perspectives [39]

By the early stages of the project the building was planned to be a multi-faculty educational and administrative building, with laboratories and lecture rooms, with additional operative and social premises, which characteristics are also nowadays true on the building. These days the building is being used for educational and administrative purposes, sharing the gross area of cc. 6400 m² of the building between 4 faculties of the university and the Chancellors Office. The structure and design stand for the trend of the era, with its pillar frame reinforced concrete structure, which operates with additional steel structure elements and prefabricated beams at certain points. Facades have been constructed with 38cm brick walls filling the gaps between the pillars and hiding them. For joists and girders monolith reinforced concrete and prefabricated beams have been applied, covering them on the external surfaces with paving bricks, resulting homogeneous external brick surfaces.

After the construction of the building up to nowadays, 3 mayor modifications and renovations had been made on the building.

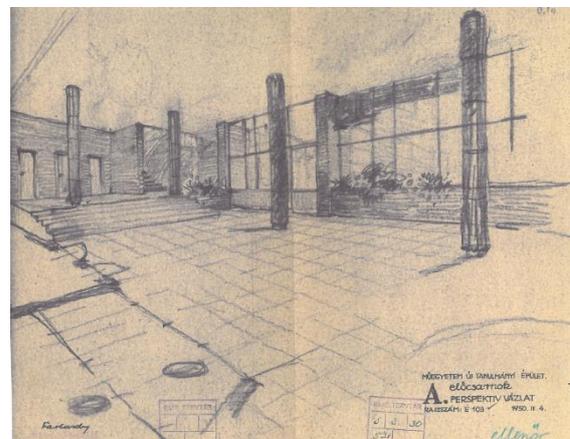


Figure 15 Sketch of the hall by Farkasdy [40]

For first, in 1979 the auditorium has been renovated, but no serious modifications have been made, only some refurbishment of the furniture and apertures, which not included the change of them.

Then, in 1985 a 4th storey has been built upon the existing B-G-3L structure, giving extra space for enlarging the available educational and administrative capacity in the building. The new level has been built directly upon the slab operating as flat roof up to the date, while the newly built facades got a 25cm brick-8cm mineral wool insulation-4cm ventilated air gap – 1cm slate covering structure, giving today's different texture and appearance of the storey.

Lastly, in 2011 a minor inside renovation have been done in the building, which mainly resulted in changing some apertures that were over their original lifespan.

3.2 Modelling

To perform reliable building energy simulations, a BIM model of the building was necessary. Since a pre-made model was not available, it has been built. To construct the BIM model, I did research for available documentation of the building. In the BME Archives [40] I have been provided with the building's original documentation from 1950 with numerous structural and architectural floorplans, cross-sections, and detail sketches. Documentation on renovation of the main auditorium in 1979, in the form of technical descriptions and some other text documents, with around 20 pieces of technical drawings on the renovation works of the auditorium wing. About the construction of the 4th Level, a much detailed documentation has been provided, with numerous drawings in the field of demolition of the until then existed flat roof, structural design of the newly built storey, installed into and having load bearing role together with the existing structure, 2 mechanical drawings of the new HVAC system, and many architectural drawings with floorplans and detail drawings on the alignment of the new level, which have

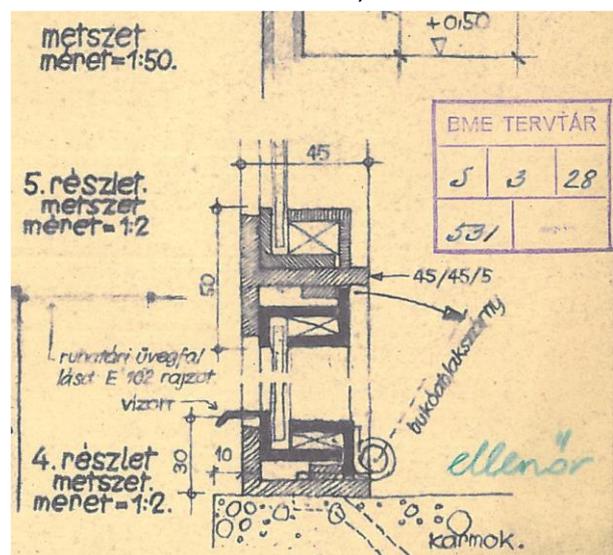


Figure 16 Detail from the 1950 Documentation [40]

been built in a similar way as the levels below.

From the provided documentations the following main order of layers that are interesting from the aspect of building energy simulations were readable:

Surface	Order of layers
Facades (until 1985) [in-out]	<ul style="list-style-type: none"> -paint, plaster -38 cm brick facade Or above apertures and ring beams: -paint, plaster - 4 cm mineral wool - 26 cm rfc beam - 8 cm paving brick
Façade of the 4 th floor [in-out]	<ul style="list-style-type: none"> -pain, plaster - 25 cm brick - 8 cm mineral wool - 4cm ventilated air gap with timber joist - 2 x 4 mm slate covering
Flat roof (since 1985) [out-in]	<ul style="list-style-type: none"> - 3 layers of bituminous sheet (waterproofing) - fixture layer of Bonomit H - 5 cm subgrade concrete - 2-25 cm slope-giving smelter slag filling - 10 cm Nikecel thermal insulation - 11 cm rfc slab on TR 65-DV metal sheet - steel load bearing structure by structural plans - cc 20 cm airgap - ceiling

Table 3 Main order of layers in the building [40]

Many more layer structure is readable in the provided documents, but those are not strictly necessary for building energy simulations.

Lastly, a status recording documentation with floorplans, cross sections and façade drawings has been provided, which served as the basic of the 2011 inner renovation works. All the

used documentation has been supplied in separate PDF files from every phase of construction mentioned above for every drawing and text files.

After studying the provided documentation, the building's BIM model has been built in Autodesk Revit 23 [41]. While building the model, the provided documentation, mostly floorplans were used in a form of imported PDF files, working as "tracing paper" or underlayer in the model space for the model being built. For these underlying PDFs the floorplans from the 2010 documentation had been used, these drawings can most certainly be said to have been made in a CAD software, providing an exact scaling of 1:50, which turned out to be a huge help when modelling, and also cannot be said on the PDF files provided from previous eras, being digitally scanned photocopies of the original drawings, whose transformation aiming to serve as underlayer in the model space would have been causing problems in scaling due to the non-DIN paper sizes and sizes of the pictures and in readability.

Within the model to set the levels' relative height in the building values were used based on the floorplans and cross sections in the provided documentation. For exact values see the table below:

Level	Relative height
Flat roof	+19,10 m
4 th floor	+15,06 m
3 rd floor	+11,45 m
2 nd floor	+7,98 m
1 st floor	+4,49 m
Ground floor 1	+1,02 m
Ground floor 2	+ - 0,00 m
Basement 1	-1,50 m
Basement 2	-2,40 m

Table 4 Relative heights of levels within the building

For modelling windows, the available documentation and on-site photodocumentaries were also used. From the 1950 and 1985 documentaries a 2-layer glazing with airgap between has been established, while based on the on-site photo documentation a 2-layer glazing with Argon gas filled between, sometimes with a low-e coating on one side can be found. It is

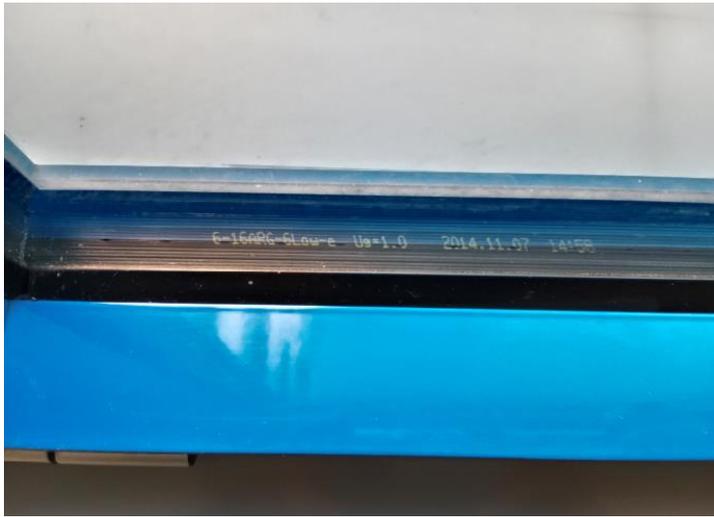


Figure 17 Glazing structure of the curtain wall in the hall [39]

needed to mention, that for the curtain wall in the hall, based on the apertures themselves the year of construction is 2014 (Figure 17) which highlights the fact that some minor refurbishment works have been done after the latest, 2011 inner renovation, but no more information has been provided regarding this. Based the prints and photos the windows and apertures

has been modelled aiming to be as realistic as possible regarding appearance and most importantly thermal and energy characteristics.

After the model has been built (Figure 18), the building energy settings have been set, including location, and building type (here: School or University) data, which is a crucial set of information regarding reliable building energy simulations. Unfortunately, Revit's inside set of HVAC systems does not contain the type of district heating system, which is operating in the building, but a first building energy simulation using as a core set of geometrical and energy data on the building elements provided an acceptable first glimpse on the energy demand of the building. The first, or so-to-say number zero simulation was run within the Revit built-in energy module which uses EnergyPlus [14] for building energy calculations. For more information on that, [see 3.4.](#)

