

M Ű E G Y E T E M 1 7 8 2

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**SUSTAINABILITY-DRIVEN OPTIMIZATION BASED
ENERGY EFFICIENCY-INCREASING REFURBISHMENT OF
THE ST BUILDING AT BME CAMPUS**

MSc Thesis Work

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Training:	MSC in Construction Information Technology Engineering	Semester:	2023/24/1
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Subject:	Sustainability-driven optimization based energy efficiency-increasing refurbishment of the ST building at BME Campus		

Project description:

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 decarbonization efforts, whether it is about newly constructed projects or the tasks of refurbish existing structures. In general, it can be said that no educational buildings at BME Campus meet the energy performance requirements of the present. Among them, the ST building requires energy-efficiency-increasing refurbishment the most. Using optimisation algorithms on the BIM-based dynamic energy performance simulations to improve the sustainability of refurbishment design could be utilized in this project for both environmental and financial aspects.

The thesis must address the following:

1. Review of the application of dynamic simulation and optimisation algorithms in the energy performance of buildings terms of international literature and practice -
2. Model the ST building using a BIM system based on plans and on-site survey
3. Design the energy efficiency-increasing refurbishment using algorithm-based dynamic simulations and test multiple thermal insulating or active energy solutions for the building envelope to meet the energy performance and environmental criteria
4. Optimize the design using a selected genetic algorithm-based method
5. Evaluate the results in case of environmental and financial aspects
6. Prepare the documentation of the work (with a 1-page summary in English and Hungarian)

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Date:	4.9.2023
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ÖSSZEFOGLALÓ

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 helyszíni felmérés, hőkamerás felvételek készítése és elemzése, valamint a rendelkezésre álló tervdokumentációk tanulmányozása után BIM modellt készítettem 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. A vizsgálati változók között szerepelt többtípusú homlokzati- és tető hőszigetelő anyag alkalmazása több rétegvastagságban, illetve a homlokzati nyílászárók és függönyfalak korszerű, épületenergetikai követelményeknek megfelelő rendszerre cserélése. Ezek után pénzügyi analízist készítettem a vizsgált épületverziók bekerülési költségének és 20 éves teljes költségének megállapítása céljából.

Munkám során cél volt a felújítási munkálatokat követő 20 éves ciklus lehető legkisebb környezetterheléssel járó változatának megállapítása a lehető legnagyobb felhasználói komforttal párosítva, a bekerülési- és üzemeltetési költségek minimalizálása mellett. 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.

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, supplemented by evaluation of thermal images of the building, 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. Within the framework of the project, application of multiple types and thicknesses of façade and roof thermal insulation materials accompanied by new system of envelope apertures and curtainwalls, fitting for recent Hungarian rules and regulations were used as examination variables. Financial analysis was done to compare the acquisition costs of the examined building versions, and the total costs on a 20-year-long scale.

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 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.

HALLGATÓI NYILATKOZAT A DOLGOZAT ÖNÁLLÓ TEVÉKENYSÉGÉRŐL

Alulírott Szatmári Levente.....(név) hallgató (Neptun kód: FW1DD4.....)
.....) nyilatkozom, hogy a Oktatási Épület BIM alapú energetikai- és környezeti szempontú optimalizációja.....(cím) című dolgozatom készítése során betartottam a szerzői jogról szóló 1999. évi LXXVI. tv. szabályait, valamint a BME TVSZ által előírt, a dolgozat készítésére vonatkozó szabályokat, különösen a hivatkozások és idézések tekintetében.

Tudomásul veszem, hogy diplomamunka esetén plágiumnak/szerzői jogsértésnek számít:

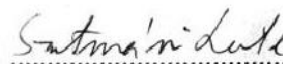
- szó szerinti idézet közlése idézőjel és hivatkozás megjelölése nélkül;
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Trondheim, 2023.12.08.

Kelt, (hely, dátum)



(hallgató)

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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 of 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 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. The examination also involves a new set of windows and curtain walls on the envelope, suitable for the new 9/2023 ÉKM decree [2]. Understanding the operation and current state of the building was also among aims, for this, on-site surveying and thermal-imaging and examination methods were used. A financial analysis is done for the examination and comparison of the different refurbishment versions, based on the global cost method [4]. During my work I apply the multi-objective optimization algorithm (MOOA) NSGA-II (Non-dominated Sorting Genetic Algorithm II) [5] to try and find Pareto-optimal [6] solutions for the applied thermal insulation solutions ([see 3.5.](#)). 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 was considered using simplified methods. As secondary limitation, the usually few centimetres thick extra technological insulation applied to make plastering possible in case of application of vacuum panel or aerogel insulations was not taken into account.

2. RESEARCH WORK

2.1 Building energy performance

Requirements for energy performance of buildings are usually set up by national authorities, 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 recent 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, building elements and constructions ([see 3.](#)) for building envelope elements within the project where minima means values in Table 1 or lower:

Construction	Thermal transmittance (U) [W/m ² K]
Façade walls	0,24
Flat roofs	0,17
Windows	1,10
Curtainwalls	1,40

Table 1 Applied minima Heat Transfer Coefficient requirements.

Which Thermal transmittance 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:

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

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] , see Table 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

For the definition of thermal transmittance values of curtainwalls on the external envelope of buildings, if numerical simulations are not done, we must apply the so called component evaluation method based on the MSZ EN ISO 12631 standard [7] [2]. The thermal transmittance factor of curtain walls is the thermal transmittance of the elements that make up the curtain wall is the area proportional average of its factor [2]:

$$U_{cw} = \frac{\sum (U_{cw,elem} * A_{cw,elem})}{\sum A_{cw,elem}}$$

Where:

$U_{cw,elem}$ = The thermal transmittance of the specific element of the curtainwall (e.g. glazing, mullion, etc.) (W/m²K)

$A_{cw,elem}$ = The area of the specific element of the curtainwall (m²)

For the definition of thermal transmittance values of windows and other openings on the external envelope of buildings, if simplified method is used, calculations must be done by the MSZ EN ISO 10077-1 standard [8] [2], but with simplifications, such as

$$U_o = \frac{\sum U_g * A_g + \sum U_p * A_p + \sum U_f * A_f + \sum c_{g,f} * l_{g,f} + \sum c_{f,p} * l_{f,p} + \sum c_{g,s} * l_{g,s}}{\sum A_g + \sum A_p + \sum A_f}$$

Where:

U_g = Thermal transmittance of glazing (W/m²K)

A_g = Area of glazing (m²)

U_p = Thermal transmittance of opaque panel (W/m²K)

A_p = Area of opaque panel (m²)

U_f = Thermal transmittance of frame (W/m²K)

A_f = Area of frame (m²)

$c_{g,f}$ = Linear thermal transmittance of the connection of glazing and frame (W/m²K)

$l_{g,f}$ = length of the connection of glazing and frame (m)

$c_{f,p}$ = Linear thermal transmittance of the connection of frame and opaque panel (W/m²K)

$l_{f,p}$ = length of the connection of frame and opaque panel (m)

$c_{g,s}$ = Linear thermal transmittance of the connection of glazing and stiffeners (W/m²K)

$l_{g,s}$ = length of the connection of glazing and stiffeners (m)

In the case of single paned windows. Specific size of doors and windows or the thermal technical data of the door and window components of the products must be used on the basis of its performance statement [2].

In case of simplified method, the transmission heat transfer factor towards the external environment and non-conditioned spaces, the connection thermal bridge losses and point-like thermal bridges arising at structural connections, must be considered such as [2]

$$H_{tr} = \sum_i A_i * U_{R,i}$$

Where:

A_i = Area of the specific envelope zone (m²)

$U_{R,i}$ = Resulting thermal transmittance of the specific envelope zone (W/m²K)

Such as

$$U_{R,i} = U_i * (1 + \xi)$$

The ξ correction factors are available in Appendix 1 of the current ÉKM decree [2] with values between 0.05 and 0.40 depending on the type of envelope element and the specificity of thermal bridges within.

The yearly energy demand and consumption, including weather and other environmental effects on the building had been examined by results of dynamic energy simulations and measured data for electricity and heating demand from 2021 ([see 3.5.1.](#)).

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 [7] (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 [8] [9] [10]. 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 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 formal 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 [11] [12] 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 [13]. 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).

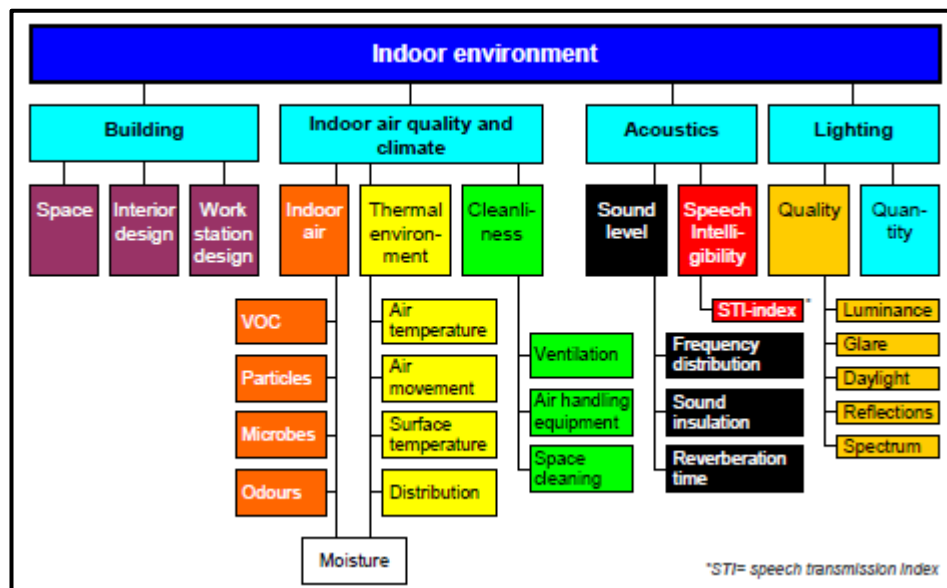


Figure 1 Parameters included in the definition of indoor environmental quality (IEQ) [12]

By WHO's (World Health Organization) definition of Health [14]: "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 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) [13].

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 [13], 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 (Figure 2). It is expressed as Met units in the ISO and CEN standards.

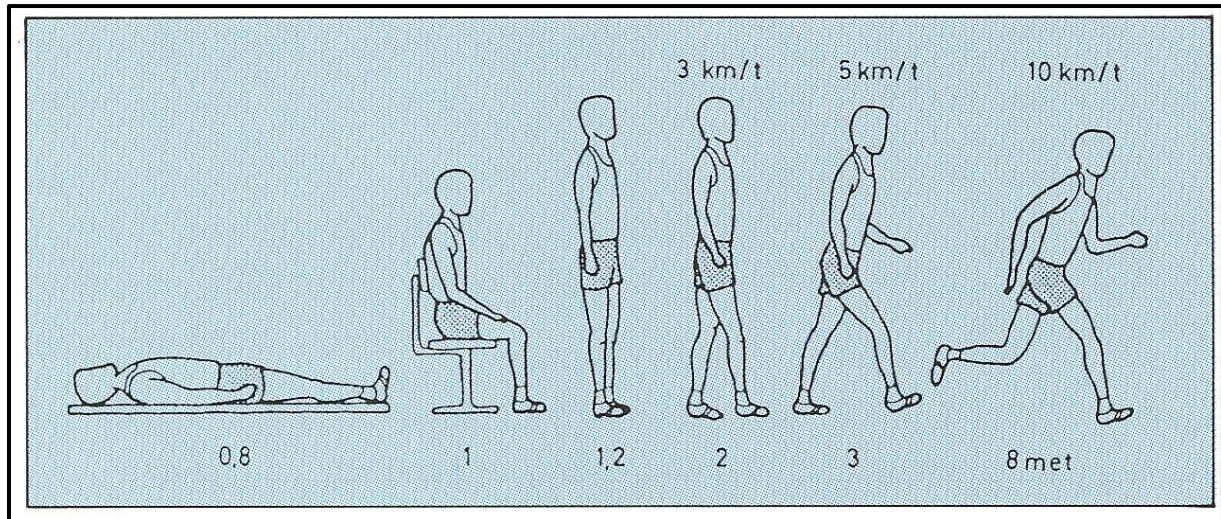


Figure 2 Metabolic rates of human body, varied by activity [11]

- Insulation (clothing) [clo]
 - The resistance to sensible heat transfer provided by clothing ensemble. Expressed in clo-units. 1 clo = 0,155 m²K/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 W/m², the room with drybulb temperature of 21 °C, relative humidity of 50%, and a 0,1 m/s wind speed. (Figure 3)

While working on this project, building energy simulations were done in EnergyPlus 23.1.0 [15] software, which applies clo and met units dynamically based on the simple ASHRAE-55-2004 standard ([see 3.5.1.](#)). These parameters are applied in the PMV and PDD calculations ([see 2.3.1.](#)).

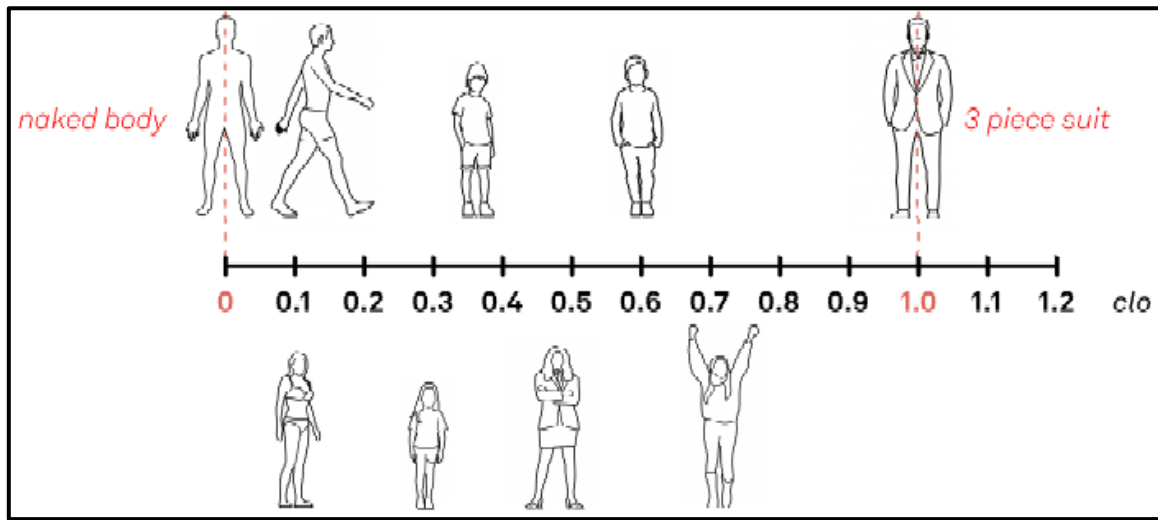


Figure 3 clo units by clothing [13]

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 PPD (Predicted Percentage of Dissatisfied) method developed by Fanger in the 1970's [16] and has been outlined in the ISO 7730 standard [17].

