IMPROVING THE ENERGY EFFICIENCY OF EXISTING BUILDINGS BY APPLYING NANOMATERIALS AND AEROGEL BASED MATERIALS

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Abstract

Improving the energy efficiency (EE) and sustainability of the buildings is crucial for meeting EU climate targets. Circular economy (CE), especially in the building sector, strive to reduce the pollution, extend the building's lifespan, reduce the material waste and use long-lasting products. Proper renovation by using sustainable materials with low embodied energy will lead to the fulfilment of both goals, EE and CE.

Aerogel-based building products and nanomaterials are currently considered to be promising insulation materials due to their great thermal performances with limited thickness and their low embodied energy. This lecture aims to explore the potential that aerogel and nanomaterials have not only in terms of EE and CE principles but as well as the cultural heritage impact after the renovation process.

The architecture of Modernism in Skopje represents an important cultural heritage of the city. Those buildings were built in lack of thermal insulation materials and have very poor thermal properties. In this lecture, a dynamic software simulation of the energy performance of a Modernist building is made, in order to see the real energy condition of the building and its possible improvements by using aerogels and nanomaterials on the façade walls, which has minimal impact on their authentic appearance.

Keywords: *circular economy, energy efficiency, aerogel based materials, nanomaterials*

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1. INTRODUCTION

In recent decades, the advancement of materials science has led to the emergence of nanomaterials substances engineered or structured at the nanometer scale, typically ranging from 1 to 100 nanometers. These materials exhibit unique physical, chemical, and mechanical properties not observed in their bulk counterparts, largely due to their high surface area-to-volume ratio and quantum effects. Nanomaterials are increasingly being applied across various fields, including environmental protection and construction, where their enhanced performance enables novel and more efficient solutions.

Aerogels represent a distinctive class of materials that, while not always initially classified as nanomaterials, often exhibit nanoscale characteristics. They are formed by replacing the liquid component of a gel with a gas, usually air, without significantly altering the solid network structure. This process results in a highly porous, lightweight material with extremely low density and exceptional thermal insulation properties. The most well-known type, silica aerogel, is composed of a three-dimensional network of silica nanoparticles, with pore sizes and particle diameters typically in the nanometer range. As such, silica aerogels and similar materials can be considered nanostructured materials due to their internal nanoscale architecture.

The unique combination of properties,such as high porosity, low thermal conductivity, and high specific surface area makes aerogels valuable for a wide range of applications. These include thermal insulation in aerospace and construction, oil spill cleanup, sensors, catalysts, and drug delivery systems. The integration of aerogels into the broader category of nanomaterials highlights the growing importance of nanoscale engineering in developing high-performance materials tailored for energy efficiency and sustainability.

As research and development in nanotechnology continue to advance, aerogels are expected to play a crucial role in the design of next-generation materials. Their classification as nanomaterials is increasingly recognized, particularly when their function and performance are directly linked to their nanostructure. Therefore, understanding the fundamental principles and properties of aerogels within the context of nanomaterials is essential for fully leveraging their potential in innovative technological applications.

2. NANOMATERIALS FROM ASPECT OF ENERGY EFFICIENCY

The scientific interest in nano and biomaterials in energy efficient buildings has significantly increased in the last decade, especially after the introduction of "Nearly zero - energy buildings" - NZEB) according to Directive on the energy performance of buildings, 2010/31/EU – EPBD (Pacheco et al., 2016). That means that the new building's energy consumption should be close to zero by 2030, which leads to great tightening of energy efficiency (EE) criteria and increase of thermal insulation materials thickness, which has important economic and technical consequences, especially high insulation costs (Attia et al., 2022). Not only the material's thickness emphasizes the need for research and development of new materials, but more significant factors, such as: finding solutions for reducing the embodied energy used for production and transportation, reducing toxicity and environmental pollution, as well as reducing material waste, favorite the use of long-lasting building materials and extending the building's lifespan. All these measures mark a new moment in the construction industry known as circular economy (CE). On the other hand, new buildings have a limited impact on overall energy reduction because they represent small part of the existing building stock (Xing et al., 2011). It is estimated that only 1% of the buildings in Europe, per year are new buildings. Therefore, existing buildings represent the greatest opportunity for CE implementation. Moreover, new buildings use 4-8 times more resources than renovated ones (Power, 2008), which is a sustainable argument in favour of buildings' renovation. An additional problem that arises during renovations is the preservation of the building's architectural appearance, that shouldn't be compromised. The selection of right materials and methods for application in renovation process are crucial for both, the EE and CE improvement, as well as for authenticity preservation.