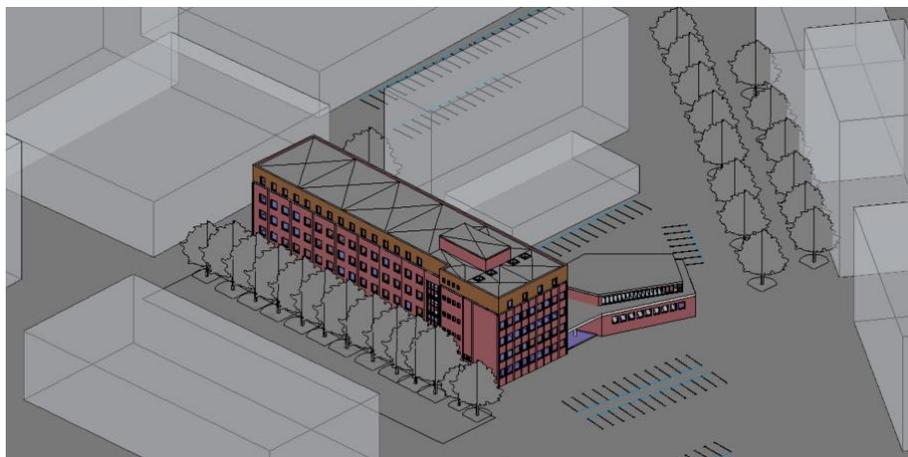


Figure 18 The model with conceptual masses of neighbouring buildings

3.3 Applied thermal insulation materials

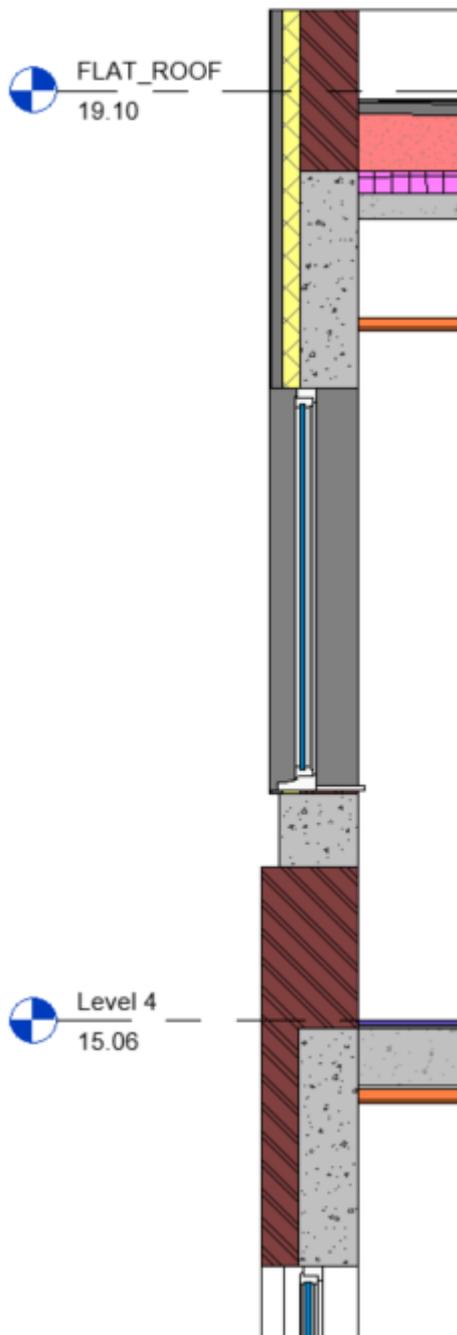


Figure 19 cross-section from the model

From the very start of the project the main task was find the best possible thermal insulation solution for the building facades and roof in terms of environmental loads, in this case $\text{kgCO}_2\text{eq.}$ – possible the lowest on a 20-year long scale – and user comfort, in this case the number of comfortable hours in a year – aiming for maximum possible. For this, based on the literature research ([see 2.4.](#)) a palette of possibly applicable thermal insulation materials was collected, with available EPDs that collected the products' environmental loads during their estimated lifespan of 50 years, which provides close to equal environmental loads for the application of thermal insulation materials with the designed lifespan of 20 years, since during their usage stage of life (B1-B7) these thermal insulation materials are not considered as direct polluters of environment.

The minimum requirement for the simulated structures (existing façade and roof constructions with applied thermal insulation materials in various thicknesses) was that even when applying the thinnest version of the given thermal insulation material, the structure must pass the thermal requirements set in [2], such that it is written above ([see 2.1.](#)). Below a list of thermal insulation materials is shown, with a summary of environmental loads for their estimated lifespan.

3.3.2 Mineral wool

Mineral wool ([see 2.4.1.1.](#)) is being used in the project for building energy simulations as a façade- and as a roof thermal insulation material. For these purposes, 2 separate products from the same manufacturer ROCKWOOL [42] were chosen.

For the summary of environmental loads of the products, see the figure below.

Parameter	Production stage	Construction stage		Use stage							End-of-life stage			D Benefits and loads beyond the boundaries of the system	
	A1-A3	A4 Transport	A5 Installation	B1 Use	B2 Maintenance	B3 Repair	B4 Replacement	B5 Refurbishment	B6 Operational energy use	B7 Operational water use	C1 De-construction/ demolition	C2 Transport	C3 Waste treatment		C4 Disposal
Global warming potential (GWP) kg CO ₂ eqv	1,21E+00	5,66E-01	1,08E-01	0,00E+00	MNA	MNA	MNA	MNA	MNA	MNA	0,00E+00	3,01E-03	0,00E+00	1,25E-02	-4,63E-02

Figure 20 ROCKWOOL products' kgCO₂eq. summary [43]

Since the manufacturer provides one EPD which is applicable for many of its products, using a predefined multiplier for each of them, a summarized value of each material can be calculated. These predefined multipliers are necessary, since the reference material which was used for the preparation of the EPD stands for a 1 m² of 39 mm thick ROCKWOOL stone wool with thermal resistivity of 1 m²K/W and a density of 28 kg / m³ [43].

For the summarized kgCO₂eq. loads for the 50-year designed lifespan of the products see the table below:

PRODUCT	APPLICATION	LOAD MULTIPLIER	SUM. kgCO ₂ eq./m ³ for 50 years
FRONTROCK SUPER (λ _D =0.036 W/mK)	FACADE	2,8	133.05
HARDROCK MAX (λ _D =0.040 W/mK)	ROOF	5.7	270.85

Table 5 applied ROCKWOOL materials and kgCO₂eq. values

The applied thicknesses of the ROCKWOOL thermal insulation materials in the building energy simulations were 10-15-20-25 cm (4 versions) in the case of roof insulation, and 12-14-16-18-20 cm (5 versions) in the case of façade insulation.

3.3.3 XPS

For thermal insulation of roof surfaces another material was also used with mineral wool, which is XPS (see 2.4.1.3.). For the application of this material in the project a multi-manufacturer EPD was used [44] which was prepared by the order of EXIBA - European Extruded Polystyrene Insulation Board Association [45]. The reference material for the assessment was an extruded polystyrene foam board of 1 m² with the thickness of 100 mm and average density of 33 kg/m³. For the summary of environmental loads of the products, see the figure below:

DESCRIPTION OF THE SYSTEM BOUNDARY (X = INCLUDED IN LCA; MND = MODULE NOT DECLARED)																
PRODUCT STAGE			CONSTRUCTION PROCESS STAGE		USE STAGE							END OF LIFE STAGE				BENEFITS AND LOADS BEYOND THE SYSTEM BOUNDARIES
Raw material supply	Transport	Manufacturing	Transport from the gate to the site	Assembly	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction demolition	Transport	Waste processing	Disposal	Reuse-Recovery-Recycling-potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
X	X	X	X	MND	MND	MND	MNR	MNR	MNR	MND	MND	MND	X	X	X	X
RESULTS OF THE LCA - ENVIRONMENTAL IMPACT: 1 m ² XPS board with a thickness of 100 mm																
Parameter		Unit	A1-A3	A4	C2	C3	C4	D								
Global warming potential		[kg CO ₂ -Eq.]	9.14E+0	2.76E-1	2.58E-2	1.11E+1	2.26E-1	-4.70E+0								
Depletion potential of the stratospheric ozone layer		[kg CFC11-Eq.]	5.69E-14	4.58E-17	4.29E-18	1.00E-15	7.91E-16	-6.49E-14								
Acidification potential of land and water		[kg SO ₂ -Eq.]	1.60E-2	6.43E-4	6.01E-5	6.54E-4	6.25E-4	-7.95E-3								
Eutrophication potential		[kg (PO ₄) ³ -Eq.]	1.89E-3	1.59E-4	1.49E-5	1.35E-4	6.33E-4	-8.60E-4								
Formation potential of tropospheric ozone photochemical oxidants		[kg ethene-Eq.]	1.41E-2	-2.13E-4	-2.00E-5	6.45E-5	7.04E-5	-6.29E-4								
Abiotic depletion potential for non-fossil resources		[kg Sb-Eq.]	2.30E-6	2.14E-8	2.00E-9	7.18E-8	4.38E-8	-8.49E-7								
Abiotic depletion potential for fossil resources		[MJ]	2.66E+2	3.76E+0	3.52E-1	1.11E+0	3.45E+0	-6.63E+1								

Figure 21 XPS products' kgCO₂eq. summary [44]

After the normalization for 1 cubic meter, the summarized kgCO₂eq. loads for the 50-year designed lifespan of the products see the table below:

PRODUCT	APPLICATION	LOAD MULTIPLIER	SUM. kgCO ₂ eq./m ³ for 50 years
XPS (λ _D =0.035 W/mK)	ROOF	10	133.05

Table 6 applied XPS kgCO₂eq. values

The applied thicknesses of the XPS thermal insulation material in the building energy simulations were 9 – 12 – 15 - 18 cm (4 versions) for roof insulation.

3.3.4 Wood Fibre

The second version for thermal insulation on façades in the building energy simulations was the application of wood fibre insulation (see 2.4.1.5.). For this, the STEICO Protect dry wood fibre insulation has been applied [46]. The reference material in the applied EPD [47] was a unit of 1 cubic meter wood fibre insulation material with a density of 140 kg/m³, which 1-in-1 corresponds, with the used material, causing the value of load multiplier to be 1.0. For the summary of environmental loads of the product, see the figure below:

DESCRIPTION OF THE SYSTEM BOUNDARY (X = INCLUDED IN LCA; MND = MODULE NOT DECLARED; MNR = MODULE NOT RELEVANT)																
PRODUCT STAGE			CONSTRUCTION PROCESS STAGE		USE STAGE							END OF LIFE STAGE				BENEFITS AND LOADS BEYOND THE SYSTEM BOUNDARIES
Raw material supply	Transport	Manufacturing	Transport from the gate to the site	Assembly	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction demolition	Transport	Waste processing	Disposal	Reuse-Recovery-Recycling-potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
X	X	X	MND	X	MND	MND	MNR	MNR	MNR	MND	MND	MND	X	X	MND	X
RESULTS OF THE LCA - ENVIRONMENTAL IMPACT according to EN 15804+A1: 1 m ³ Holzfaserdämmstoff aus dem Trockenverfahren																
Parameter	Unit	A1	A2	A3	A5	C2	C3	D								
GWP	[kg CO ₂ -Eq.]	-1.85E+2	2.43E+0	1.01E+2	1.70E+1	4.06E-1	2.22E+2	-1.05E+2								
ODP	[kg CFC11-Eq.]	1.41E-7	4.04E-16	3.25E-13	6.62E-15	6.76E-17	3.67E-16	-3.06E-12								
AP	[kg SO ₂ -Eq.]	7.22E-2	1.02E-2	2.04E-1	2.86E-3	1.70E-3	1.00E-2	-1.05E-1								
EP	[kg (PO ₄) ³ -Eq.]	1.34E-2	2.56E-3	2.41E-2	6.08E-4	4.28E-4	2.17E-3	-1.83E-2								
POCP	[kg ethene-Eq.]	1.15E-2	-4.28E-3	4.06E-2	1.47E-4	-7.16E-4	9.82E-4	-1.02E-2								
ADPE	[kg Sb-Eq.]	8.13E-5	2.05E-7	1.06E-5	3.29E-7	3.42E-8	1.02E-7	-3.04E-5								
ADPF	[MJ]	9.74E+2	3.35E+1	1.29E+3	5.34E+0	5.61E+0	1.49E+1	-1.76E+3								

Figure 22 STEICO products' kgCO₂eq. summary [47]

The summarized kgCO₂eq. loads for the 50-year designed lifespan of the product are shown in the table below:

PRODUCT	APPLICATION	LOAD MULTIPLIER	SUM. kgCO ₂ eq./m ³ for 50 years
STIECO Protect dry (λ _D =0.040 W/mK)	FACADE	1	52.84

Table 8 applied wood fibre kgCO₂eq. values

The applied thicknesses of the STEICO Protect dry wood fibre thermal insulation material in the building energy simulations were 14 – 16 – 18 – 20 – 22 cm (5 versions) for façade insulation.