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 [18]. 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 [13], shown on Figure 4 and can be calculated by the following formula [13](Figure 4):

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

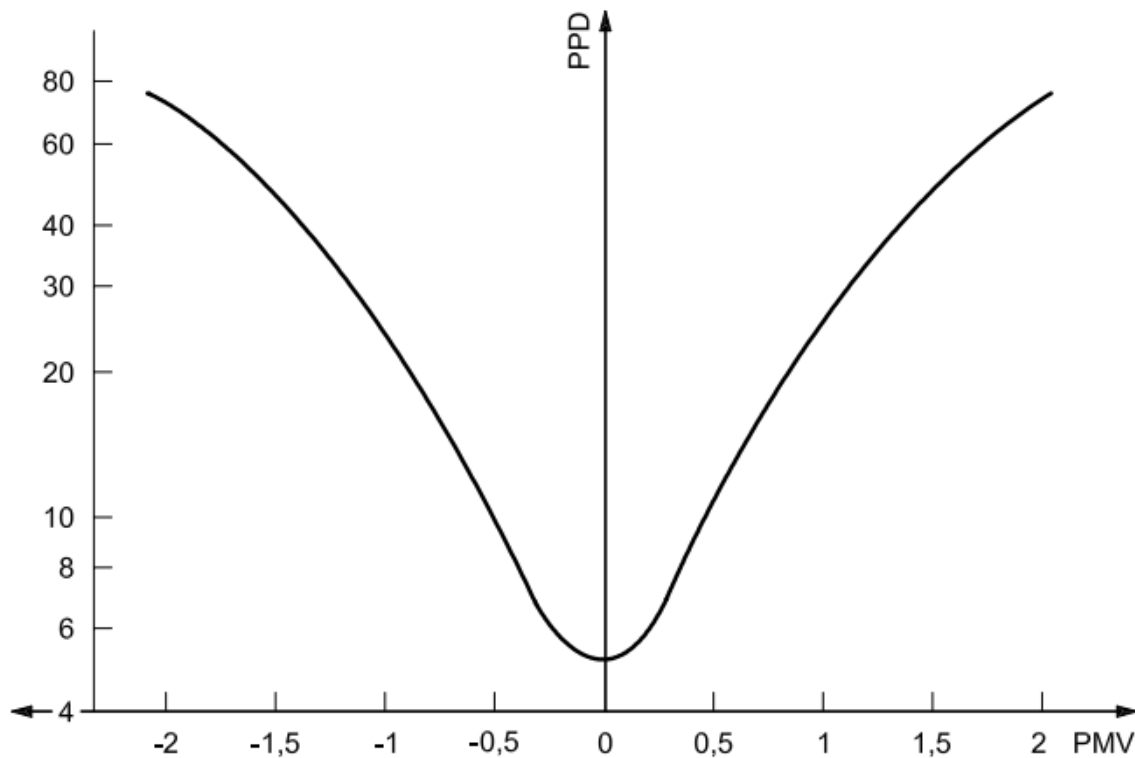


Figure 4 value of PPD by PMV [19]

For all the typical types of activities, a range of optimal operative temperature is ordered. These temperature ranges are dependent on clothing and activity level [17]. 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 [17]. 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 [18], when running building energy simulations in the EnergyPlus [15] 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 4.1.](#)).

2.4 Improving building energy efficiency

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 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 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 of 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 thermal insulator. The key property of thermal insulation materials is the thermal conductivity (W/mK) [20], 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 (W/m²K). Low thermal conductivity is 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 [20]. 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 [20]. Theoretically there are thermal insulation materials, e.g., VIP (Vacuum Insulation Panels) which by their characteristics make the coupling effect negligible [20]. There are also several other properties of thermal insulation materials regarding applicability and other technical requirements, which are out of this paper's scope.

In the workflow, I have tried and collect most up to date and the near future's possible thermal insulation materials [20] [21], aiming to find solution of thermal refurbishment of this paper's subject building ([see 3.1.](#))

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 [23]

Year of
construction: 1950



Figure 5 BME Building ST on Google Maps [22]

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 [23]. 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 of the BME Campus, having numerous buildings with protection due to their historical value in the area. The ST building itself is not under protection, but the site (HRSZ.: 4110) is under historical, archaeological and world heritage protection [24]. 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 6) 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 6 the secondary entrance and the curtainwall in different perspectives

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.

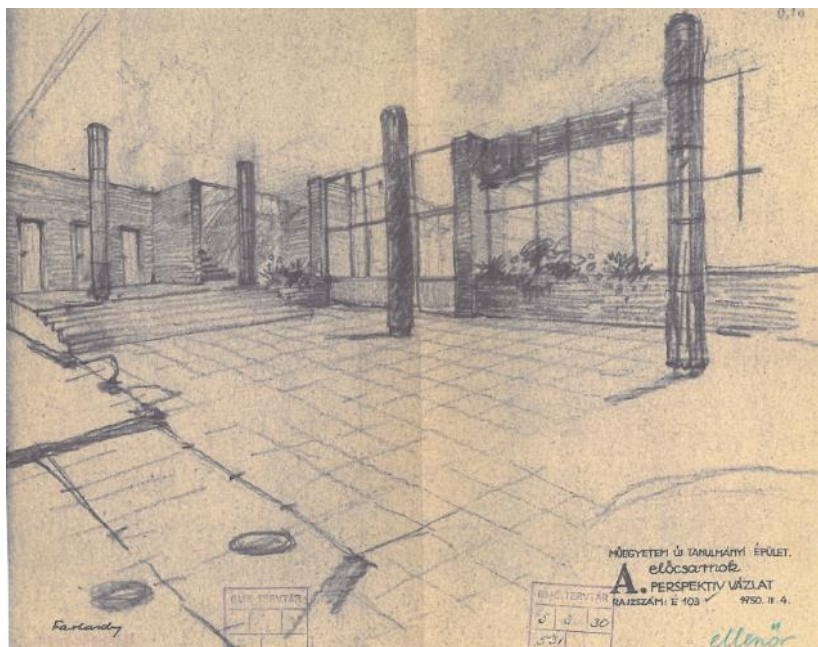


Figure 7 Sketch of the hall by Farkasdy [28]

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. 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.

3.1.1 On-site survey

On-site surveying and measurements were made to make sure the building's current state and well-separable function units are synchronized with the provided documentation. Some major dimensions of the construction such as inner heights of premises and façade sections with negative corner were measured with a handheld laser distance meter. All the measured inner heights were within a ± 5 cm limit, while the façade sections were within a ± 10 cm limit from the values readable in the 2010 status recording documentation, which fulfils the requirements of the regular 1:100 scaling of these drawings.

While walking around and inside the building, a basic understanding of the construction was possible, such as the original (pre 1985) roof's ventilation, shown on Figure 8, which gives also a glimpse on the aesthetical state of the 4th storey façade.



Figure 8 Air vent holes on the facade

Wet marks and numerous proofs of moisture on the facade and within the building are generally can be found. On Figure 9 the main entrance is shown with a large wet spot caused most likely by the failure of rainwater insulation on the roof of the auditorium wing, while on Figure 10 a window of the north-west façade is shown, with a window having some leakage issues on its bottom, fixed section, which is not general on the building, but can be found numerously.

Proofs and marks of previous interventions and works can be found on all the envelope sections, such as old, currently unused lightning rods and randomly finishing cable harnesses, with some patches on the façade as a memento of ad hoc fixing of casual problems in the past, shown on Figure 11 Facade with marks of former intervention



Figure 9 The main entrance with wet marks



Figure 10 Window with moisture



Figure 11 Facade with marks of former intervention

3.1.1 Thermal imaging

To achieve a better understanding of the operation and state of the existing building, thermal images have been created from the external envelope with a Testo 885 Thermal Camera [25]. During thermal imaging, we determine the temperature or heat distribution of surfaces, which parameters are dependent on the infrared radiation (emission (ϵ)) and heat reflectivity (reflection (ρ)) capabilities of the examined surfaces [25] [26].

The pictures were taken on 25th of November 2023, around 12 pm with overcast skies and cc. +5°C of external temperatures.

The evaluation of images was done in Testo IRTSoft v4.8 thermal imaging software [27], which provides a wide range of possibilities and options in terms of examination of thermal images.

The principle is simple, the warmer the colour of the given spot on the picture, the warmer the spot in the real construction. The pictures were used to check the occurrence of thermal bridges on the envelope, while as a side effect, they also provided useful information about the structure of the building, and comparability of information in the provided documentation ([see 3.2.](#)). On Figure 12, the structural elements of the north-eastern envelope made of precast RFC beams and columns are clearly visible with colours of yellow/red having a temperature of cc. 8-9 °C, proving the existence of thermal bridges of a considerable scale, while with darker colours the general brick wall is shown with temperatures in the 5-6 °C range. Based on the pictures can be stated, that the windows are having high sized thermal bridges all around their structure and immediate environment. Also, the wall cuttings for radiators below the windows are visible with warmer spots of colour red.



Figure 12 Thermal bridges and structure on the envelope

The thermal image of the connection between the 3rd and 4th levels (Figure 13) shows an interesting result of not having a significant difference between the different layer structures of the envelope, while the structural elements, especially the concrete beam connecting the

façade of the 4th storey to the bottom left of the building itself provides a huge thermal bridge. The windows and the fitting areas here also provides thermal bridges which are highly rising the energy demand of the building at the current state. Also, spot-like local thermal bridges are noticed just below the 4th storey façade, which holes provided as ventage for the original roof of the building until 1985.

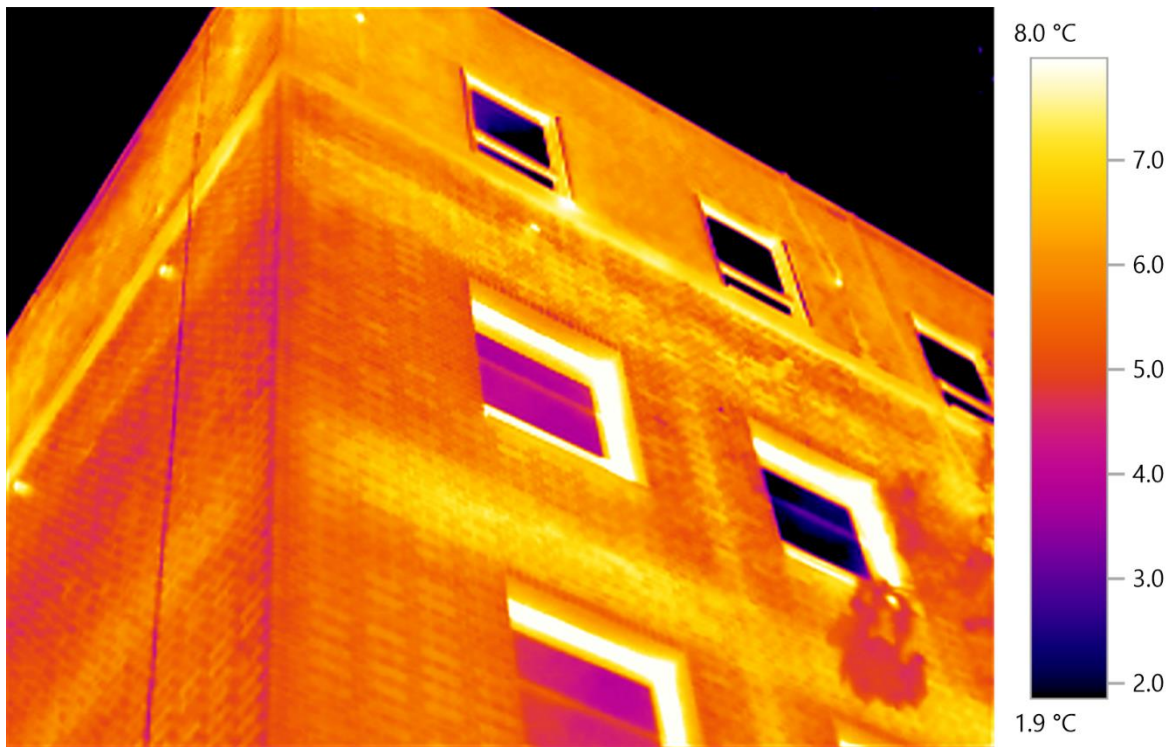


Figure 13 Connection of levels 3 and 4

On Figure 14, thermal image of the curtain wall above the secondary entrance on the north-eastern façade is shown. Based on the picture can be stated, that the framing of the curtainwall has a relatively homogenic structure with a close-to-isothermal thermal transmittance, while the opening panels are easy to find, since they have significant local thermal bridges around them. Also, the whole curtainwall has relatively large thermal differences around the edges and fitting areas, providing thermal bridges, which from all the examined thermal images of the building (around 100 pcs.) have the largest relative thermal differences between the given building element and the connecting surfaces with a value of more than 5 °C.

On Figure 15 the façade of the auditorium wing is shown. The reinforced concrete columns and beams are clearly visible, they are providing thermal bridges. The slope and elevation of the auditorium floor is also visible, it provided a huge help during the modelling of the building. The picture is taken from the southern direction, which was covered by shadows in the time of the picture, which is a possible reason for the slightly lower surface temperature values than on façades of other orientation, and keeping a generally lower temperature in the auditorium and other big volume zones of the building might also be a reason behind this phenomenon.

On Figure 16 thermal image of the relatively new curtainwall system in the main hall of the building is shown, which is having significantly lower surface temperature values than the original curtainwall systems on Figure 14, but it must be highlighted, that this area of the building envelope was covered from sunlight during the time of thermal imaging.