This role of nanomaterials in the building sector, is not only in terms of EE (energy consumption ad cost improvements), but also in terms of CE (reduction of embodied energy, environmental toxicity, recyclability, adaptive reuse, as well as the relationship of the new materials to the cultural heritage buildings). The nanomaterials based on silica aerogel as well as the nano ceramic coatings are the most promising building materials, according to all of the above-mentioned criteria.

This lecture highlights the potential that aerogel have in EE and CE of the building sector, and therefore, the further analysis refers only to aerogel-based materials. Comparing to all of the researched types of aerogel-based materials, the silica aerogel thermal plaster proved to be the most appropriate solution in terms of energy efficiency, sustainability, circularity and historical buildings' compatibility.

3. NANOMATERIAL SELECTION CRITERIA

In terms of improving the energy efficiency, the following commercially available nanomaterials have been developed so far:

- Expanded polystyrene with graphite powder-based products (graphite nanotubes or carbon particles are added to the granular structure of polystyrene;
- Aerogel-based products - have a wide range of products for insulating transparent or non-transparent surfaces (Bozsaky, 2016);
- VIPs - vacuum thermal insulation panels, based on nano particles, with high thermal insulation power and very low thickness (Lakatos, 2018);
- Nano-ceramic thermal insulation coatings (extra thin film coatings) for insulating transparent or non-transparent surfaces (Bozsaky, 2017);
- PCMs - phase change materials based on paraffin nanoparticles and salt hydrate, whose paraffin globules with a diameter between 2 and 20 nm are encapsulated in a plastic shell. They can be integrated into building materials, whereby, with a concentration of about 3 million such capsules in one square centimeter, they

change their aggregate state from solid to liquid when the temperature changes, and thus maintain the required temperature in buildings (Baetens, 2010).

The five types of building facade nanomaterials are analysed in this paper according to their properties in relation to the following established criteria, shown of Fig.1:

- Criteria 1 - thermal conductivity;
- Criteria 2 - environmental impact (toxicity, pollution and embodied energy);
- Criteria 3 - material thickness;
- Criteria 4 - cultural heritage impact.

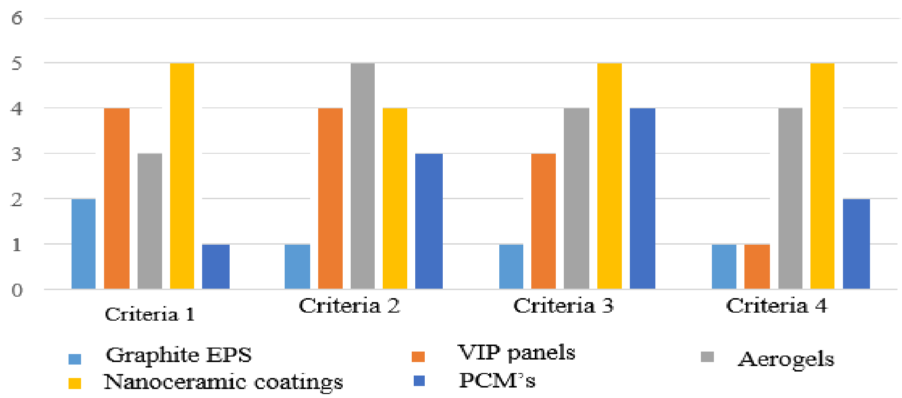

Figure 1 - Nanomaterials evaluation according to their properties and established criteria

From the conducted research, it can be concluded that aerogel based products and nano-ceramic coatings showed the best results in terms of the established criteria. These materials have the lowest rate of toxicity to the environment, low embodied energy and pollution in their production process, high thermal insulation properties (thermal conductivity), availability in extremely small thicknesses and above all, small impact on the original architectural appearance after façade renovations.

4. SILICA AEROGEL BASED MATERIALS

Aerogel-based building products are currently considered to be promising insulation materials mostly due to their high thermal properties with small thickness. Furthermore, they have quite low embodied energy, lower than traditional insulation products and other nanomaterials (Curto and Cinieri, 2020).

Different types of aerogel-based building nanomaterials are investigated in this paper, in order to give an overview of the state of the art use of aerogel nanomaterials in construction industry and their potential and significance for the EE improvement, CE implementation and cultural heritage proper renovation.