3.3.5 Aerogel

The third version for thermal insulation on facades in the building energy simulations was the application of aerogel insulation ([see 2.4.2.2.](#)). For this, the Aspen Spaceloft Aerogel [48] insulation was used. The reference material in the applied EPD [49] was a sheet of aerogel thermal insulation with a thickness of 10 mm and area of 1 m², density of 150 kg/m³ and a thermal conductivity of 0.015 W/mK. For the summary of environmental loads of the product, see the figure below:

Parameter	Unit	Product Stage	Construction Stage	Use Stage	End of Life Stage	Total
Global warming potential	kg CO ₂ eq	1.23E+01	1.80E-01	n/a	n/a	1.25E+01

Figure 23 Aspen Spaceloft Aerogel thermal insulation material's kgCO₂eq. summary [49]

The summarized kgCO₂eq. loads for the 50-year designed lifespan of the product are shown in the table below:

PRODUCT	APPLICATION	LOAD MULTIPLIER	SUM. kgCO ₂ eq./m ³ for 50 years
Aspen Spaceloft Aerogel (λ _D =0.015 W/mK)	FACADE	100	1248.00

Table 8 applied wood fibre kgCO₂eq. values

It is worth to mention that this is the thermal insulation material with the highest embodied GWP value of all applied in the project, this is caused mostly by the great transport distances from the manufacturing in USA to the site in Hungary.

The applied thicknesses of the Aspen Spaceloft Aerogel thermal insulation material in the building energy simulations were 1 – 2 – 3 – 4 – 5 cm (5 versions) for façade insulation.

3.3.6 Vacuum Insulation Panels

The fourth – and within the framework of this paper the last – version of applied thermal insulation materials of facades of the building was the Vacupor NT-B2-S vacuum insulation panel. The reference material in the applied EPD [50] was a sheet of VIP thermal insulation with a thickness of 25 mm and area of 1 m², density of 180 kg/m³ and a thermal conductivity of 0.020 W/mK. For the summary of environmental loads of the product, see the figure below:

ANGABE DER SYSTEMGRENZEN (X = IN ÖKOBILANZ ENTHALTEN; MND = MODUL NICHT DEKLARIERT; MNR = MODUL NICHT RELEVANT)																
Produktionsstadium			Stadium der Errichtung des Bauwerks		Nutzungsstadium							Entsorgungsstadium				Gutschriften und Lasten außerhalb der Systemgrenze
Rohstoffversorgung	Transport	Herstellung	Transport vom Hersteller zum Verwendungsort	Montage	Nutzung/Anwendung	Instandhaltung	Reparatur	Ersatz	Erneuerung	Energieeinsatz für das Betreiben des Gebäudes	Wassereinsatz für das Betreiben des Gebäudes	Rückbau/Abriss	Transport	Abfallbehandlung	Beseitigung	Wiederverwendungs-, Rückgewinnungs- oder Recyclingpotenzial
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
X	X	X	X	X	X	X	MNR	MNR	MNR	MND	MND	X	X	X	X	X
ERGEBNISSE DER ÖKOBILANZ – UMWELTAUSWIRKUNGEN nach EN 15804+A1: 1 m ² VIP mit 25 mm Dicke																
Parameter	Einheit	A1-A3	A4	A5	B1	B2	C1	C2	C3/1	C3/2	C4/1	C4/2	D/1	D/2		
GWP	[kg CO ₂ -Äq.]	40,60	0,02	1,66	0,00	0,00	0,00	0,10	0,93	0,58	0,00	0,06	-40,26	-0,81		
ODP	[kg CFC11-Äq.]	4,83E-12	7,95E-18	3,49E-16	0,00E+0	0,00E+0	0,00E+0	3,27E-17	1,50E-14	3,91E-16	0,00E+0	3,24E-16	-5,99E-13	-1,74E-14		
AP	[kg SO ₂ -Äq.]	1,03E-1	1,57E-5	5,23E-4	0,00E+0	0,00E+0	0,00E+0	6,09E-5	4,82E-4	6,42E-5	0,00E+0	3,70E-4	-9,68E-2	-7,00E-4		
EP	[kg (PO ₄) ³⁻ -Äq.]	1,21E-2	2,91E-6	1,32E-4	0,00E+0	0,00E+0	0,00E+0	9,41E-6	9,68E-5	1,43E-5	0,00E+0	4,16E-5	-1,12E-2	-1,33E-4		
POCP	[kg Ethen-Äq.]	1,29E-2	-2,50E-7	3,13E-5	0,00E+0	0,00E+0	0,00E+0	-2,92E-6	4,03E-5	5,95E-6	0,00E+0	2,81E-5	-1,24E-2	-7,03E-5		
ADPE	[kg Sb-Äq.]	8,69E-4	2,02E-9	4,08E-9	0,00E+0	0,00E+0	0,00E+0	3,79E-9	1,41E-7	4,08E-9	0,00E+0	5,91E-9	-8,69E-4	-1,85E-7		
ADPF	[MJ]	623,14	0,32	0,35	0,00	0,00	0,00	1,42	3,75	0,24	0,00	0,83	-591,70	-10,72		

Figure 24 Vacupor products' kgCO₂eq. summary [50]

The summarized kgCO₂eq. loads for the 50-year designed lifespan of the product are shown in the table below:

PRODUCT	APPLICATION	LOAD MULTIPLIER	SUM. kgCO ₂ eq./m ³ for 50 years
Vacupor NT-B2-S (λ _D =0.020 W/mK)	FACADE	40	115.20

Table 8 applied wood fibre kgCO₂eq. values

The applied thicknesses of the Vacupor NT-B2-S vacuum insulation panel thermal insulation material in the building energy simulations were 2.5 – 5 – 7.5 – 10 – 12.5 cm (5 versions) for façade insulation.

3.4 Programming and data analysis

With the input parameters provided, such as the energy simulation of the existing building and the chosen thermal insulation materials as input variables, the task was to prepare the building's models with the different thermal insulation scenarios and run building energy simulations for each, to have a comparable dataset for further observations and optimization. For this, the Python 3.10 [51] programming language was used.

3.4.1 Programming surface and packages

The codes written while working on the project were scripted in the PyCharm 2022.2.1 Community Edition IDE (Integrated Development Environment) [52]. To run building energy simulations from the Python interface, the Energyplus Eppy v0.5.63 [53] package has been installed

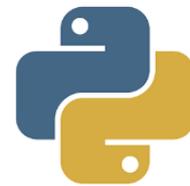


Figure 25 the Python logo

and applied. Eppy is a scripting language operating in Python, developed specifically for making changes in the EnergyPlus input files, run simulations from the Python IDE, and make further changes in the building energy simulation result files ([see 3.4.2.](#)). working with the eppy package provided a wide range of predefined functions and capabilities work with multiple EnergyPlus input and output files at the same time. To handle the data provided by the building energy simulations results, the Pandas [54] package was used within Python. Pandas is a data management toolkit to make operations on existing, or to create new datasets, with built-in easy to handle functions and integrated indexing, which turned out to be much useful, when the certain thermal insulation versions of the building could be used as indexes by their names ([see 3.4.2.](#)). For the visualization of data and the summary tables (see 3.) the Matplotlib [55] package was applied. The optimization task was performed with the Pymoo v0.6.0 [56] multi-objective optimization Python package, which has a toolkit [57] for the NSGA-II [3] optimization procedures, and many more to visualize data. During the research period, further optimization frameworks were examined such as Argos Suite and Ārtap [58] [59].

3.4.2 Building Energy simulations

To run building energy simulations in EnergyPlus, 3 input files are needed [60]. First, the EnergyPlus input file, which has a “.idf” extension. This is a text file with a strict format regarding the order of data about the building with all the necessary information, which is used for building energy simulations, e.g., site and location, building sizes, orientation, sizes of thermal zones, construction materials, structures with all the layers etc. Second, the IDD file, which is a dictionary text file, which helps the program to be able to understand and process the information in the IDF file, and makes possible to use the same IDF, so basically the same building, with multiple versions of the program (preferably from an older version to a newer version). And lastly, the weather file with a “.epw” extension. This contains the weather data, the closer to the site in time and space the weather station the better and provides information for the program on the weather around the site within the simulated timeframe.

To run the 1st simulation in the Revit built-in energy module, none of the above was required, since, by setting the correct location of the site in the Project Location option within Revit, the best possible weather file is ordered from an online database to the model. The IDF file is being made within the first steps of simulation based on the built BIM model, and the IDD file is ordered to the simulation from the previously installed EnergyPlus version on the computer. That is why having a pre-installed EnergyPlus version on the computer is a must.