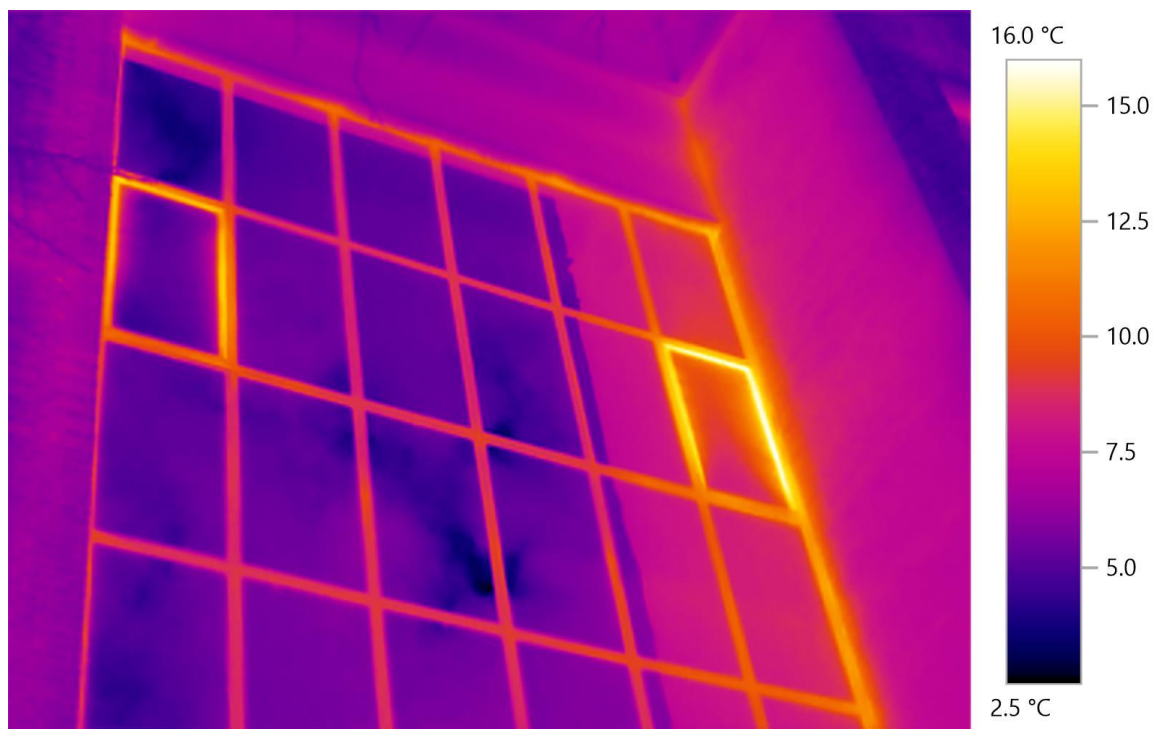


Figure 14 Thermal bridges on curtainwalls

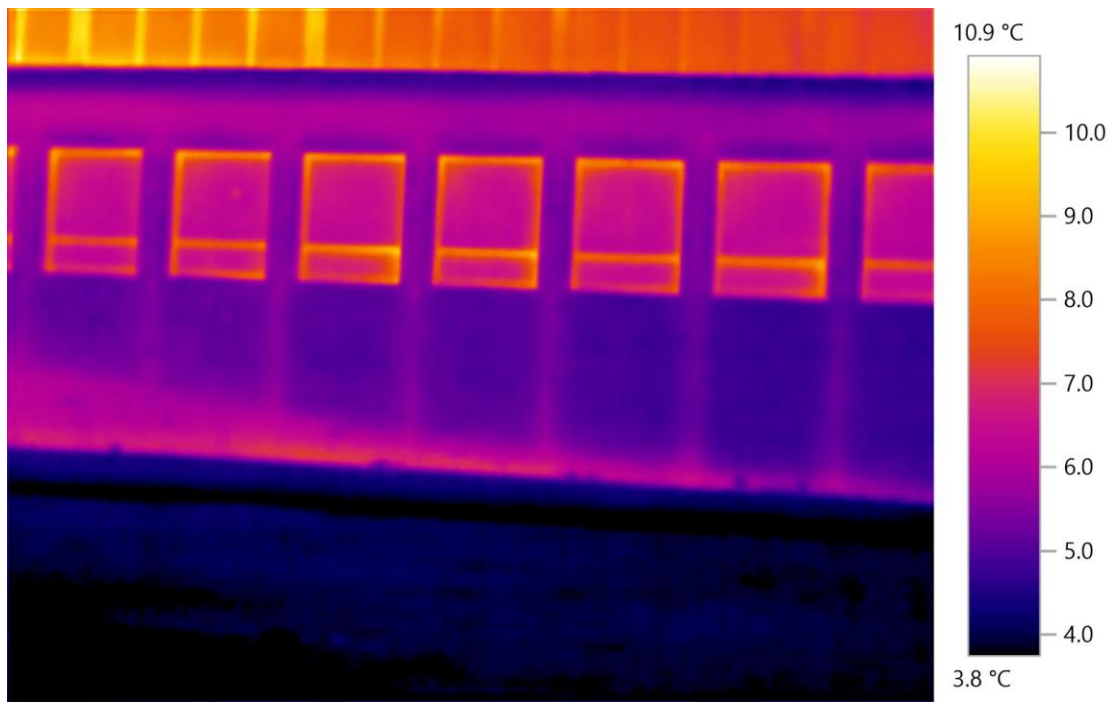


Figure 15 The auditorium wing's facade

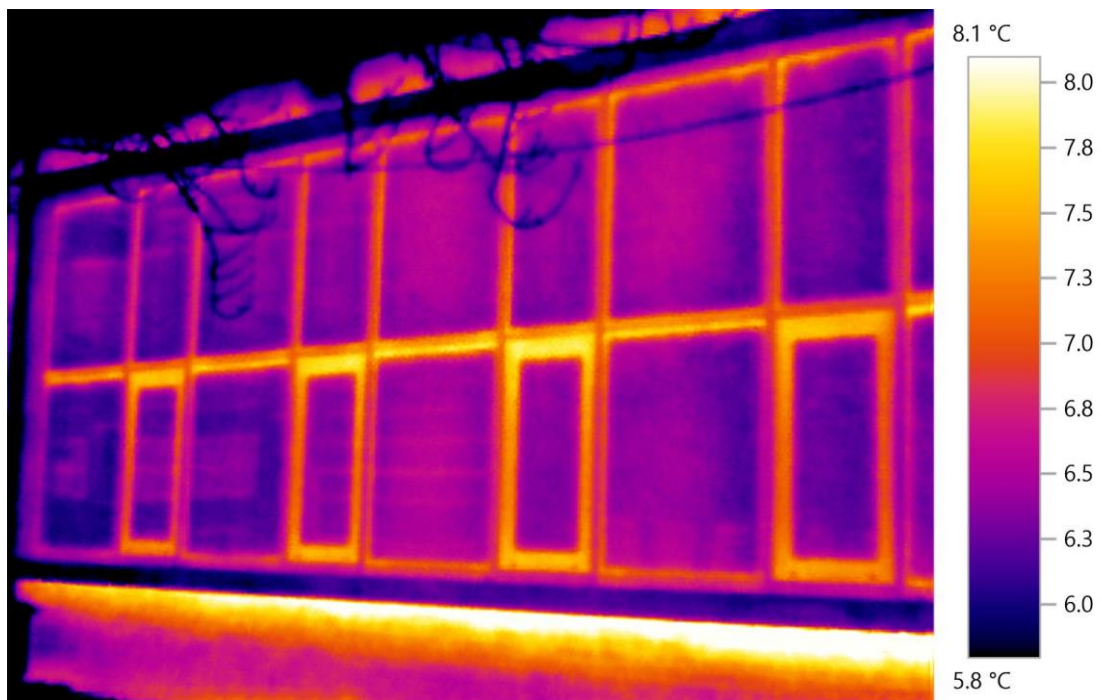


Figure 16 The relatively new curtainwall of the hall

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 [28] I have been provided with the building's original documentation from 1950 with numerous structural and architectural floorplans, cross-sections, and detail sketches.

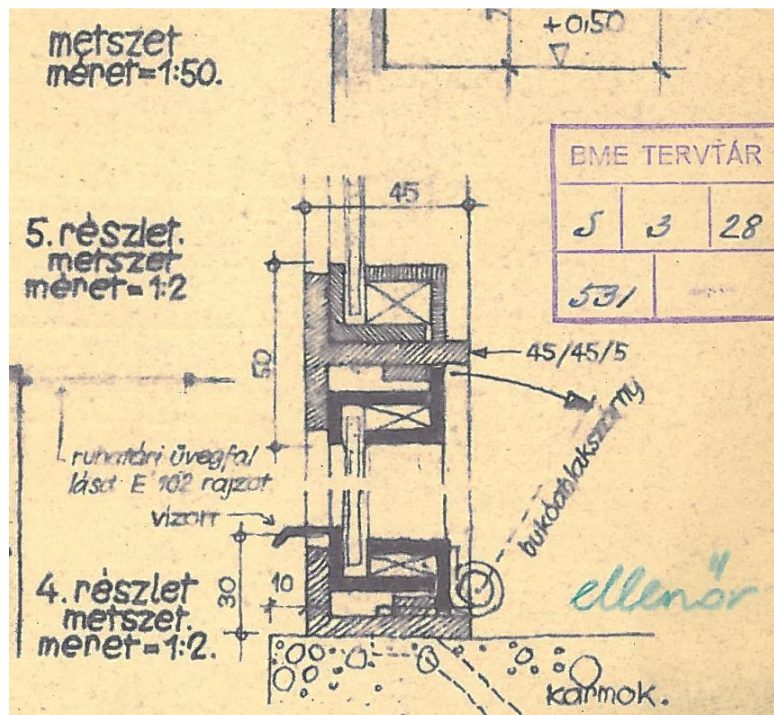


Figure 17 Detail from the 1950 Documentation [28]

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 has 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]	-paint, plaster -38 cm brick façade	U = 1,43 W/m ² K
	Or above apertures and ring beams: -paint, plaster - 4 cm mineral wool - 26 cm rfc beam - 8 cm paving brick	U = 0,75 W/m ² K
Façade of the 4 th floor [in-out]	-paint, plaster - 25 cm brick - 8 cm mineral wool - 4cm ventilated air gap with timber joist - 2 x 4 mm slate covering	U = 0,40 W/m ² K
Flat roof (since 1985) [out-in]	- 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	U = 0,29 W/m ² K

Table 3 Main order of layers in the building [28]

Many more layers 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 [29] (Figure 19). 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
1st 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 needed to mention, that for the curtain wall in the hall, based on the apertures themselves the year of construction is 2014 (Figure 18) 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.

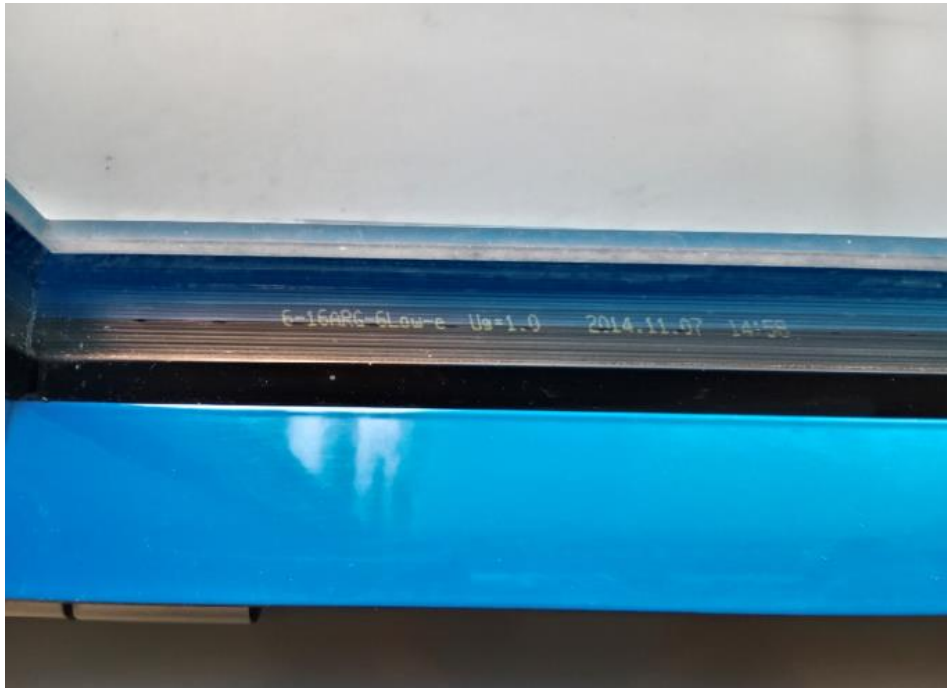


Figure 18 Glazing structure of the curtain wall in the hall [93]

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 19), 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 [15] for building energy calculations. For more information on that, [see 3.5.](#)

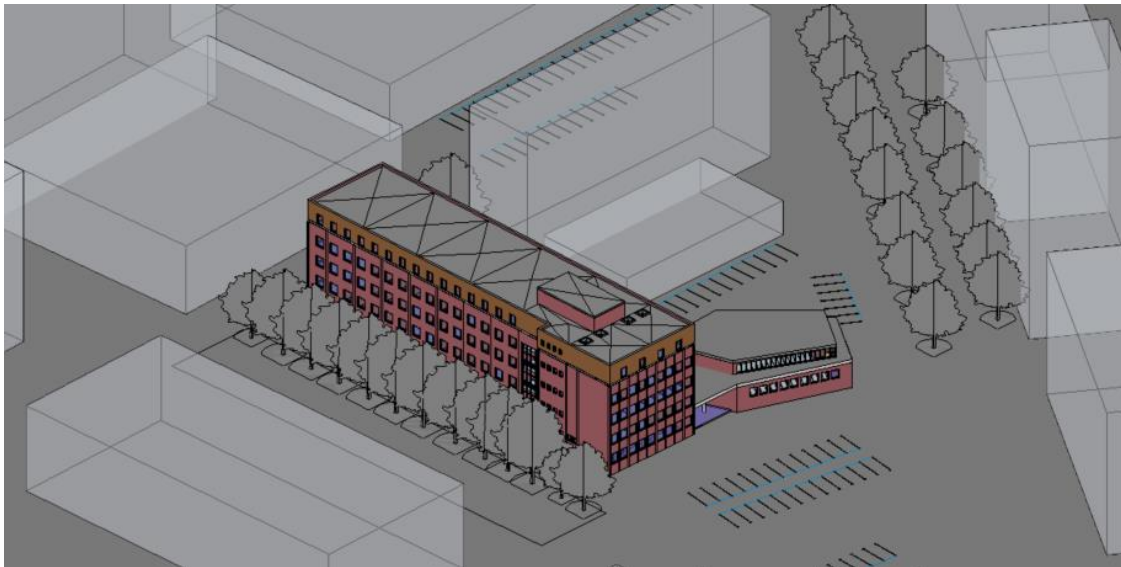


Figure 19 The model with conceptual masses of neighbouring buildings

3.3 FINANCIAL ANALYSIS

Financial analysis was done based on the fees and advised prices in the Építőipari Költségbecslési Segédlet 2023 (ÉKS) [30], which is a generally accepted collection of core prices and fees in the Hungarian AEC industry for each year, for the estimation of acquisition costs of the examined thermal insulation systems. If the ÉKS provides a range of costs for the given item or works, the highest defined value was applied. If the ÉKS has not defined specific costs for a given material, such as VIPs or the Aerogel solutions, I tried to collect the regarding information via internet research and do cost estimations based on the referred sources. All the applied values regarding the Building ST, such as sizes or volumes are calculated based on schedules in the Revit model. Financial analysis was done only on the 72 building versions which by their characteristics fulfil the requirements of the new ÉKM decree [2]. It is important to mention, that the costs and fees in the ÉKS [30] are VAT excluded.

3.3.1 Operating- And Globals Costs

Within the framework of this paper, when talking about operating costs, the author means only the sum of costs for electricity and district heating. Other utilities, such as drinking water, sewage, or costs of mandatory maintenance are not involved in the calculations, since those are not strictly related to building energy demand, which is the main scope of work.

Since the focus is on the operation of the building on a 20 year long period after the application of the new thermal insulation systems and apertures, it is more useful to calculate and compare the global costs [4] of each building versions on this timescale, rather than just compare the differences of yearly energy demand multiplied by a price factor.

The global cost for buildings and building elements must be calculated by adding up the different cost types, then applying the discount rate to the above with the help of a discount factor and adding the discounted residual value to determine their starting year value [4] such that:

$$C_g(\tau) = C_1 + \sum_j \left[\sum_{i=1}^{\tau} (C_{a,i}(j) \times R_d(i) - V_{f,\tau}(j)) \right]$$

Where:

τ = calculation period (here 20)

$C_g(\tau)$ = global cost for the calculation period, applied for the $\tau=0$ starting year

C_1 = acquisition costs of the action or series of actions “j”

$C_{a,i}(j)$ = yearly costs of the action or series of actions “j” in the year “i”

$V_{f,\tau}(j)$ = residual value of the action or series of actions “j” at the end of calculation period, discounted for the $\tau=0$ starting year

$R_d(i)$ = discount rate for year “i”, which is based on discount rate “r”, and must be calculated such that:

$$R_d(p) = \left(\frac{1}{1+r/100} \right)^p$$

where:

p = the number of years since the $\tau=0$ starting year

r = the real discount rate, which is based on [4] : $r = 3$

For the calculation of global cost, the applied starting or “year 0” gross price of electricity is 155 HUF/kWh, while for district heating this gross price is 190,44 HUF/kWh. It is worth to mention, that the public utility discounts are not applied on non-residential consumers in Hungary. The applied factor of price increase was 5% each year compared to the previous year. [31] This way, using the compound interest method:

$$C_o(i) = C_o(0) * (1 + \frac{r}{100})^i$$

where:

i = the specific year after the installation of thermal insulation systems and new apertures

$C_o(i)$ = operating cost in the specific year “ i ” (here: cost of electricity + district heating)

$C_o(0)$ = operating cost calculated in the year of installation, by simply adding up the simulated electricity and heating demands of the building multiplies by the applied prices

r = applied yearly price increasing factor (here: $r = 5$)

This way, via application of the discounting procedure mentioned above, the net present value of each year’s operating costs for each building version can be calculated, which yearly net present values added up together with the acquisition costs of the specific building version provides the global cost of the specific building version. The comparison of these global costs is shown in [chapter 5](#).

3.4 Applied thermal insulation materials and building elements

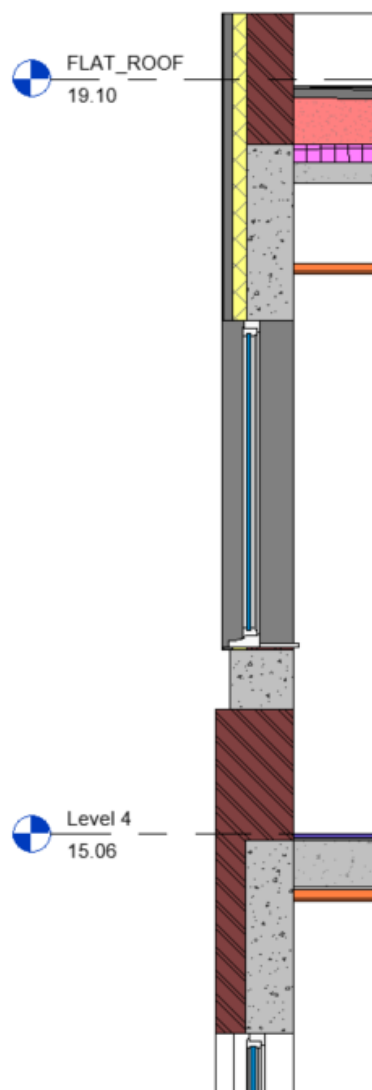


Figure 20 cross-section from the model

From the very start of the project the main task was to find the best possible thermal insulation solution for the building facades and roofs in terms of environmental loads, in this case $\text{kgCO}_2\text{eq.}$ – possibly 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, providing the possibly lowest global cost on the 20-year long scale after installation. For this, based on literature research ([see 2.](#)) a palette of possibly applicable thermal insulation materials was collected, supplemented by applicable window and curtainwall systems, 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 and elements are not considered as direct polluters of environment. The requirement for the simulated structures (existing façade and roof constructions with applied thermal insulation materials in various thicknesses) was that the structure must pass the thermal requirements set in [2], such that it is written above ([see](#)

[2.1.](#)). While a wide range of thermal insulation materials was applied, there were versions for all the examined materials which are having higher thermal transmittance than the maxima values in the new ÉKM decree [2], they were used as references of comparability in the simulated results, to make the observation of trends in the change of simulation results such as in comfort hours possible. For the versions passing the requirements in the new ÉKM decree [2], windows and new curtain wall systems were added, to make sure the whole envelope fulfils these postulates. Below a list of thermal insulation materials and the applied window- and curtain wall systems is shown, with a summary of environmental loads for their

estimated lifespan. The prices and acquisition costs of the applied thermal insulation solutions, windows and curtainwalls are also shown. All façade thermal insulation versions were calculated with a general external façade plastering. For roof insulations, both in the Rockwool and XPS cases PVC rainwater insulation was applied, which is suitable for both straight and reversed order of layers, but it is calculated in [4.1.2](#) as the part of common costs for all construction versions. The material prices and acquisition costs were estimated based on ÉKS [30] and online research with referred sources.

3.4.1 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 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 [20].



Figure 21 Mineral wool insulation [92] [102]

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 3-5 mm [32]. 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 and density 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 0.035 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 [20].

For the application of mineral wool within this project, 2 separate products from the same manufacturer ROCKWOOL [33] were chosen.

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

	Production stage	Construction stage	Use stage								End-of-life stage				
Parameter	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	D Benefits and loads beyond the boundaries of the system
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 22 ROCKWOOL products' kgCO₂eq. summary [34]

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 [34].

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. Bolded the thicknesses which fulfil the requirements with the examined multilayer-structures.

Acquisition costs for ROCKWOOL products are well documented in the ÉKS [30]. If the given thickness is not declared, assuming a simplification in order of comparability, simple mathematical mean calculations were done.

For the roofs of 1640 m² on the building, the following mineral wool thermal insulation costs are calculated based on ÉKS [30].

MATERIAL	THICKNESS [cm]	UNIT COST [HUF/m²]	AREA [m²]	TOTAL COST [HUF]
RW HardRock Max	15	12.400	1640	20.336.000
RW HardRock Max	20	16.000	1640	26.240.000
RW HardRock Max	25	20.500	1640	33.620.000

Table 6 ROCKWOOL roof insulation acquisition costs [30]

For the façade of net 3122 m² on the building, the following mineral wool thermal insulation costs are calculated based on ÉKS [30].

MATERIAL	THICKNESS [cm]	UNIT COST [HUF/m²]	AREA [m²]	TOTAL COST [HUF]
RW FrontRockSUPER	14	29.500	3122	92.092.215
RW FrontRockSUPER	16	32.500	3122	101.457.525
RW FrontRockSUPER	18	33.800	3122	105.515.826
RW FrontRockSUPER	20	34.800	3122	108.637.596

Table 7 ROCKWOOL facade insulation acquisition costs [30]

3.4.2 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) [20] [35] and varies with temperature, moisture content [36], and mass density. XPS is versatile, allowing perforation, cutting, and on-site adjustments without compromising thermal resistance [20]. 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 23 XPS roof insulation [25] [46]

For the application of this material in the project a multi-manufacturer EPD was used [37] which was prepared by the order of EXIBA - European Extruded Polystyrene Insulation Board Association [38]. 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 24 XPS products' kgCO₂eq. summary [37]

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

PRODUCT	APPLICATION	LOAD MULTIPLIER	SUM. kgCO ₂ eq./m ³ for 50 years
XPS ($\lambda_D=0.035$ W/mK)	ROOF	10	160,68

Table 8 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. Bolded the thicknesses which fulfil the requirements with the examined multilayer-structures.

For the roofs of 1640 m² on the building, the following XPS thermal insulation costs are calculated based on ÉKS [30].

MATERIAL	THICKNESS [cm]	UNIT COST [HUF/m ²]	AREA [m ²]	TOTAL COST [HUF]
XPS	12	10.700	1640	17.548.000
XPS	15	13.800	1640	22.632.000
XPS	18	17.100	1640	28.044.000

Table 9 XPS roof insulation acquisition costs [30]

3.4.3 Wood Fibre

Wood fibre insulation, a notable alternative in the realm of thermal insulating materials, is crafted from natural wood fibres, often sourced from softwood species [39]. 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) [40], 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 [39] [40] [41] [42].



Figure 25 Wood fibre thermal insulation [43] [44]

The second version for thermal insulation on façades in the building energy simulations was the application of wood fibre insulation. For this, the STEICO Protect dry wood fibre

insulation has been applied [43]. The reference material in the applied EPD [45] 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 26 STEICO products' kgCO₂eq. summary [45]

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 10 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. Bolded the thicknesses which fulfil the requirements with the examined multilayer-structures.

Acquisition costs for STEICO Protect dry products are documented in the ÉKS [30], though only a range of costs are presented. To calculate acquisition costs for these versions, assuming a simplification in order of comparability, simple mathematical mean calculations were done.

MATERIAL	THICKNESS [cm]	UNIT COST [HUF/m ²]	AREA [m ²]	TOTAL COST [HUF]
STEICO Protect dry	16	35.600	3122	111.135.012
STEICO Protect dry	18	39.950	3122	124.714.712
STEICO Protect dry	20	44.300	3122	138.294.411
STEICO Protect dry	22	48.650	3122	151.874.112

Table 11 STEICO Protect dry facade insulation acquisition costs [30]

3.4.4 Aerogel

Aerogels are easily considered as nowadays' cutting-edge thermal insulation solutions, currently holding the highest potential among various contenders [20] [46]. 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 exhibit thermal conductivities between 0.013 and 0.014 W/(mK) at ambient pressure [20] [47]. 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 [20].



Figure 27 Aerogel [48]

Within the framework of this project, 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 28 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 12 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. It must be mentioned, that within the simulations and further calculations, the technologically required few centimetres additional insulation was not taken into account.

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. Bolded the thicknesses which fulfil the requirements with the examined multilayer-structures.

The acquisition costs for aerogel thermal insulation systems were not found in ÉKS, but via online research [50] an estimation was possible, calculating in the plastering works too. Even without the estimation of additional costs, aerogel is the most expensive material in the scope of this paper.

MATERIAL	THICKNESS [cm]	UNIT COST [HUF/m ²]	AREA [m ²]	TOTAL COST [HUF]
Aerogel	5	322.500	3122	1.006.770.822

Table 13 Aerogel insulation acquisition costs [50]

3.4.5 Vacuum Insulation Panels

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 [20]. 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 [20]. 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 [20]. 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 [51] [52] [53].



Figure 29 Vacuum Insulation Panels [54] [55]

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 [56] 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 m			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 m² 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 30 Vacupor products' kgCO₂eq. summary [56]

The summarized kgCO₂eq. loads for the 50-year designed lifespan of the product are shown in the table below, yet it must be mentioned, that within the simulations and further calculations, the technologically required few centimetres additional insulation was not taken into account.:

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 14 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. Bolded the thicknesses which fulfil the requirements with the examined multilayer-structures.

The acquisition costs for VIP thermal insulation systems were not found in ÉKS, but via online research [57] an estimation was possible, calculating in the plastering works too. Even without the estimation of additional costs, such as the necessary additional thermal insulation materials due to the burdens of application of VIPs and other technical restrictions it can be stated, the VIPs are the 2nd most expensive thermal insulation material in the scope of this paper. It also must be mentioned, that due to nowadays global economic difficulties, manufacturers providing VIPs in Hungary are not likely to present an official and reliable price list for their VIP products, since the author could not find any reliable prices for VIPs directly developed for façade insulations in the region. But to make the financial analysis possible, after some considerations the BauderVIP TE-ST insulation was used with prices provided by the Hungarian distributor [57].

MATERIAL	THICKNESS [cm]	UNIT COST [HUF/m²]	AREA [m²]	TOTAL COST [HUF]
VIP	7,5	196.000	3122	611.866.920
VIP	10	236.000	3122	736.737.720
VIP	12,5	266.000	3122	830.390.820

Table 15 VIP façade insulation acquisition costs [57]

3.4.6 Windows

The applied window system in the building versions with thermal insulation systems fulfilling the requirements of the new ÉKM decree [2], was the SCHÜCO AWS 75.SI aluminium framed window system with triple glazing [58]. The product was developed directly for applications within energy-efficiency building envelopes. The wide range of possible opening methods provides solutions to have system-integrated apertures of all required types on the envelope.