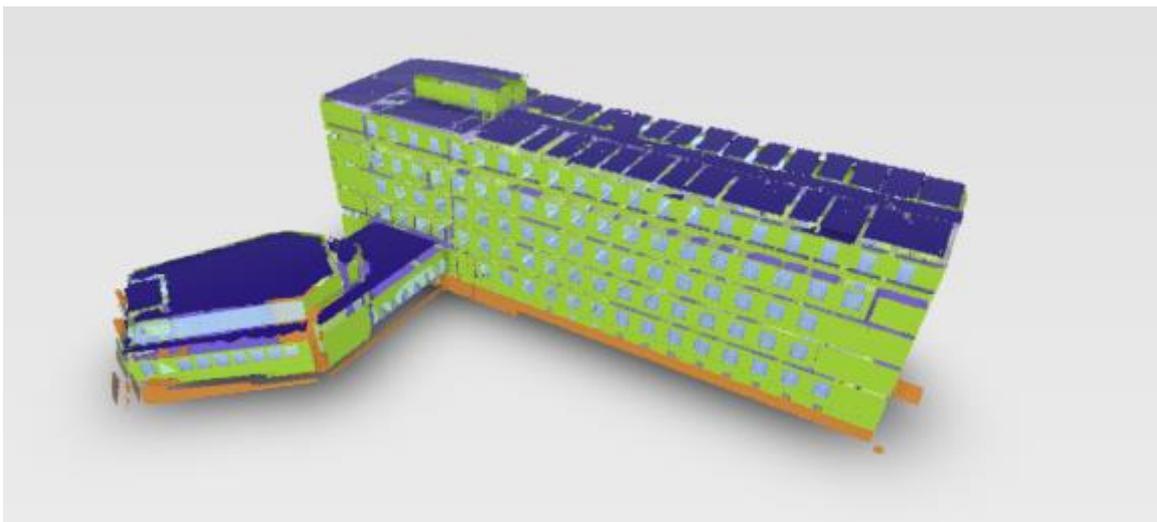


Figure 26 Model of the building with the thermal zones on the Autodesk Insight online surface

When running energy simulations in Revit, an optimization module for Autodesk Insight [61] is automatically attached to the model, which is an online interface which provides building design option comparisons (Figure 26), with a schematic material and construction library. One of the weaknesses of the surface that it does not directly applies the materials and constructions from the Revit model families but uses a considered as standard library of model elements with major thermal and building energy characteristics.

The first building energy simulation based on the BIM in Revit took around 25 minutes, which, regarding the number of upcoming simulations, raised the need of shortening. After some consideration of the thermal zones which in the original model were handled totally separately, representing one premise in the building each, a simplified BIM model was built based on the original model, but without the septum walls, causing a drastic decrease in the number of thermal zones and elements within the IDF file. A simulation was also conducted on this model, having a runtime of 11 minutes, and after comparing the two simulations' results, (see the table below) showing no significant difference between each other, yet a significant difference in runtime, a decision was made to use the simplified model for further investigation.

MODEL	heating demand [GJ/a] (difference %)	Number of non-comfortable hours (difference %)
Original	1212,04 (-)	2941 (-)
Simplified	1244,22 (+ 2,70%)	2960 (+0,65%)

Table 7 differences between the original and the simplified model

The “Time Not Comfortable Based on Simple ASHRAE 55-2004” values of the simulations are summed up in hours by the time when any zone is occupied that the combination of humidity ratio and operative temperature is not in the ASHRAE 55-2004 summer or winter clothes region [60].

After having the simulation done in the Revit environment, the task was to somehow find and be able to use the created IDF file, which is not saved individually within the reports folder created while running EnergyPlus in Revit. After researching the question, the solution [62] was that when running EnergyPlus in Revit, an IDF file, having all the required formal and technical data is being saved into the temporary folder of the computer, from where the IDF is easy to reuse and modify.

Having the IDF from the “donor-building” the next step was to prepare all the IDF files with the required thermal insulation materials and thicknesses applied on the necessary surfaces. For this, the eppy [53] package was used within Python [51]. First,

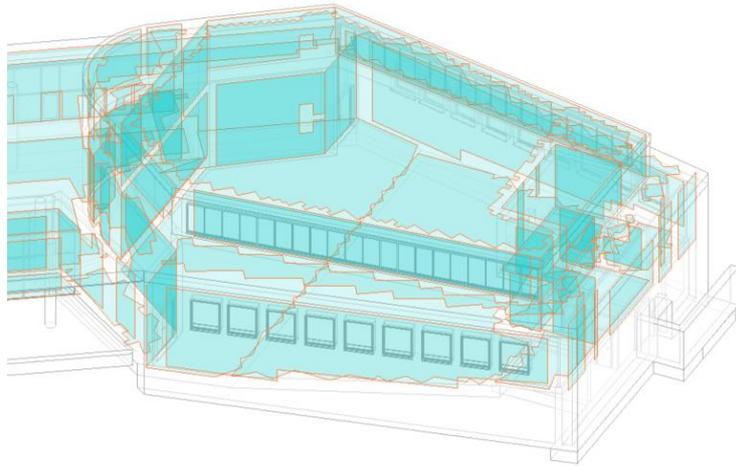


Figure 27 Analytical spaces in the Auditorium wing in the BIM model

the original IDF, made from the simplified model was

referred as input file, then within a loop of predefined steps one-by-one for every new building version with different thermal insulation materials applied on roof and facades, the thermal insulation materials applied on facades were inserted into the material collection of the IDF with all the necessary information, e.g., thickness (varied in every version), thermal conductivity and density. Then, for the “BuildingConstruction:Detailed” elements which in IDF terms mean the multilayer objects such as walls and roofs or floors within the IDF file, while applying an externality criteria, the materials were ordered as outside layer of the walls, while appending the number of the until then existing layer elements, creating a new layer structure with the thermal insulation materials in the given thickness. The method was the same with the roofs. This way, 160 different versions of the building in separate IDF files has been created ($4_{\text{typ.of.fac.insu.}} * 5_{\text{thickness.of.fac.insu.}} * 2_{\text{typ.of.roof.insu.}} * 4_{\text{thickness.of.roof.insu.}} = 160$) for all the predefined materials and thicknesses (see 3.3.). The nomenclature of the new IDF files was created that way, that while looking the name of the file, the thermal insulation method can be read, such as e.g., “BME_ST_RW15_XPS12.idf” meaning the given IDF model stands for the textfile to perform EnergyPlus building energy simulation of the building version of Rockwool insulation of 15 cm on the facades and XPS insulation of 12 cm on the roofs.

When the IDFs were ready, there was a need for a weather file with “.epw” extension. For this, the Meteonorm 8.0.2 [63] software was used, to create a reliable and up-to-date weather file for the location of the building, which can be read by EnergyPlus.

Lastly, the IDD was needed, which was already available on the computer since it is an always-involved file with every version of EnergyPlus.

To run all the 160 building energy simulations, a multiprocessing code was used – and modified as necessary – from the Eppy documentation, to make parallel processing possible on multiple cores of the CPU (Central Processing Unit) of the computer. This way, the 160 simulations were done in 18.5 hours, which is equal to less than 7 minutes for one simulation in average.

The result of the simulations were several output files for all of them, summarizing the simulation process itself, and containing the calculated building energy demands and comfort indicators in the format of e.g., .html and .csv files. Using the Pandas data manager toolkit in Python, the data of electricity and heating yearly demand, and the “Time Not Comfortable Based on Simple ASHRAE 55-2004” data in hours were raised into a common .csv file for all the building versions, having indexes as their names. Based on these results, further values were calculated in the summary .csv file, using the kgCO₂eq. values ([see 2.3.](#)) and the conversion factors in [2].

3.4.3 Application of LCA

To understand the GWP values in the applied EPDs ([see 2.3.1.](#)) the methodology behind and meaning of the data shown in these documents must be understood. In this chapter, a summary on the methodology of LCA is presented, which is followed by the implementation of EPDs into this work.

One of the oldest and most widely accepted test methods for summarizing environmental loads of products is LCA (Life Cycle Assessment). The procedure has been used since the end of the 1960s to summarize and analyse the impact of various products and services on the environment [64] t. It quickly became clear that reliable results can only be obtained based on accurate data. To calculate the total environmental impact of products, the entire life cycle of the product must be considered, starting from the extraction of raw materials, through production and distribution to the end of use or the start of reuse, where the used product is re-entered into the cycle as a raw material. The former is called the Cradle to Grave (C2G) method, and the latter the Cradle to Cradle (C2C) method [9] [10] [64].

LCA quantifies the environmental effects of products, helps in the systemic understanding of the product's life cycle, thus facilitating the further development of the product and decision-making related to developments. With its help, we can find the key aspects that are the biggest environmental burdens of the product's life cycle (raw materials, work processes), which can be changed to reduce the product's environmental footprint [64].

LCA distinguishes between direct and indirect environmental effects. The direct effects are clear, such as raw materials mined from nature, or any environmental impact or waste resulting from the use or wear of the product. Indirect effects are often invisible, hidden loads. Electricity, drinking water, and exhaust gas released into the environment during transport are also used during the production of the product. When these effects are summed up over the entire life cycle of the product, from the raw material state to the end of life, we apply the life cycle approach [9] [10]. The method can also be used for buildings. The LCA summarizes all materials entering the building and their typical environmental loads, including direct and indirect effects. From an LCA point of view, the life cycle of a building is divided into stages according to Figure 28.

PRODUCT STAGE			CONSTRUCTION PROCESS STAGE		USE STAGE							END OF LIFE STAGE				BENEFITS AND LOADS BEYOND THE SYSTEM BOUNDARIES
Raw material supply	Transport	Manufacturing	Transport from the gate to the site	Assembly	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction demolition	Transport	Waste processing	Disposal	Reuse-Recovery-Recycling-potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D

Figure 28 LCA stages

Sections A1-5 run from the raw material state to the incorporated material, to the finished building. Sections B1-7 include maintenance and renovation work, replacements, and energy consumption during the period of use of the building. Stages C1-4 are the end of the traditional C2G model, ending with the depositing of the demolished materials of the building. Section D summarizes the "discounts" that go beyond the traditional model, generated in the cradle-to-cradle method, and can be used from the loads of sections B and C, for starting the new life cycle, based on the idea that the more recycled loads that are

already in the system are incorporated into a new building, the more less new load needs to be added to the system except from nature.

The course of the life cycle analysis method is described in the ISO 14040 and ISO 14044 standards, and its form is fixed [65] [66]. Accordingly, at the beginning of the investigation, we must know what and why we are investigating, the investigation must have a purpose. This is the first step in applying LCA.

We need to define the functional unit, which, when comparing raw materials, is typically a product with a surface area of 1m^2 or a volume of 1m^3 , or e.g., production under 1 year. In this case, the life cycle of the examined materials in the applied EPDs is 50 years.

Also, we must define the system limit, which means the test interval between the stages of the product's life cycle. E.g., from factory gate to factory gate, from cradle to grave. IN this paper, based on the applied EPDs [43] [44] [47] [50] [49], the C2G method has been used. The step of defining the above three parameters is called Goal and scope definition in the literature. That is, the definition of the purpose and authority. This is followed by the inventory analysis, which practically means the exact quantitative and qualitative collection of the materials entering the building. With traditional planning methods, this means manual data entry, but with modern BIM methods, this process can be automated with high accuracy. Impact assessment is the quantification of the impact on the environment of the inputs (incoming energy) and outputs (materials leaving the system, loads) collected in the inventory analysis. The emissions and raw materials are assigned to the impact categories ([see 2.2.](#)), and then the total load is calculated according to some impact assessment method. Due to the cycle nature of the life cycle, what counts as input raw material and what is output environmental load must be specified by defining the system boundary. The last step is the interpretation of the results, which is predominantly the task of the expert preparing the test, as a traditional textual analysis. There are LCA software that can also compare building versions, in which case the expert's task is exhausted by checking the correctness of the documentation.