Figure 31 SCHÜCO AWS 75.SI window system [58]

Also, multiple types of profiles are available, including a wide range of mullions, making sure the free form usage of the product in the desired shapes and division. The product was developed based on the Cradle-to-Cradle (C2C) principle, providing the applicability in environment-efficiency projects. Due to the product's powder coating, it is easy to adapt any desired colours. The product is having some system-optimised components, providing the applicability of manual and automated shading systems in the future [59]. The reference item in the applied EPD [58] was an aluminium framed window with frame thickness of 75 mm and area of 1.23 m x 1.48 m, and a combined heat transfer coefficient of the triple glazing and frame of 1.10 W/m²K. 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)																
PRODUCT STAGE			CONSTRUCTION PROCESS STAGE		USE STAGE							END OF LIFE STAGE				BENEFITS AND LOADS BEYOND THE SYSTEM BOUNDARY:
Raw material supply	Transport	Manufacturing	Transport from the gate to the site	Assembly	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction demolition	Transport	Waste processing	Disposal	Reuse-, Recovery-, Recyclingpotential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
X	X	X	X	MND	MND	MND	MND	MND	MND	X	MND	MND	MND	X	X	X

RESULTS OF THE LCA - ENVIRONMENTAL IMPACT:							
Schüco AWS 75.SI+/AD UP 75 W x H: 1230 mm x 1480 mm							
Parameter	Unit	A1-A3	A4	B6	C3	C4	D
GWP	[kg CO ₂ -Eq.]	220,72	5,84E-2	0,00	17,44	1,77E-2	-74,75
ODP	[kg CFC ₁₁ -Eq.]	1,56E-8	0,00	0,00	3,40E-15	9,76E-17	-9,49E-10
AP	[kg SO ₂ -Eq.]	6,14E-1	1,91E-5	0,00	5,68E-3	1,13E-4	-2,34E-1
EP	[kg (PO ₄) ³ -Eq.]	9,55E-2	4,89E-6	0,00	1,44E-3	1,27E-5	-1,48E-2
POCP	[kg Ethen Eq.]	6,63E-2	-7,41E-6	0,00	3,73E-4	8,55E-6	-1,45E-2
ADPE	[kg Sb Eq.]	2,06E-3	0,00	0,00	4,39E-8	1,79E-9	-1,75E-3
ADPF	[MJ]	2966,00	0,00	0,00	4,31	2,52E-1	-812,06

Figure 32 SCHÜCO windows' kgCO₂eq. summary [58]

The environmental loads in the case of windows and curtainwalls have been normalized to m² units as a simplification of calculations. 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 ² for 50 years
SCHÜCO AWS 75.SI (U _D =1.10 W/m ² K)	WINDOW	0.55	89.81

Table 16 applied window kgCO₂eq. values

Acquisition costs for SCHÜCO window and curtainwall products are documented in the ÉKS [30].

BUILDING ELEMENT	THICKNESS [cm]	UNIT COST [HUF/m ²]	AREA [m ²]	TOTAL COST [HUF]
SCHÜCO AWS 75.SI windows	7.5	240.000	650	156.000.000

Table 17 SCHÜCO apertures acquisition costs [30]

3.4.7 Curtainwalls

The applied curtainwall system in the building versions with thermal insulation systems fulfilling the requirements of the new ÉKM decree [2], was the SCHÜCO FWS 50 aluminium framed curtainwall system with triple glazing [60]. The product provides a wide range of connectivity with the manufacturer's window and door systems, making sure the system is adaptable with required openings on all the desired surfaces of the building. Due to its 50 mm wide mullions, the new curtainwall system can keep the original, currently applied curtainwalls' shape and outfit, providing the best possible keeping of the heritage of the existing façade.



Figure 33 SCHÜCO FWS 50 curtainwall system [60]

The product was developed based on the Cradle-to-Cradle (C2C) principle, providing the applicability in environment-efficiency projects. Due to the product's powder coating, it is easy to adapt any desired colours. The product is having some system-optimised components, providing the applicability of manual and automated shading systems in the

future [61]. The product is having some system-optimised components. The reference item in the applied EPD [60] was an aluminium framed curtainwall with frame thickness of 50 mm and area of 3.05 m x 3.05 m, and a combined heat transfer coefficient of the triple glazing and frame of 1.30 W/m²K. For the summary of environmental loads of the product, see the figure below:

ANGABE DER SYSTEMGRENZEN (X = IN ÖKOBILANZ ENTHALTEN; MND = MODUL NICHT DEKLARIERT)																
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	Entsorgung	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	MND	MND	MND	MND	MND	MND	X	MND	MND	MND	X	X	X

ERGEBNISSE DER ÖKOBILANZ UMWELTAUSWIRKUNGEN:							
Schüco FWS 50 B x H: 3050 mm x 3050 mm							
Parameter	Einheit	A1-A3	A4	B6	C3	C4	D
GWP	[kg CO ₂ -Eq.]	952,88	2,98E-1	0,00	29,93	5,66E-2	-264,43
ODP	[kg CFC ₁₁ -Eq.]	5,73E-9	0,00	0,00	3,57E-15	3,11E-16	-3,71E-9
AP	[kg SO ₂ -Eq.]	2,86	9,74E-5	0,00	1,86E-3	3,60E-4	-8,69E-1
EP	[kg (PO ₄) ³ -Eq.]	5,00E-1	2,49E-5	0,00	4,06E-4	4,04E-5	-5,30E-2
POCP	[kg Ethen Eq.]	3,37E-1	-3,78E-5	0,00	1,86E-4	2,73E-5	-5,29E-2
ADPE	[kg Sb Eq.]	1,35E-3	0,00	0,00	4,43E-8	5,71E-9	-8,65E-4
ADPF	[MJ]	11673,17	0,00	0,00	3,94	8,02E-1	-2793,01

Figure 34 SCHÜCO curtainwalls' kgCO₂eq. summary

The environmental loads in the case of windows and curtainwalls have been normalized to m² units as a simplification of calculations. 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 ² for 50 years
SCHÜCO FWS 50 (U _b =1.30W/m ² K)	CURTAINWALL	0.11	77.23

Table 18 applied curtainwall kgCO₂eq. values

Acquisition costs for SCHÜCO window and curtainwall products are documented in the ÉKS [30].

MATERIAL	THICKNESS [cm]	UNIT COST [HUF/m ²]	AREA [m ²]	TOTAL COST [HUF]
SCHÜCO FWS 50 curtainwalls	5	250.000	170	42.500.000

Table 19 SCHÜCO apertures acquisition costs [30]

3.5 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 [62] programming language was used.

```
22 def main():
23     iddf_file = "Energy+.idd"
24     IDF.setiddname(iddf_file)
25     epwfile = "BME_ST.epw"
26
27     folder_path = os.getcwd() # Get the current working directory
28     file_extension = '.idf'
29
30     # Use os.listdir to get a list of all files in the current directory
31     all_files = os.listdir(folder_path)
32
33     # Filter out only the files with the .idf extension
34     idf_files = [file for file in all_files if file.endswith(file_extension)]
35
36     idfs = (IDF(idf_file, epwfile) for idf_file in idf_files)
37     runs = ((idf, make_eplaunch_options(idf)) for idf in idfs)
38
39     num_CPUs = 4
40     runIDFs(runs, num_CPUs)
41
42 if __name__ == '__main__':
43     main()
```

Figure 35 Code snippet - running simulations based on Eppy [63]

3.5.1 Building Energy simulations

To run building energy simulations in EnergyPlus, 3 input files are needed [64]. 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, dimensions 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.

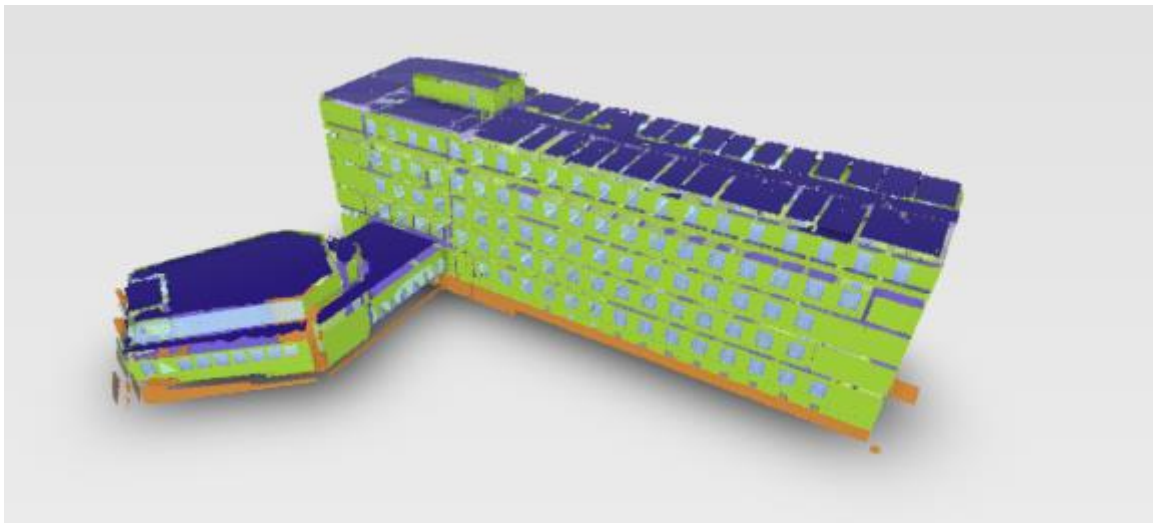


Figure 36 Model of the building with the thermal zones on the Autodesk Insight online surface

When running energy simulations in Revit, an optimization module for Autodesk Insight [65] is automatically attached to the model, which is an online interface which provides building design option comparisons (Figure 36), 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.

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 20 differences between the original and the simplified model

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, models of thermal zones shown on Figure 37. A simulation was also conducted on this model, having a runtime of 11 minutes, and after comparing the two simulations' results, (see Table 12) 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.

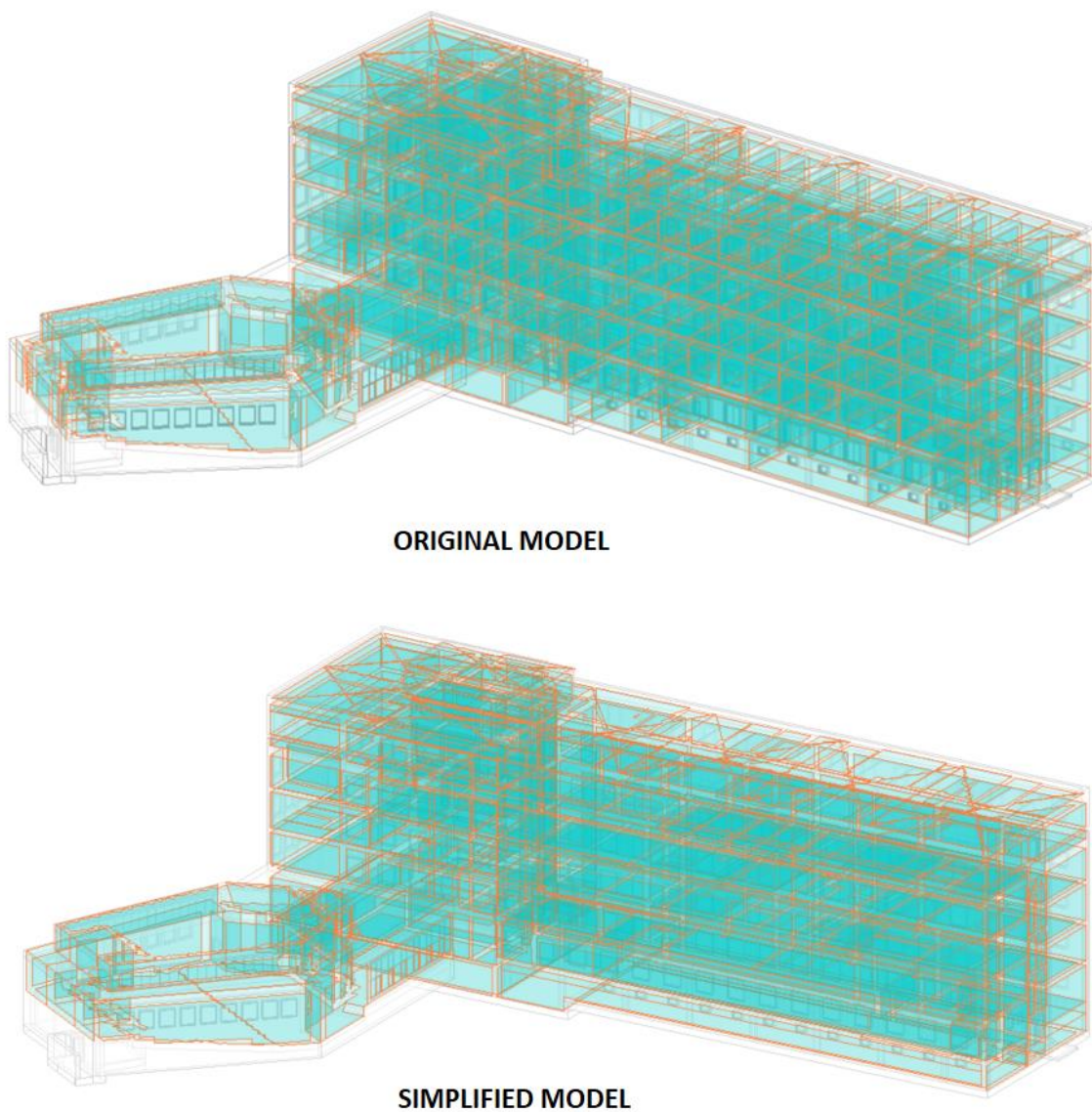


Figure 37 Original and the simplified model - without septum walls

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 [64].

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 [66] 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 [63] package was used within Python [62]. First, 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 3.4.](#)). 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 text file 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 IDF files were ready, there was a need for a weather file with “.epw” extension. For this, the Meteotorm 8.0.2 [67] 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 and the conversion factors in [2].

After the examination of these results, noticing major trends, a second round of energy simulations were run for the construction versions which fulfil the requirements of the new ÉKM decree [2], supplemented by the new set of windows and curtainwalls. This way, 72 versions from the original 160 remained for further examination such as financial analysis ([see 4.2.](#)).

3.5.2 Application of LCA

To understand the GWP values in the applied EPDs 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 [68]. 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 [11] [12] [68].

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 [68].

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 [11] [12]. 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 38.

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 38 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 [69] [70]. 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 [34] [37] [45] [56] [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.

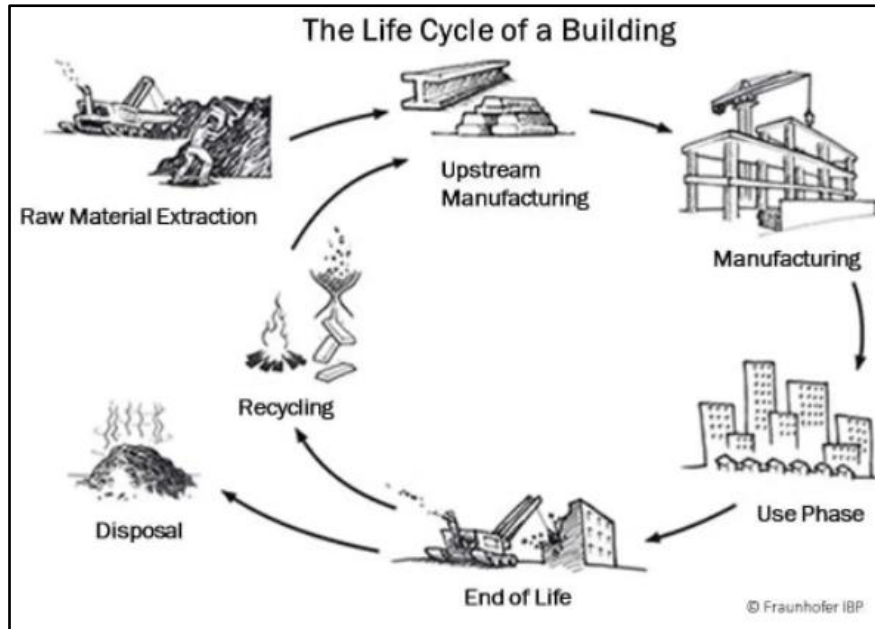


Figure 39 the life cycle of a building [71]

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 [72], [73], [74], [75], [76]. 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 [34]. 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 applied EPDs and considering the materials' characteristics by nature ([see 3.4.](#)), 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.

3.5.3 Optimization

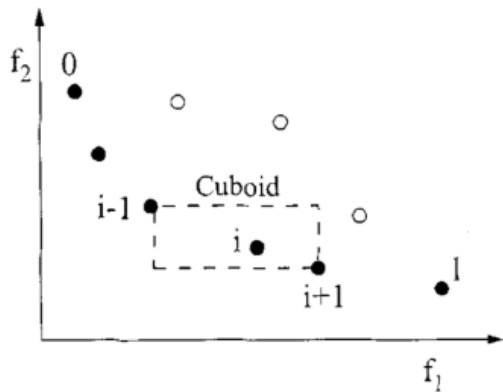


Figure 40 method for the crowding distance in Pymoo NSGA-II [77] [80]

To search the Pareto-optimal [6] 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 [5], causing a frontier of equally good solutions from the aspect of the examined parameters, called the Pareto front, the Pymoo nsga2 [77] Python package was used. This method has a history in building optimization projects, with promising applicability and adaptability for wide range of

problems [1] [78] [79]. 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) [5] 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 40 method for the crowding distance in Pymoo NSGA-II) [80], while taking care of not to drop the extreme values, while getting a crowding distance of infinity [77]. 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 [77]. 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 41). Pymoo also can be used for several other applicable methods to solve multi-objective optimization tasks [81]. 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.

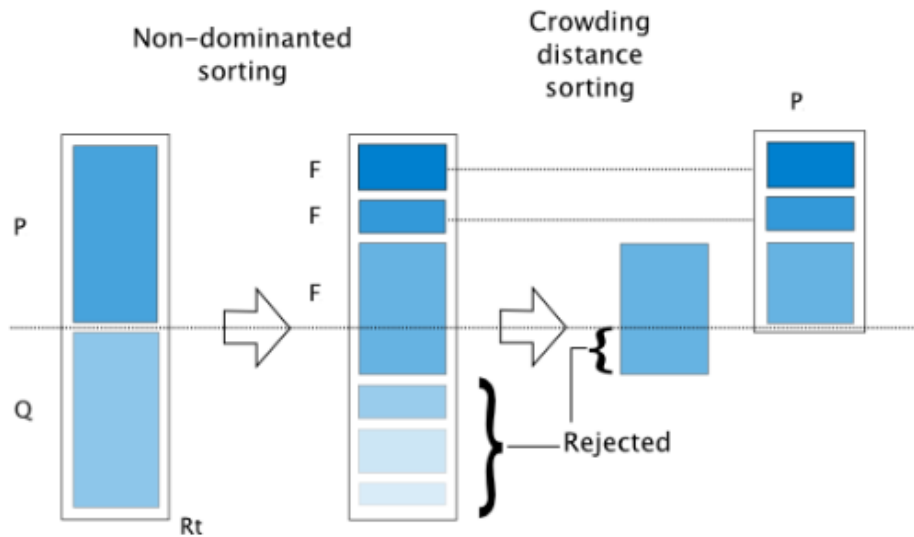


Figure 41 sorting mechanism of NSGA-II [63]

A consideration to apply other sorting algorithms such as R-NSGA-II [82] and NSGA-III [83] 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.

3.5.4 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 [84] [85] [86]. The applied thermal insulation materials have different fire safety characteristics. Rockwool products are considered generally firesafe [34] [85], the Vacupor NT-B2-S VIP has a fire safety paint coating [56], 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 [45] [37].

3.5.5 Workflow, research matrix

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

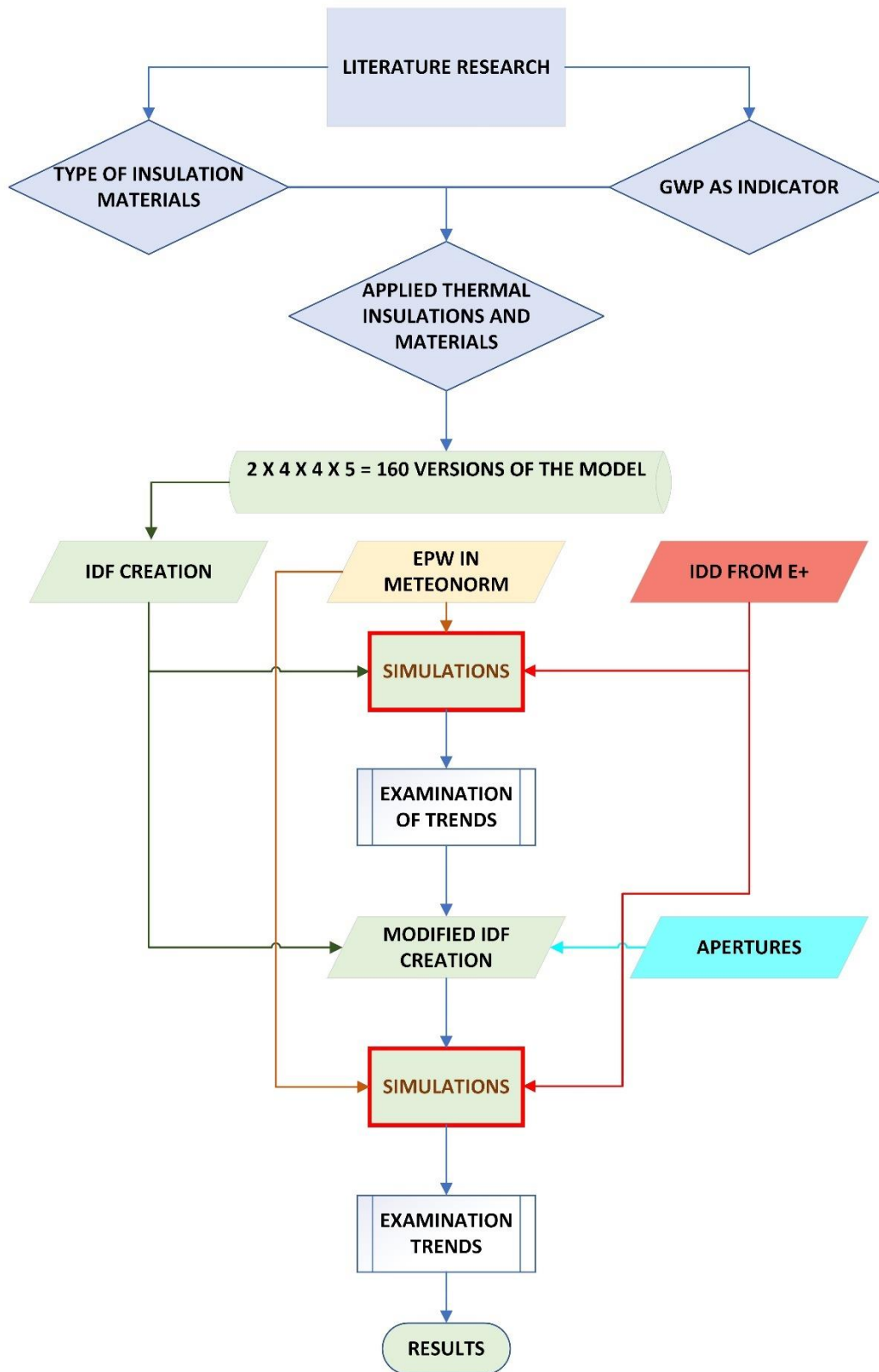


Figure 42 Workflow of the project

The research matrix, the examined combinations of thermal insulation materials and thicknesses are shown in the flowchart below. Bolded and underlined the versions which were examined in the second stage, supplemented by apertures.

Roof thermal insulation, thicknesses

Facade thermal insulation, thicknesses

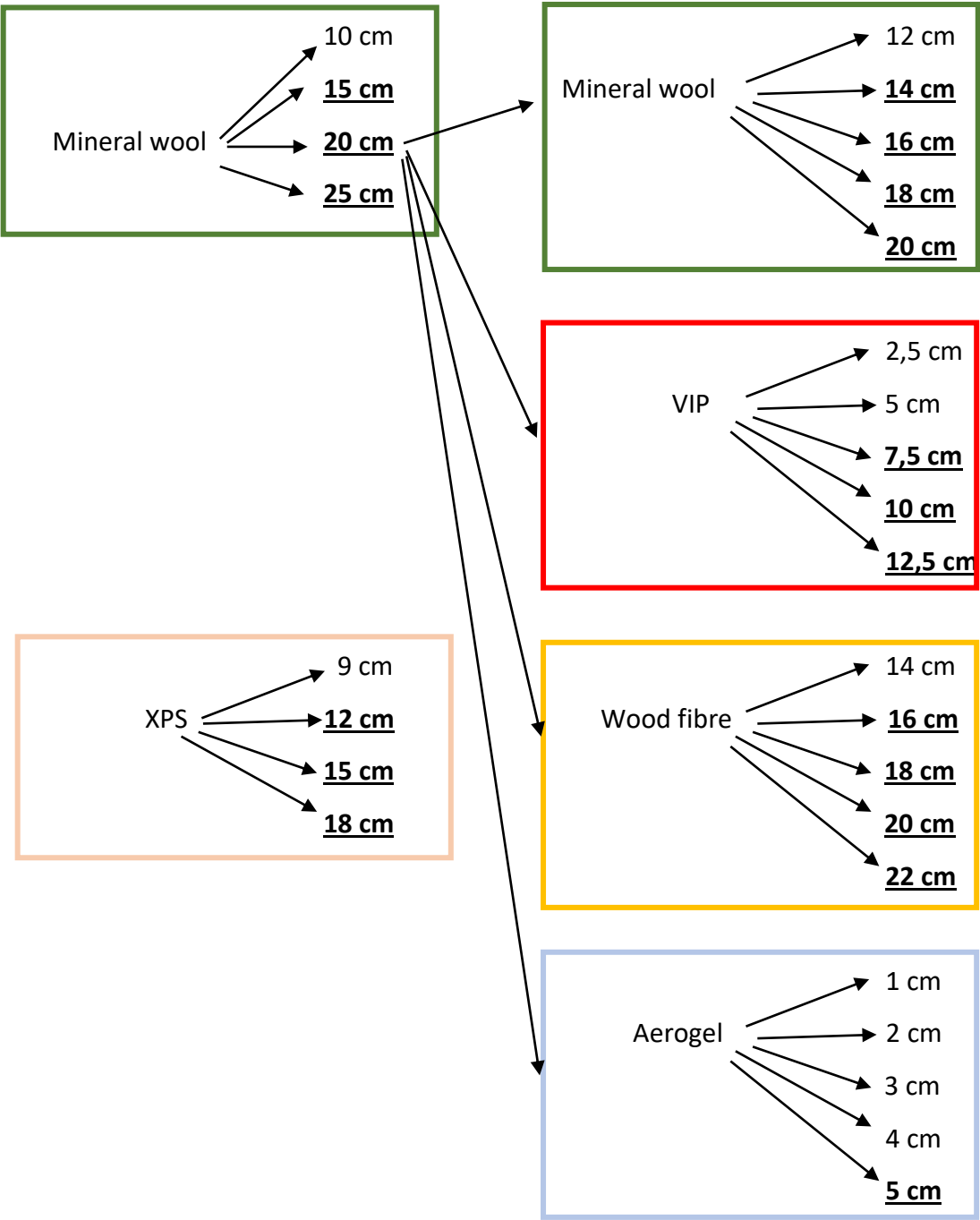


Figure 43 applied thermal insulation thicknesses

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.

3.5.6 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, accompanied by the possibly lowest global cost on the same period. 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

The evaluation and comparison of results are shown in this chapter, based on the four main points of view of the paper, such as user comfort, embodied GWP, yearly site energy demand and global cost of each building version.

4.1 User Comfort

A comparison plot of the embodied GWP and the number of comfortable hours in the building with the pareto-front is shown on Figure 44. If the aerogel versions (cyan) are left out, a general trend of increasement of comfortable hours parallel with the increasement of embodied kgCO₂eq. of each version is noticed. On the plot, a colour label is shown for the façade insulation materials, while the colour of outline shows the material of roof insulation of XPS of Rockwool with pink and blue, respectively. All the elements of the pareto front are within the range of 6222-6242 hours a year, which is a huge step forward from the reference model's 5800 hours by a solid 430 hours a year.

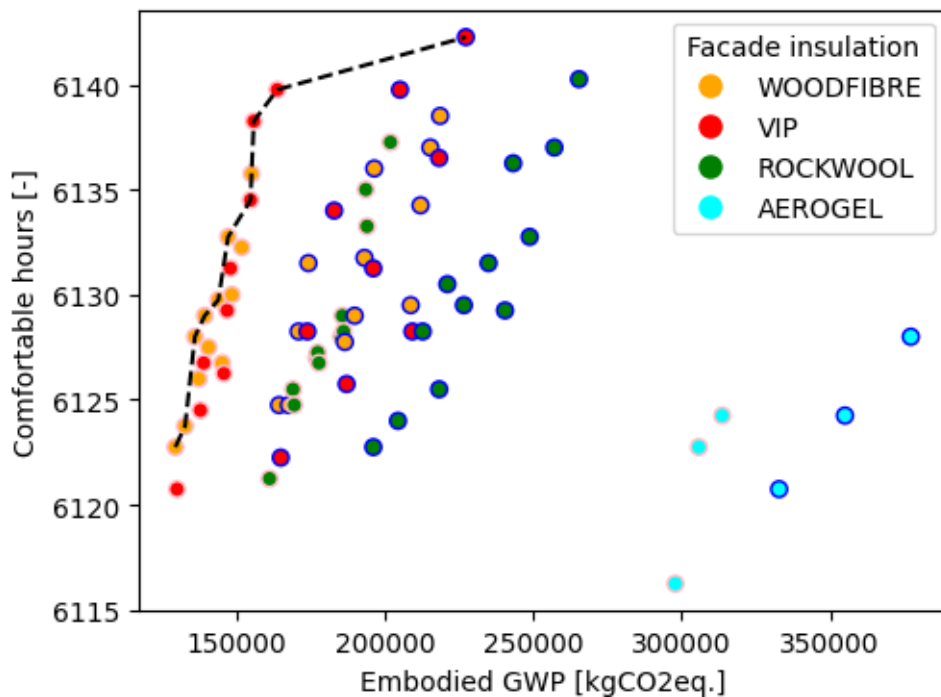


Figure 44 Embodied GWP - Comfortable hours

The elements of the pareto-front are all having embodied GWP values, as a sum of the kgCO₂.eq values of the specific applied thermal insulations, windows, and curtainwalls in the range of 130000 to 230000 kgCO₂.eq. but the last element can be considered as an outlier, see Figure 44. Since the comfortable hours are varying in a such niche range, it might be better to show another model parameter compared to user comfort in the different model versions.