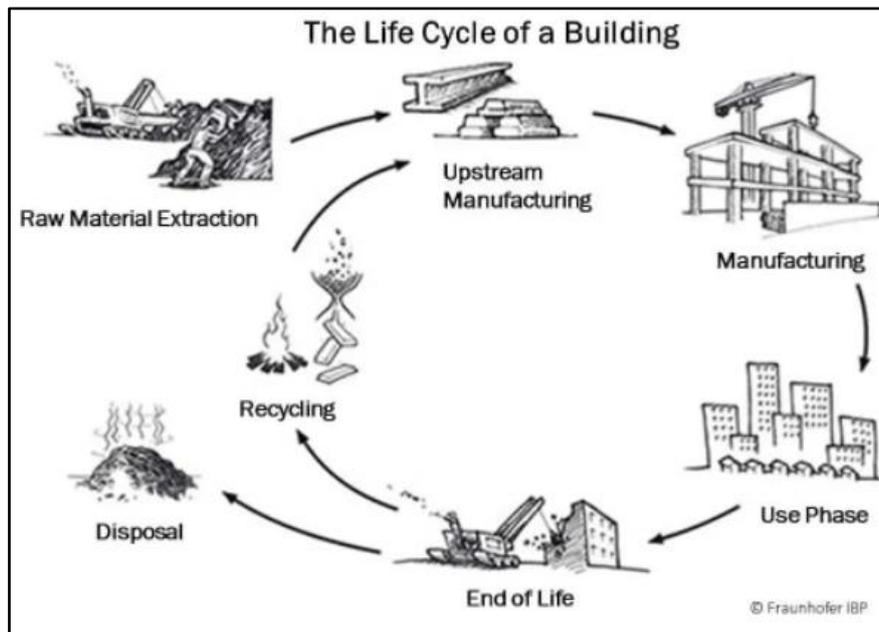


Figure 29 the life cycle of a building [67]

To be able to determine environmental loads of construction materials, application of EPDs was needed. To find EPDs of applicable thermal insulation materials and viable summary of environmental loads possibly for Hungary and in worst case for Middle Europe, online EPD catalogues and surfaces were researched, such as [68], [69], [70], [71], [72]. Also, as a welcomed consequence of manufacturers' need of constant improvement and environmental consciousness many of them provides nowadays EPDs directly prepared for their specific products, so manufacturers' websites were also researched such as [43]. Since the different EPDs not necessarily contain values for environmental loads for each and every stage of the product life cycle, it was a preliminary task to determine, which values to count into the summary of environmental loads when comparing the different applied thermal insulation materials. By studying the used EPDs and considering the materials' characteristics by nature ([see 2.4.](#)), the decision was to sum up and apply every value available in the EPDs, with the necessary volume corrections, which normalizes the compared values for cubic meters, generating a viable comparison of kgCO₂eq. loads for the materials in question, on an equal scale.

3.4.3 Optimization

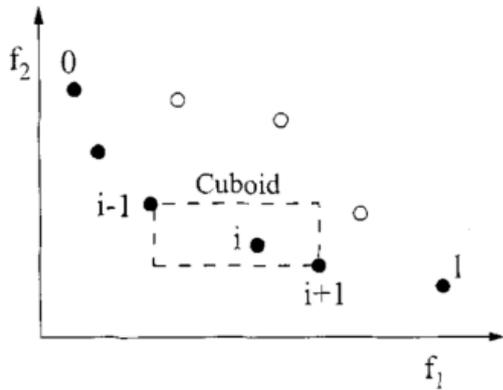


Figure 30 method for the crowding distance in Pymoo NSGA-II [57] [75]

To search the Pareto-optimal [4] solutions for the thermal insulation system of the building, which means to find the solutions in the model space which are non-dominated by others [3], causing a frontier of equally good solutions from the aspect of the examined parameters, called the Pareto front, the Pymoo nsga2 [57] Python package was used. This method has a history in

building optimization projects, with promising applicability and adaptability for wide range of

problems [1] [73] [74]. NSGA-II provides a set of possible best solutions for the decision makers in any type of projects, making possible the work and focus only on the solutions with the best trade-offs within the set, and making the weak solutions fall off from the scope of work. NSGA-II (Non-dominated sorting Genetic Algorithm) [3] is an extension of genetic algorithms, incorporating non-dominated sorting and crowding distance. In NSGA-II the applied crowding distance is the Manhattan Distance (Figure 30 method for the crowding distance in Pymoo NSGA-II) [75], while taking care of not to drop the extreme values, while getting a crowding distance of infinity [57]. To increase some selection pressure, NSGA-II uses a binary tournament mating selection. Each individual model value is first compared by rank and then crowding distance [57]. The algorithm operates on a population of potential solutions, evolving through generations, these generation are provided through crossover and mutation operations which are applied to generate new candidate solutions (Figure 31). Pymoo also can be used for several other applicable methods to solve multi-objective optimization tasks [56]. Users can visualize and analyse the results to gain insights into the trade-offs inherent in the optimization problem. The Pymoo library is well-documented, making it accessible for researchers and practitioners, helping to use the best suitable method for many different types of MOO tasks.

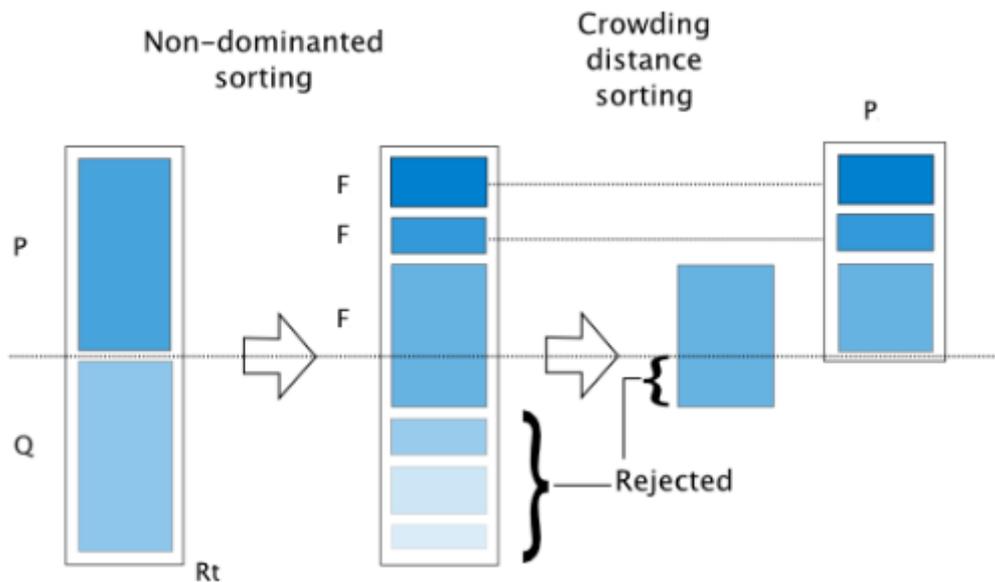


Figure 31 sorting mechanism of NSGA-II [63]

A consideration to apply other sorting algorithms such as R-NSGA-II [76] and NSGA-III [77] to have a base of comparison between different methods was made, but the R-NSGA-II did not provided significant differences with NSGA-II, while the runtime was significantly longer, and the application of NSGA-III ran into hardware problems.

3.4.5 Simplifications, limitations

The workflow did not involve the examination of fire section boundaries of the building, nor the aspect of façade and roof fire safety [78] [79] [80]. The applied thermal insulation materials have different fire safety characteristics. Rockwool products are considered generally firesafe [43] [79], the Vacupor NT-B2-S VIP has a fire safety paint coating [50], while the Aspen Spaceloft aerogel has a declared fire safety classification of C,s1,d0 according to DIN EN 13510-1 [49], while the same classification on the Steico protect dry wood fibre insulation and for the applied XPS materials is Class E based on the same standard [47] [44].

3.4.4 Workflow, research matrix

The workflow of the project is shown in the flowchart below:

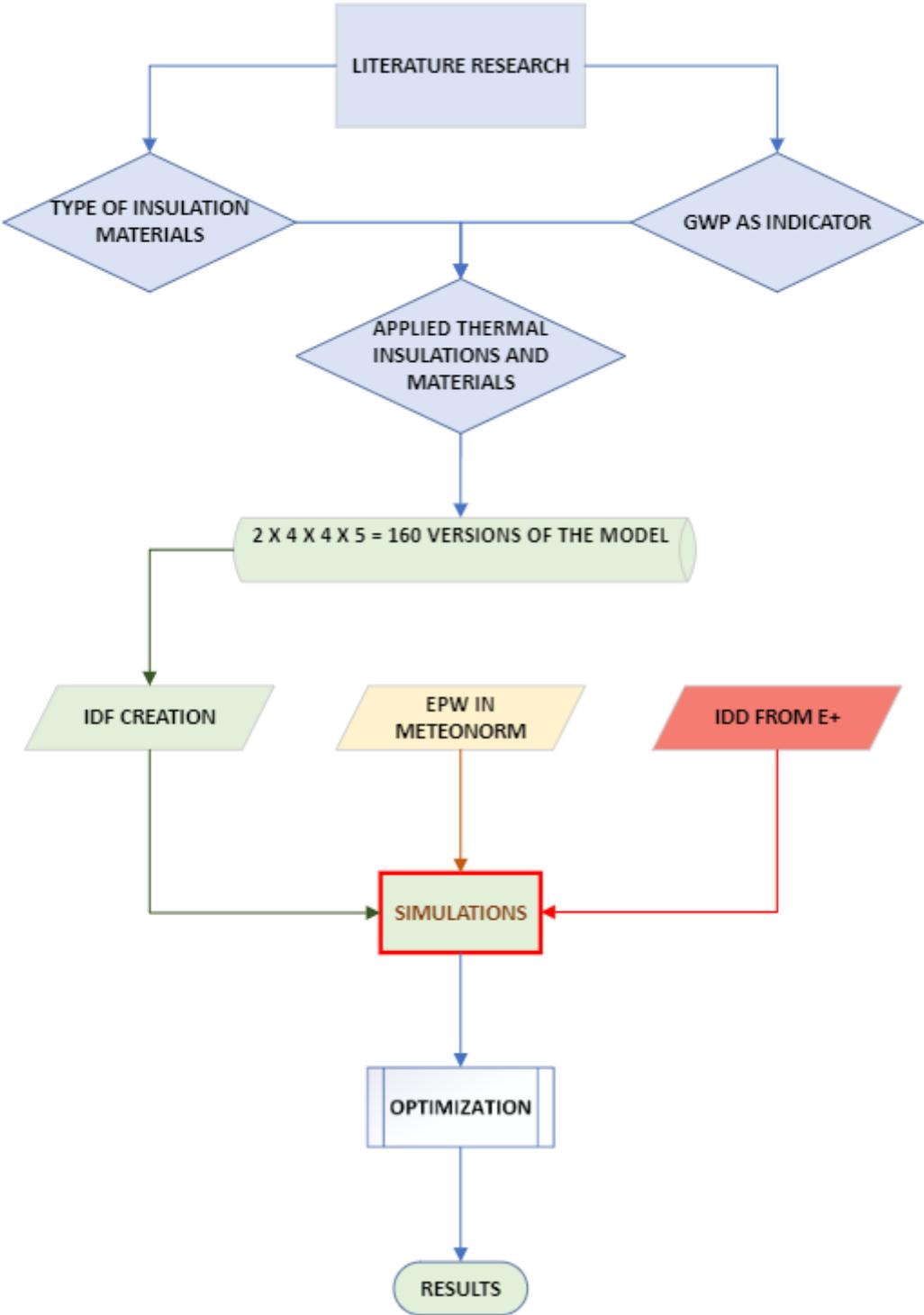


Figure 32 workflow of the project

The research matrix, the examined combinations of thermal insulation materials and thicknesses are shown in the flowchart below:

Roof thermal insulation, thicknesses

Facade thermal insulation, thicknesses

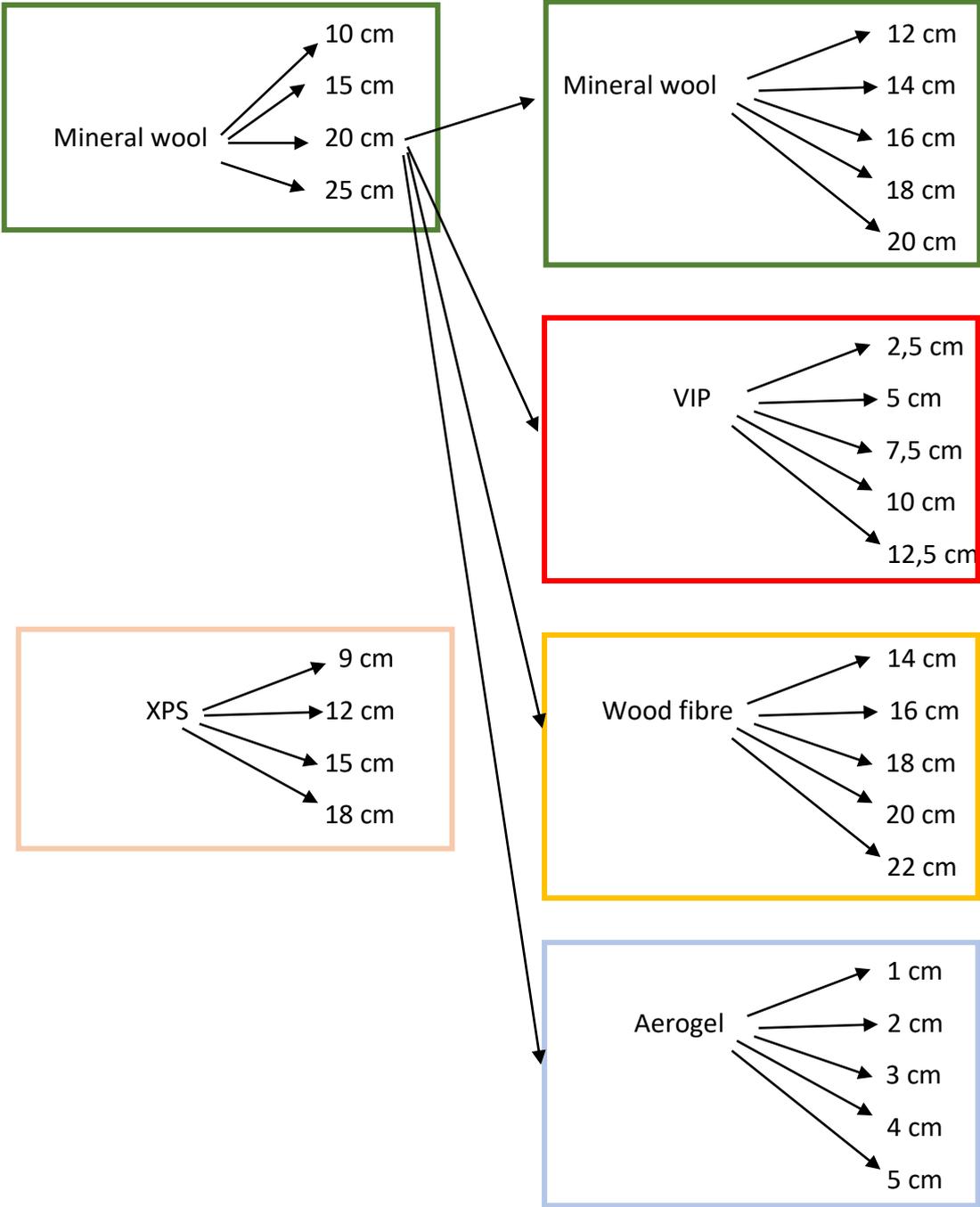


Figure 33 applied thermal insulation thicknesses

With the combination of both roof insulation materials with all the thicknesses to all the four façade insulation materials with all the thicknesses, a sum of 160 thermal insulated building was created.

3.4.6 Examination of results

Having all the simulation results and the optimization part done, based on the plots of the dataset several examination and observations were done ([see 4.](#)). The goal of these observations was to find the best possible thermal insulation solutions for the building regarding user comfort and environmental loads of the embodied GWP of the thermal insulation materials and the environmental loads and site energy demand in the 20-year long use of the building after the application of thermal insulation. Due the size and many thermal zones within the building the PMV and PPD values turned out to be not likely useful, and because of this, the user comfort in the building has been estimated such that, the building energy simulations consisted a “Time Not Comfortable Based on Simple ASHRAE 55-2004” unit, expressed in hours, based on what the amount of comfortable hours in the building has been estimated as subtracting the simulated value of the parameter above from the 8760 hours from the year. Also, with the optimisation process a set of possibly best solution were collected, which are worth to consider from the aspect of application cost and cost of usage of the building in the 20-year long period after application, but that is out of the scope of this paper.

4. RESULTS

In this chapter, based on the visualization of the dataset, a collection of observations and plots are presented.

While visualizing the dataset, an unexpected problem occurred. The originally thought to be independent dataset of the specific site energy demand, and due to the simple multiplication of conversion factors the specific GWP of the building from the comfortable hours within the building turned out to be not independent, no significant scattering was not observable on the plot, see figure 33. The visualization of the dataset always has a colour legend for the

façade insulation materials, having blue or pink edges. If the edge of the marker is blue, the applied roof insulation material is Rockwool, and if it is pink, the applied material is XPS.

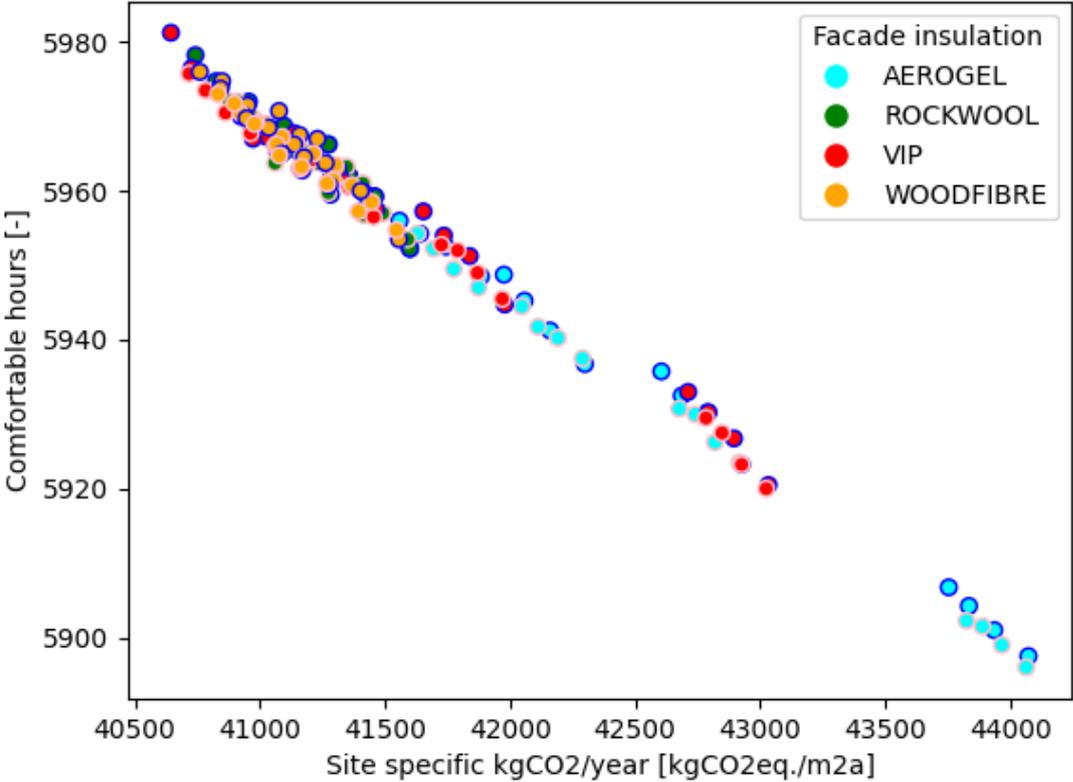


Figure 34 site kgCO2/m²a - CH plot

Based on this can be seen that all the versions of the applied thermal insulation materials on the scale of user comfort have a deviation of 80 hours through the year, but it is needed to mention, that for the 2960 uncomfortable hours of the reference building without insulation (see Table 8) the amount of comfortable hours in the building add up to $8760 - 2960 = 5800$ comfortable hours, which is around 100 hours less, then the worst simulated value, which means, due to the use characteristics of the building, even the worst solution from the aspect of comfortable hours through the year (1cm Aerogel on facades and 9cm XPS on the roofs) has around 100 more hours of comfortable time in the building through the year. It can be also highlighted, that this comparison has an “absolute winner” variation with the version having 12.5 cm VIP applied on the facades and 25 cm Rockwool thermal insulation on the roofs, causing the number of comfortable hours within the building to be 5981, which is by more than a week more comfortable time to be in the building than the reference model’s

result, and having the value of 40644,07 kgCO₂eq./m²a of GWP, while the reference model performs for the same parameter 47824.06 kgCO₂eq./m²a, setting the difference between the construction version with the lowest GWP and the reference model of cc. 7200 kgCO₂eq./m²a, which is considered the size of the building, a meritorious difference on the total scale, and also from the aspect of possible energy cost savings.