On Figure 45 a comparison of the 20-year global cost and the yearly comfortable hours is shown. Based on this, due to the cc. 1 billion HUF difference between the two ends of the pareto-front it can be stated, that the VIP and Aerogel versions are out of contest from the financial aspect.

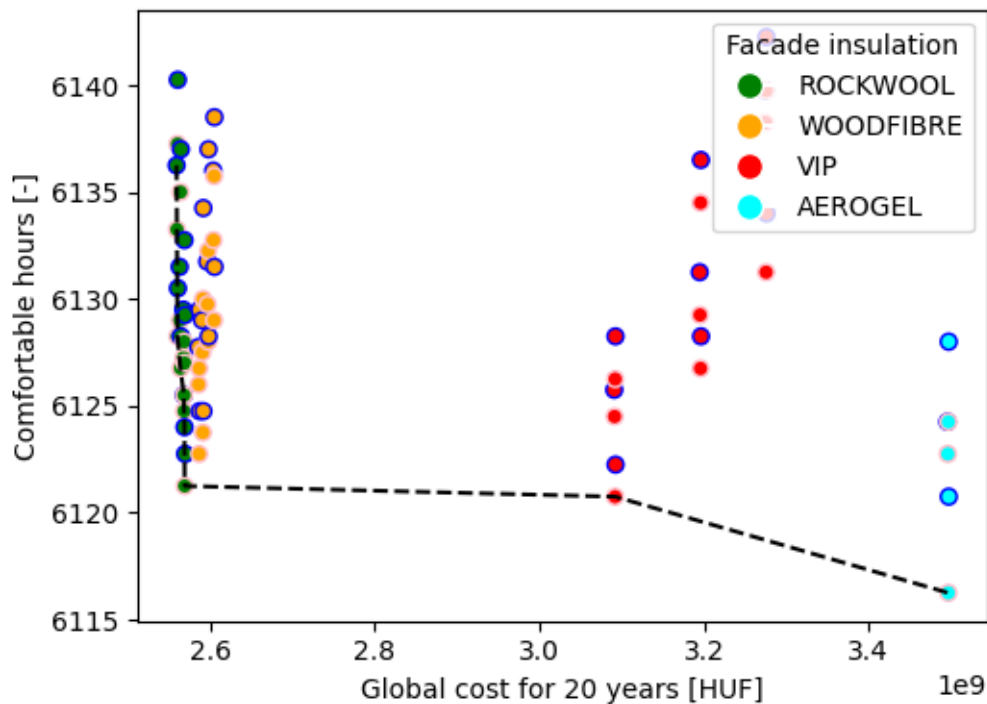


Figure 45 Global cost - Comfortable hours

4.2 Financial Aspect

4.2.1 Common-, or Fixed Costs

Since there are no mayor differences in geometry or location between the examined thermal insulation solutions, given the subject is the same building in every version, it is possible to

estimate some common costs which are generally true for each version of thermal insulation solutions in the paper. Below a collection of these common costs are shown. There are tables shown at the end of subsections in this chapter, and a summary table at the end of the chapter to make a quick readability and understanding of these costs possible.

4.1.1 Plinth walls

To make the thermal insulation of plinth walls possible, there is firstly a need for deconstruction of the existing site connection of the building. The applied dimensions of the cross section of the working ditch of the thermal insulation of the plinth walls are 1 m in width from the existing façade of the building and 60 cm depth from the existing site connection level. The total length of site connection of the building is 234,12 m, of which 20,10 m are existing entrances, which are must to stay with their positions. The remaining 214 m contains 18 m of connection to an existing plantation of evergreen thujas, which area's preparation for extraction of surface into



Figure 46 Existing plinth wall connections

the depth of 20 cm costs 6500 HUF/m² [30], including the necessary rarefaction of the vegetation. This adds up the cost of this item as $6500 \frac{\text{HUF}}{\text{m}^2} * 18 \text{ m} * 1 \text{ m} = 117.000 \text{ HUF}$. The other 196 m is covered with asphalt. The machine aided demolition of an existing asphalt pavement costs 4500 HUF/m² [30], into the depth of 15 cm. This means the asphalt demolition works cost is $4500 \frac{\text{HUF}}{\text{m}^2} * 196 \text{ m} * 1 \text{ m} = 882.000 \text{ HUF}$. The extraction of soil with target tools and machines costs 6000 HUF/m³ [30], which adds up for the applied cross section to

$$6000 \frac{\text{HUF}}{\text{m}^3} * [(18 \text{ m} * 0,4 \text{ m}) + (196 \text{ m} * 0,45 \text{ m})] = 572.400 \text{ HUF}.$$

The applied thermal insulation for plinth walls is XPS in every case, in a depth of 60 cm under the future site connection level, and 40 cm above it, causing a 1 m high plinth wall insulation of XPS in the thickness of 10 cm, causing the plinth walls of 38 cm brick and the additional 10

cm XPS to have the thermal transmittance value of 0,29 W/m²K based on Auricon Energetic 5.0.9 software [87], which fulfils the requirements of the new ÉKM decree [2] for plinth walls. The application of the new plinth wall thermal insulation costs 9200 HUF/m² [30], for 10 cm of width, while the plastering of plinth walls costs 12900 HUF/m² [30]. This sums up as $\left(9200 \frac{\text{HUF}}{\text{m}^2} + 12900 \frac{\text{HUF}}{\text{m}^2}\right) * 214 \text{ m} * 0,4 \text{ m} = 1.891.760 \text{ HUF}$

Keeping the existing connection levels of the building is a goal, so after the plinth insulation and plastering works the connection must be reset. The cost of refill and concentration of the site stored previously extracted soil is 4400 HUF/m² [30], causing a cost of $4400 \frac{\text{HUF}}{\text{m}^3} * [(18 \text{ m} * 0,6 \text{ m}) + (196 \text{ m} * 0,45 \text{ m})] = 435.600 \text{ HUF}$.

The restoration of the asphalt pavement on the affected sections has a cost of 23000 HUF/m² [30], adding up as $23000 \frac{\text{HUF}}{\text{m}^2} * 214 \text{ m} * 0,9 \text{ m} = 4.429.800 \text{ HUF}$.

The transportation of the demolished pavement from the site costs 7800 HUF/m³ [30] in a range of 20 km, which means $7800 \frac{\text{HUF}}{\text{m}^2} * 196 \text{ m} * 1 \text{ m} = 1.528.800 \text{ HUF}$

The summary of cost for thermal insulation of plinth walls are shown in the table below.

SUMMARY OF COSTS FOR PLINTH WALL INSULATION	
ITEM	COST [HUF]
Surface extraction (with vegetation)	117.000
Asphalt demolition	882.000
Soil extraction	572.000
Thermal insulation and plastering	1.814.720
Refill of soil	435.600
Restoration of pavement	4.429.800
Transport of demolished asphalt	1.528.800
SUM	9.856.960

Table 21 SUMMARY OF COSTS FOR PLINTH WALL INSULATION

4.1.2 Scaffolding, roof insulation against rainwater and tinman works

To make the thermal insulation of facades possible, a scaffolding of cc. 3860 m² is needed, which is the gross area of facades. This adds up with the price of 6000 HUF/m² [30] as

$$6000 \frac{\text{HUF}}{\text{m}^2} * 3860 \text{ m}^2 = 23.160.000 \text{ HUF}$$

To make the application of the new thermal insulation of roof possible, removing the existing rainwater insulation is needed. This costs 5000 HUF/m² [30], while the total roof area of the building is cc. 1640 m², meaning a total cost of $5000 \frac{\text{HUF}}{\text{m}^2} * 1640 \text{ m}^2 = 8.200.000 \text{ HUF}$

The new rainwater insulation of roofs, applying has a specific cost of 14000 HUF/m² [30], meaning a total cost of $14000 \frac{\text{HUF}}{\text{m}^2} * 1640 \text{ m}^2 = 22.960.000 \text{ HUF}$

The tinman works contain the new covering of the façade wall tops of the main, multistorey wing, with a specific cost of 30000 HUF/m [30], resulting a total cost of $30000 \frac{\text{HUF}}{\text{m}} * 173 \text{ m} = 5.190.000 \text{ HUF}$

The summary of costs for scaffolding, roof insulation against rainwater and tinman works are shown in the table below.

SUM. OF SCAFFOLDING, ROOF INSULATION AGAINST RAINWATER AND TINMAN WORKS	
ITEM	COST [HUF]
Scaffolding	23.160.000
Removing existing rainwater insulation	8.200.000
New rainwater insulation	22.960.000
Tinman works	5.190.000
SUM	59.510.000

Table 22 SUMMARY OF SCAFFOLDING, ROOF INSULATION AGAINST RAINWATER AND TINMAN WORKS

The summary of all common costs of all the modelled versions are shown in the table below.

SUMMARY OF COMMON COSTS FOR ALL MODEL VERSIONS	
ITEM	COST [HUF]
Plinth Wall Insulation	9.856.960
Scaffolding, Roof Insulation Against Rainwater and Tinman Works	59.510.000
SUM	69.366.960

Table 23 Summary of common costs

4.1.3 Table of ranges of costs

Below a summary table of ranges of the costs of materials in the applied thicknesses in the paper is presented, to give a glimpse into the differences of prices and comparability.

MATERIAL	APPLICATION	RANGES OF UNIT COSTS [HUF/m ²]	
		MIN.	MAX.
ROCKWOOL HardRock Max	Roof insulation	12.400	20.500
XPS	Roof insulation	10.700	17.100
Aerogel	Façade insulation	322.500	
VIP	Façade insulation	196.000	266.000
ROCKWOOL FrontRockSUPER	Façade insulation	29.500	34.800
STEICO Protect dry	Façade insulation	35.600	48.650
SCHÜCO AWS 75.SI windows	Windows	240.000	
SCHÜCO FWS 50 curtainwalls	Curtainwalls	250.000	

Table 24 Ranges of unit prices of the applied materials

4.3 Acquisition Costs of Model Versions

All the 72 examined building versions have different acquisition costs due to their different characteristics of applied materials and thicknesses, but in every case, acquisition costs are stand together from the elements below:

$$AC.COST_{i=1...72} = Common_i + Window_i + Wall_i + Roof_i$$

Where:

AC.COST = The acquisition cost of the given building version

i = the given model version

Common = Common costs (see 4.1.)

Window = Cost of windows and curtainwalls (see 4.2.3.)

Wall = Cost of façade insulation (see 4.2.2.)

Roof = Cost of roof insulation (see 4.2.1.)

The model versions with the highest and lowest acquisition costs are:

	VERSION	ACQUISITION COST [HUF]
HIGHEST ACQUISITION COST	AG5_RW25	1.308.207.785
LOWEST ACQUISITION COST	RW14_XPS12	377.457.175

Table 25 Highest and lowest acquisition cost model versions

It is easy to read out from Table 25, that the most expensive version from the aspect of acquisition cost will be the one with 5 cm aerogel on the facades and 25 cm Rockwool insulation on the roofs, while the cheapest version is also obviously the version with the thinnest possible Rockwool (14 cm) on facades and 12 cm XPS on the roofs. The difference between these two versions is a rough 930.000.000 HUF in acquisition costs, all the other 70 versions are within this range, but each of them differs in user comfort, operating cost and embodied GWP.

From the financial aspect a comparison of global- and acquisition costs are shown on Figure 47, which picture is hardly readable due to the huge differences in the acquisition costs, but it can be stated that VIP and aerogel versions have significantly larger global costs, with a 2-3 times multiplied acquisition cost compared to the mineral wool and wood fibre façade insulation versions.

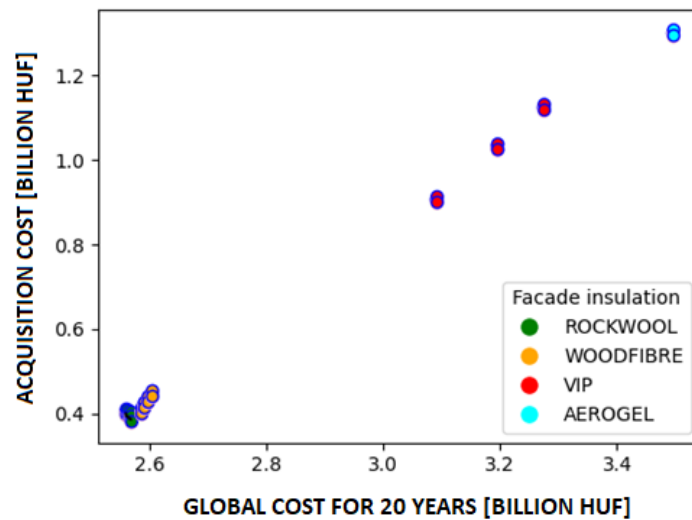


Figure 47 Global cost - Acquisition cost

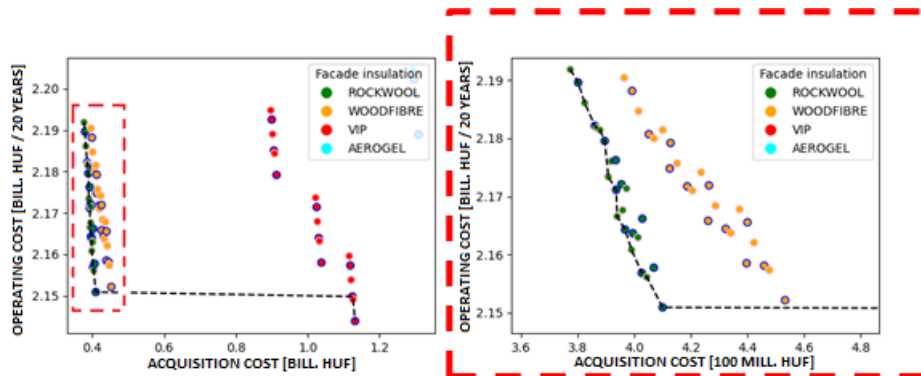


Figure 48 Acquisition Cost - Operating Cost

On Figure 48 a scatter plot with the pareto-front is shown comparing acquisition and operating costs (operating costs are calculated by subtracting acquisition costs from global costs). On the right, highlighted with dashed red tetragon a zoom into the red dashed tetragon on the left is shown, providing a better visibility of the major part of the pareto front. Based on this, it can be stated, that the Rockwool façade insulation versions are financially the best solutions.

4.4 Energy Demand

On Figure 49 a plot of the yearly site energy demands and the number of yearly comfort hours in the building versions is shown. There is a relatively straight inverse relationship between these two parameters in the examined construction versions, the lower the energy demand, the higher the number of comfort hours. This can be explained as the thicker the insulation, the lowest the effect of external climate on the building in the examined ranges of materials and thicknesses. The construction version prospering best in this comparison is the one with 12.5 cm VIP on the facades and 25 cm Rockwool insulation on the roofs, while the following versions are all the possibly thickest insulated ones.

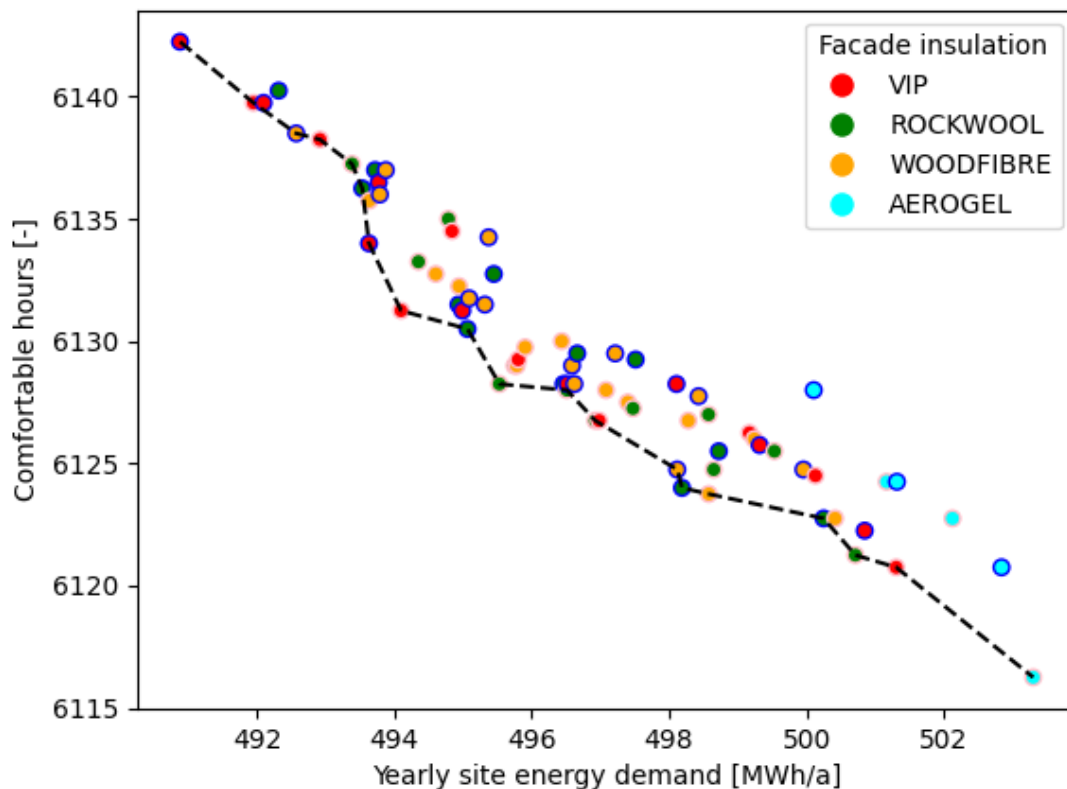


Figure 49 Yearly energy demand - Comfortable hours

Based on Figure 50 an increase in the yearly energy demand is noticeable with the decrease of embodied GWP. This correlates with Figure 49 as the more embodied GWP, which provides generally thicker insulation in the examined model versions, the less impact the external climate has on the building. It is generally true based on Figure 50 that XPS roof

insulation versions (pink outline) have significantly lower embodied GWP values compared to Rockwool roof insulation versions (blue outline), that is caused by the difference of specific embodied GWP values of XPS and Rockwool, 160 and 270 kgCO₂eq./m³, respectively, and difference in their design thermal conductivity values 0.035 and 0.040 W/mk, respectively, which provides the possibility of applying thinner roof insulations from XPS with similar thermal characteristics. The pareto-front consists of wood fibre and XPS façade insulation versions, which materials have the lowest specific embodied GWP values of the examined façade thermal insulation materials with values of 53 and 115 kgCO₂eq./m³, respectively. Which provides the possibility for the wood fibre versions to be the most environmentally friendly façade thermal insulation solution, even though it needs to be applied with highest thicknesses of the examined materials.

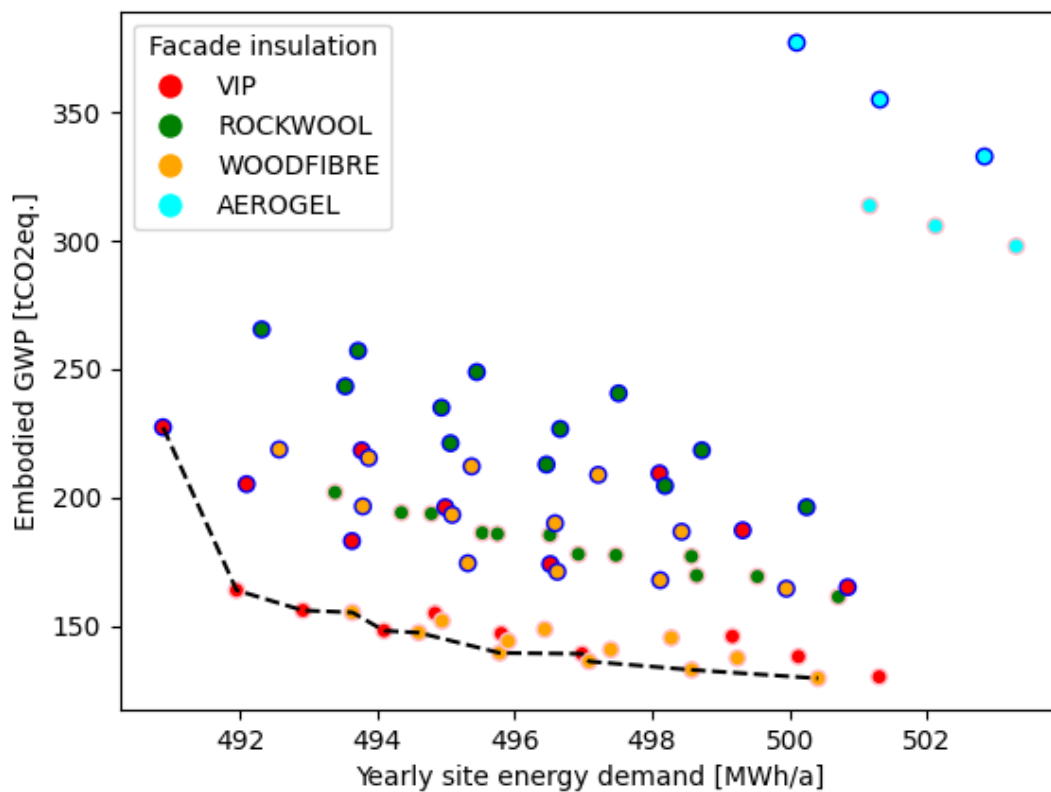


Figure 50 Yearly energy demand - Embodied GWP

On Figure 51 the comparison of yearly energy demand of the examined building models and the global costs. The yearly energy demands are within a range of cc. 20000 kWh energy

annually, while the Rockwool and wood fibre façade insulation versions are having a significantly lower global cost.

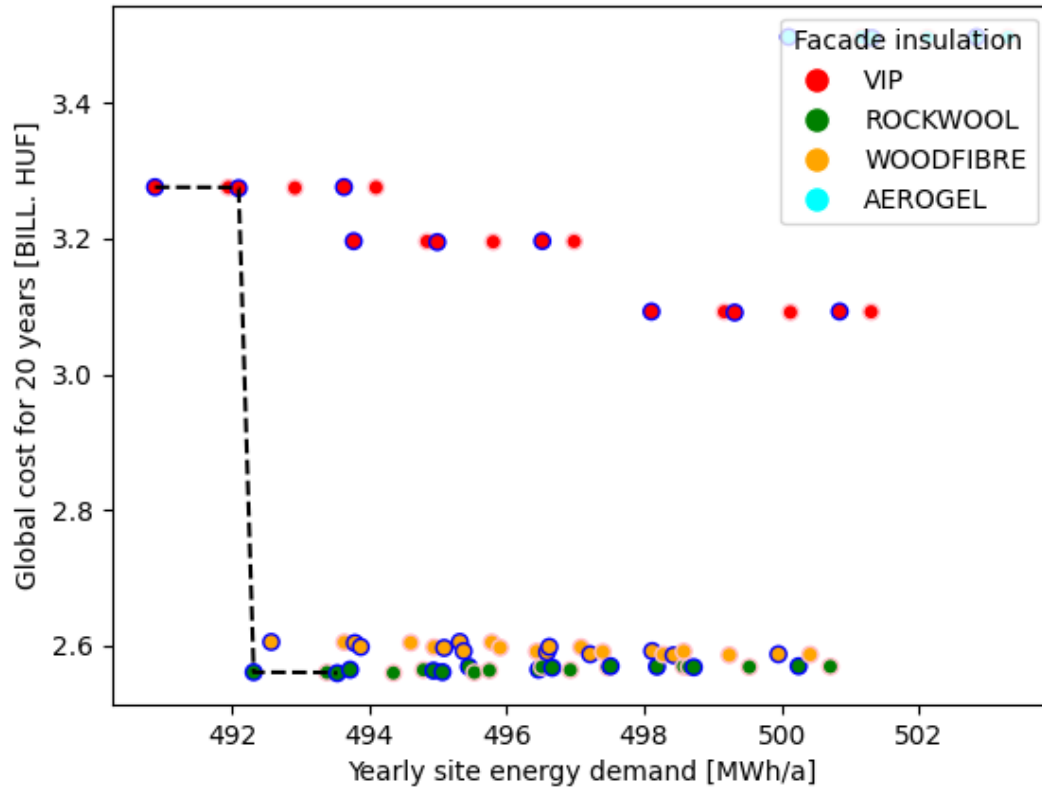


Figure 51 Yearly energy demand - Global cost

4.5 Environmental Aspects

Figure 52 is showing the comparison of embodied GWP values of the examined building versions with the yearly site energy GWP, which parameter comes directly from energy demands, multiplied by conversion factors of 455 and 374/kWh for electricity and district heating [2], respectively. As the site GWP values are coming from energy demands, the plot and the pareto-front was expected to have similar shape as on Figure 50. Also in this comparison, wood fibre and VIP façade insulation versions with XPS roof insulation are providing the possibly lowest values of the specific parameters. Due to price differences, and the significantly lower specific embodied GWP values, from an environmental aspect, the wood fibre façade insulation versions are favourable than others.

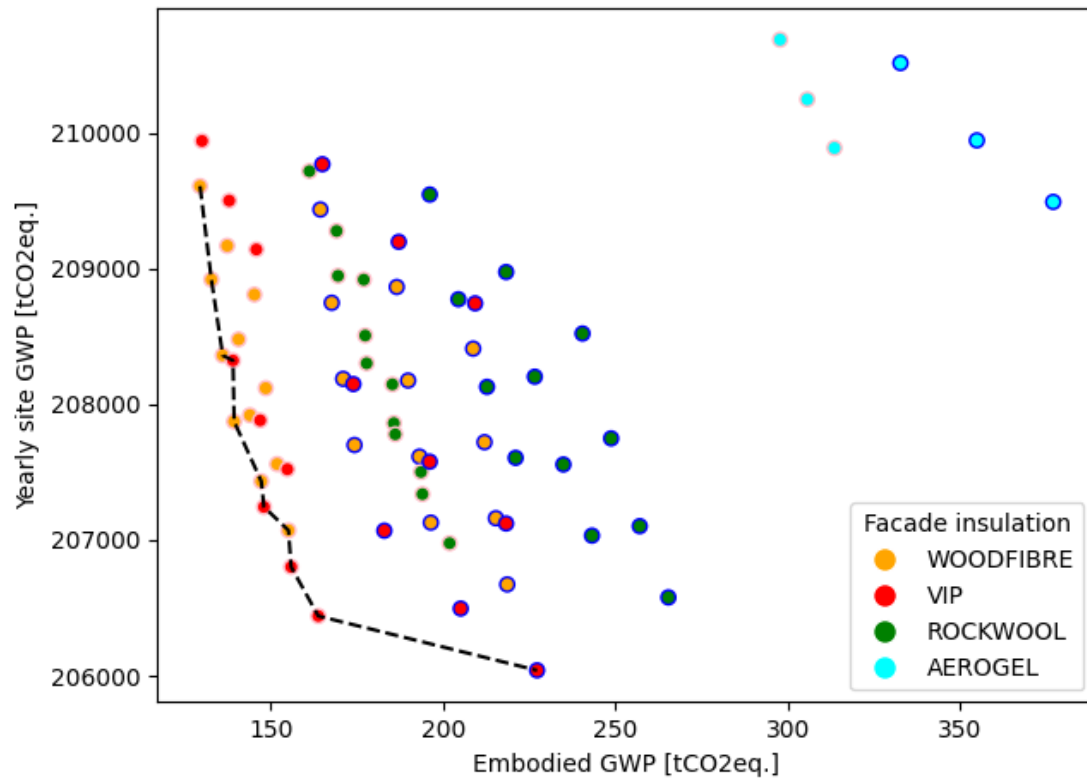


Figure 52 Embodied GWP - Yearly site GWP

5. CONCLUSION, IMPACT

A comparison of application of different thermal insulation materials in various thicknesses on the facades and roofs, supplemented by new windows and external curtainwalls 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 the 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	12,5 cm VIP	25 cm Rockwool	6.142 hours
Lowest embodied GWP	16 cm Wood fibre	12 cm XPS	129.465,7 kgCO ₂ eq.
Lowest site energy demand	12,5 cm VIP	25 cm Rockwool	490.882,2 kWh/a
Lowest acquisition cost	14 cm Rockwool	12 cm XPS	377.457.175 HUF
Lowest total cost (20 years)	20 cm Rockwool	20 cm Rockwool	2.559.535.327 HUF

Table 3 Best versions

Determining THE Best version of the examined constructions is pretty much impossible on an objective scale, but there are major trends and parameters observable, whose considerations can provide a significant help when making decisions regarding energy related refurbishment of buildings, which can lead to a better quality and comfort of real estates on a long term. 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 and many more aspects.

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