To perform a viable optimization process, independent input variables were needed. Seeing through the simulation results, it turned out to be clear that the electricity demand of the building in all the simulations were handled as a constant of 277,16 MWh for a year, being a value of 51,2 kWh/m²a. This could have happened most likely due to the characteristics of the building, having a “School or University” type in the simulations, which is in one hand true, but on the other hand, further refinements are suggested to estimate a more precise value for the different building version for demand of electricity.

After performing further visualizations, it became clear, that the most varying variables in the simulations are the embodied GWP values of the applied thermal insulation materials.

On Figure 35, the representation of the embodied GWP values of the applied thermal insulation materials in the different construction versions compared to the number of comfortable hours in the building can be seen. After the optimization process, and visualization of the Pareto front (black) on the plot it can be said, that the wood fibre façade insulation versions and some VIP façade insulation versions are ruling this comparison. The aerogel façade insulation, when having 1cm of thickness does not provide enough number of comfortable hours, while when having more thickness, the embodied GWP skyrockets. On the two ends of the Pareto frontier lies the thinnest VIP façade insulation solution with 2,5 cm and the thinnest version of XPS roof insulation by 9cm of thickness, and the thickest VIP with 12,5 cm and thickest simulated rockwool insulation of 25 cm. Between these border values are taking place the wood fibre façade insulation versions in all the simulated thicknesses with possibly the lowest value of XPS on the roofs such as 9-12-15 cm. It is worth to mention that the difference between the lowest and highest value of embodied GWP within the members of the pareto front has an almost fivefold difference between them, which asks the question, whether it is worth to install the thermal insulation system with the highest number of comfortable hours, while it is only 60 hours more a year, and has so much

more embodied kgCO₂eq. The answer may lie in the difference in the long-term operation and installation costs.

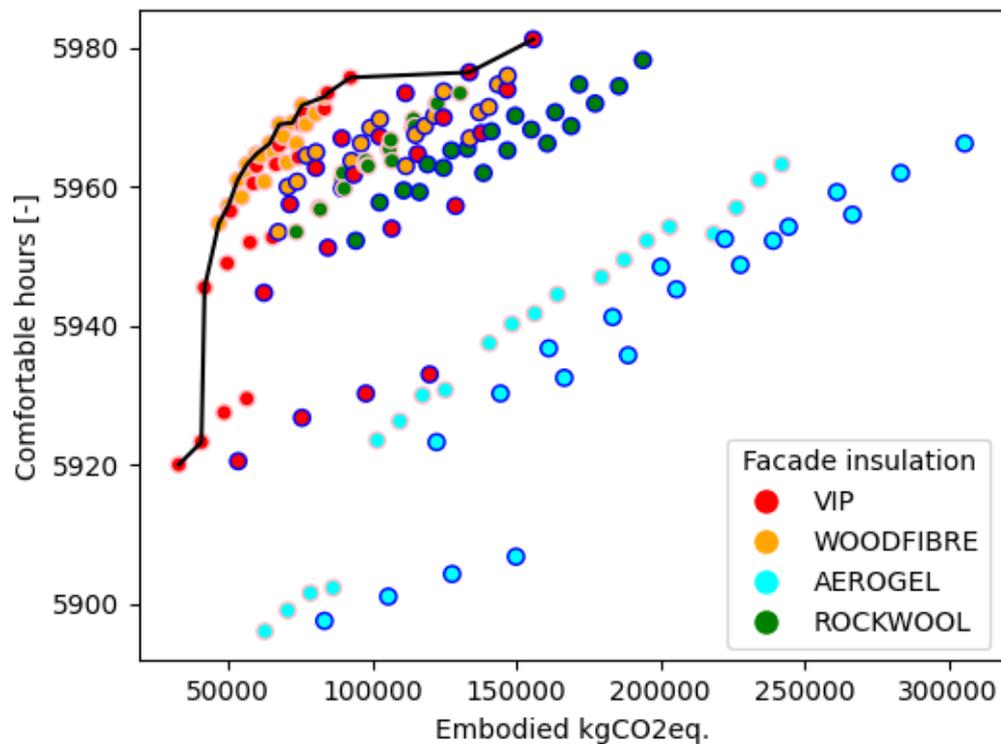


Figure 35 embodied kgCO₂eq. of thermal insulation materials - CH plot

On Figure 36, the plot and the Pareto front for the embodied GWP of the applied thermal insulation materials and the site energy demand of the different building versions for 20 years after the installation of the thermal insulation system is shown. This figure shows probably the best the difference between application of the same insulation and thickness on facades compared to the same façade insulation solution but with different roof insulation. Here also, blue edges mean rockwool, pink edges mean XPS roof insulation. Based on the picture, it can be stated, that the rockwool roof insulation solutions have a generally higher GWP than the XPS versions, but it also must be mentioned that rockwool is being applied in general with greater thickness values, and the specific GWP is much higher in the case of Rockwool compared to XPS, 270.85 and 160.68 kgCO₂eq./m³ respectively.

Aerogel performs badly compared to the other materials in this comparison also, but it is clear, since it has a ninefold more GWP value than Rockwool wall thermal insulation with the second highest GWP, 1248.00 and 133.05 respectively.

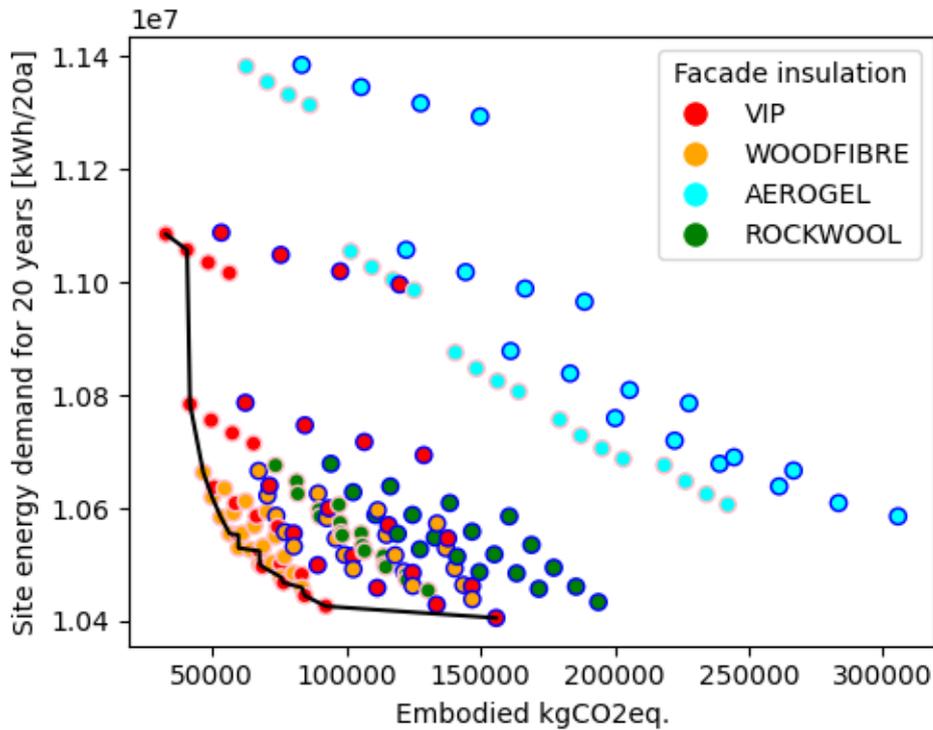


Figure 36 Embodied GWP of materials - 20-year site energy demand plot

The Pareto front in this case also stands up around the wood fibre versions, having the same border members as on Figure 37, (VIP façade with 2,5 and 12,5 cm and XPS with 9 or rockwool roof insulation of 25cm respectively). The key to these results in the case of the wood fibre façade insulation is caused by the lowest value of GWP in the examined materials with a value of 52.84 kgCO₂eq.

If we take a look at Figure 37, we can see that the presentation of the comparison of embodied GWP of the applied thermal insulation materials and the GWP value of the site energy demand for the upcoming 20 years after the application of thermal insulation solutions is having the same picture with the exactly same Pareto front. In this case also the reference building's values are shown, which tells us, there is a difference of $5 \cdot 10^8$ kgCO₂eq. between the reference building and the 1st member of the Pareto front in GWP values on the run of 20 years.

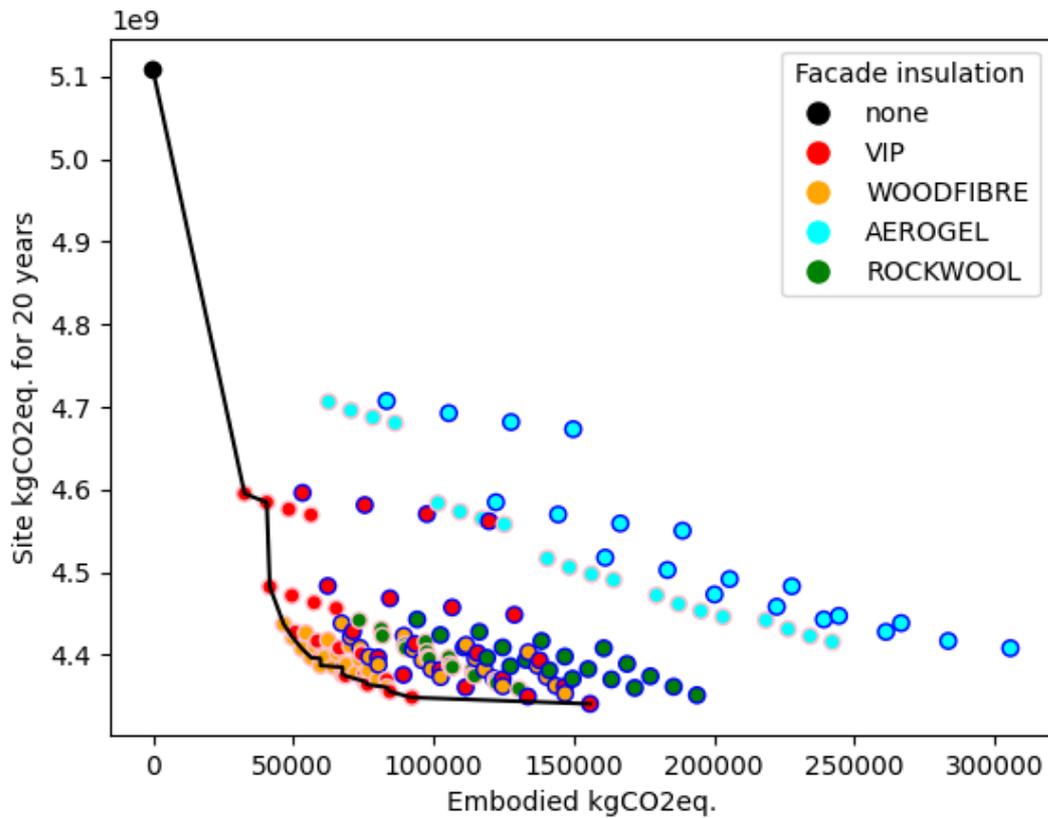


Figure 37 Embodied GWP - site GWP for 20 years plot

If we see Figure 38, where the embodied GWP values and the yearly heating demands are compared, we can see a significant difference in the amount of required energy. On this scale, monetary considerations are worth to make. The difference between the yearly heating demand of the reference building and the 1st member of the Pareto front in this case is $345644.316 \text{ kWh} - 277116.612 \text{ kWh} = 68527.70 \text{ kWh}$ which is, counted with a gross price of district heating as 190,44 HUF/kWh adds up to a difference of cc. **13.05 M HUF a year**, not to mention potential savings on a 20 year long period and net present value, but that requires the installation cost of the thermal insulation system to be considered, but that's out of the scope of this paper.

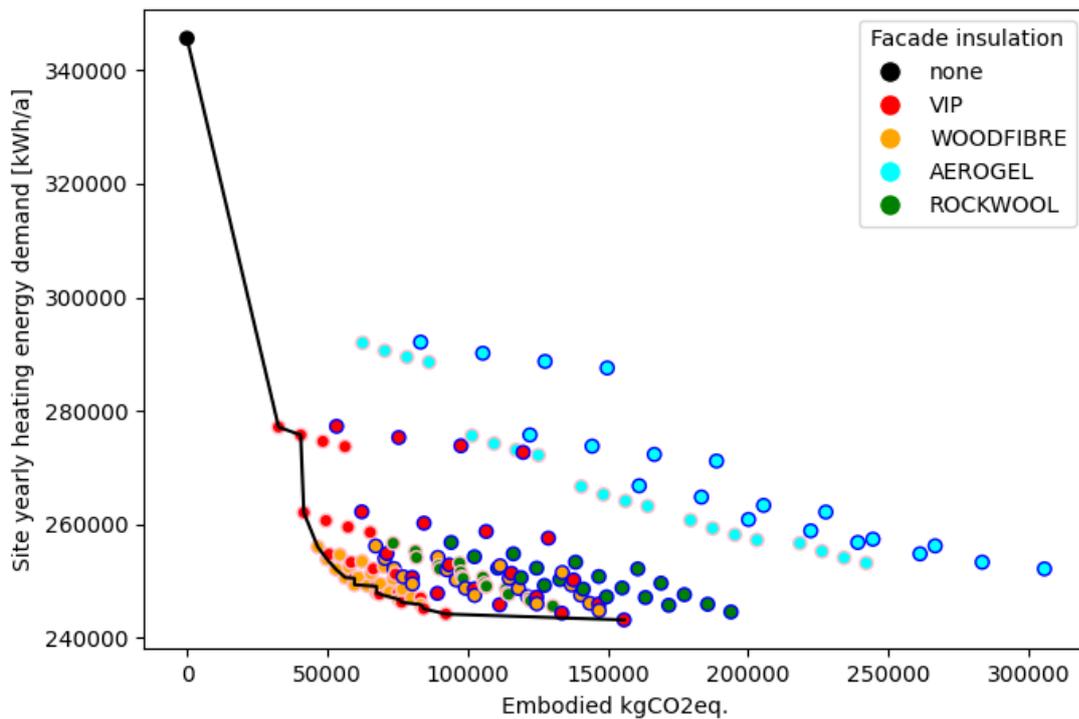


Figure 38 Embodied GWP - site heating energy demand plot

An attempt was made to find the possibly best from all the simulated building versions, regarding site yearly energy demand and site yearly GWP. The version with the lowest value of both examined parameters is the model version with 12.5 cm VIP on the facades and 25 cm Rockwool thermal insulation on the roofs. The difference between this version and the reference model from the aspect of site yearly energy demand (electricity and heating combined) is $622,808.154 - 520,291.620 = 102,516.534$ kWh of energy, which is remarkable difference, regardless of prices of public utilities (see Figure 39). Yet, it must be mentioned, that VIP is one of, if not the most expensive material from the catalogue of applied thermal insulation materials in the simulations.

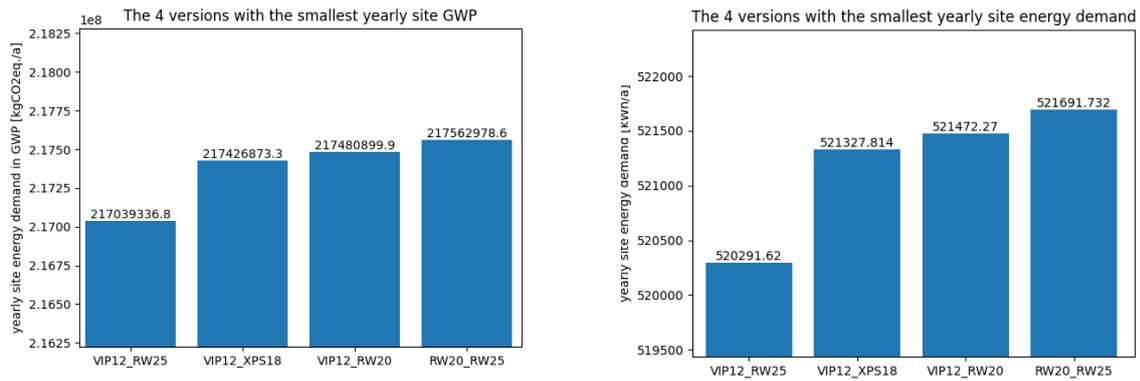


Figure 39 The smallest site GWP and site energy demand versions

On Figure 40 the four building version with the smallest embodied GWP values are shown. The model with the smallest embodied GWP is the version with 2.5 cm VIP insulation on the facades and 9 cm of XPS on the roof. In the case of application of this version, the yearly site energy demand is 554,280.45 kWh, which is by **68,527.704 kWh less** than the reference building's yearly site energy demand.

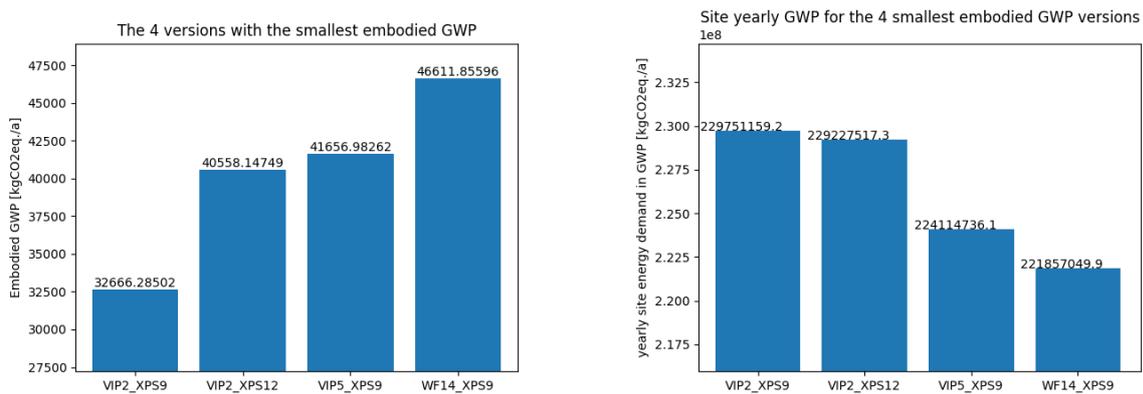


Figure 40 The 4 smallest embodied GWP versions and their site yearly GWP

From these versions (Figure 40) with the lowest embodied GWP, the model with 14 cm of wood fibre insulation on the facades and 9 cm of XPS on the roofs has the lowest value of site yearly GWP, having a site yearly energy demand of 533, 173.206 kWh, which is by **89,634.948 kWh less** than the reference building's yearly site energy demand. It is important to mention that the lowest embodied GWP is resulted by scenarios including less thermal insulation than required by the ÉKM decree.

5. CONCLUSION, IMPACT

A comparison of application of different thermal insulation materials in various thicknesses on the facades and roofs of the BME Building ST based on dynamic building energy simulations and optimization procedures had been done. The novelty of the project was the usage of direct programming interfaces to run numerous building energy simulations at the same time and then based on the results, have a possibility to quickly and effectively optimize the collected dataset, to help and develop a wide range of possible construction solutions for the BME building ST's thermal insulation in order to enhance user comfort and reduce to building's carbon footprint and the operation costs. During the examination of results a correlation between the embodied GWP values of the different thermal insulation materials and the site energy demand for a long term has been discovered, while a seek to eliminate extremes was always in focus. The best versions from certain aspect are summarized in the table below:

ASPECT	VERSION		VALUE
	FACADE	ROOF	
Most comfortable hours	22 cm wood fibre	25 cm rockwool	5981 h
Smallest kWh/a	12,5 cm VIP	25 cm rockwool	520,291.620 kWh/a

Table 8 Table 8 The best versions from the examined aspects

To have deeper learning on the building of subject, a wider range of variables, such as application of shaders, modified thermal characteristics of apertures and possible application of renewable energy sources such as photovoltaic panels on the roof or facades are suggested. The methodology and the workflow applied can be extended to any building (planned or existing) of which has an IDF file based on its geometry and technical data which fulfils the .idf extension's requirements. Above that, the workflow requires a valid IDD file to make the data exchange between the simulation running environment and the model file possible, and a valid EPW file for the project site, which also makes the adaptability and comparison of the different model version for any location possible. The applied workflow and the developed codes written provides the reusability of the method for further BIM based CIT optimization projects, applications on future research works are definitely

possible, with a wider range of scope of work, such as alternative shading solutions, change of schedule of the building, operation and planting costs and many more aspects.

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