Silica aerogels have amazing thermal properties, ie. they have a density of 1.9kg/m^3, a volume porosity of 99.8% or a specific surface of 400 – 1000 m^2/g. Pure silica has an extremely low thermal conductivity λ = 0.014 W/mK, while for different silica aerogel products \ it varies (0.01-0.02 W/mK) (Berardi, 2017). They are great sound absorbers, especially due to their high porosity with a pore size of 1-100 nm. Due to the silanol in their composition, they are waterproof. Thermal insulation materials based on silica aerogel are present in many forms and under different commercial brands. The most common forms are: aerogel panels, blankets, plasters, light concrete, granules, transparent films etc. (Fig.2)



a) b) c)


d) e)

Fig.2 Silica aerogel products a) blankets; b) panels; c) light concrete; d) granules; e) plaster

5. AEROGEL BASED PRODUCTS ANALYSYS AND RESULTS

From the analysed types of aerogel-based products, it can be concluded that each of them has a similar composition, excellent thermal performances and above all, all of the aerogel based materials are sustainable, eco-friendly and since the silica based aerogel is mineral, it can be reused as an insulation material after a recycling process, which meets the CE criteria. Silica aerogel material has many applications and it can be modified to meet a number of specific purposes required by CE, since they have low embodied energy, lower than traditional insulation products (Handojo et al.,2022), (Ganobjak, 2019).

Aerogel can be mixed to develop a green building material with unique characteristics and have a great potential for an application in green and sustainable buildings (Ganobjak, 2019). (Castro-Diaz et al., 2022). However, one of the criteria, such using the aerogel as a façade material in cultural heritage buildings is not possible for all types of aerogel based products, which also has an impact to the CE principles since building renovation and adaptive reuse is one of the main CE goals.

Table 1 - Aerogel based products comparisons according to their cultural heritage impact

Type of aerogel product	Authenticy	Integrity	Reversibility	Compatibility
Aerogel blanket	Can be used where proportions cannot be changed (windows, doors) or where not enough space is available. Flexible for uneven surfaces	Removal and replacement of original material and necessary anchoring points should be minimised	Reversibility of the application is required. Possible addition to existing façade. Visual difference to original material is positive	Physical compatibility with historical materials and techniques is required. Vapour openness can be influenced by exterior render. Scientific proof of compatibility should be given
Panel/ board	The authentic appearance should be preserved and cannot be covered by boards. Boards can only be used in the interior if there are no protected parts.	Removal and replacement of original material and anchoring points should be minimised. Boards can be used without anchors, but glued by glue.	Reversibility of the application is required. Possible addition to existing façade. Visual difference to original material is positive	Physical compatibility with historical materials and techniques (vapour open, durable) is required. Vapour openness can be influenced by exterior render. Scientific proof of compatibility should be given
Plaster/ render	The original visual appearance of the building is possible to be reproducted by plasters. On uneven surfaces, mouldable render can be used for artistic and architectural details	Removal and replacement of original material should be minimised. The aerogel render can be an addition to the existing render	The aerogel plaster is considered reversible and can be removed down to original layers with a trowel and residues by hard brush. Its softness is considered a positive property	Physical compatibility with historical materials and techniques (vapour open, durable) required. Proof should be given scientifically.

Granular form	Authenticity not affected by filling of a cavity with granules if it is not exposed	Addition of granules do not affect the integrity of building	Reversible to previous status	Material can cause decrease of adhesion of other materials. If dust escapes, it can lead to skin and eye irritation. Increased hydrophobicity
Transluce nt panel	Daylighting of interior with diffusive effect can be achieved. Translucent elements are recognisable from original glazing. Better noise protection is achieved	Replacement of old translucent panels possible without change of integrity, depending on original frame. Additional structural frame might be required	Reversible to previous status	Compatibility is comparable with original forms of glazing. Panels might fit into original frames. Panels made out of glass and polycarbonate used for outer part of layered panel are considered as compatible

For this purpose, analysis of different types of aerogel based products are carried out terms to their methods of application in cultural heritage buildings and the results are explained in Table 1. The technical characteristics of the different aerogel products and their use and impact in the processes of cultural-historical heritage restoration and renovation are explained, according to four significant criteria for cultural heritage: authenticity, integrity, reversibility and compatibility. From the conducted analysis, it can be concluded that the most appropriate aerogel based material for renovation and preservation of historical buildings are the aerogel thermal insulation plasters (Table 1). Despite the fact that aerogel particles have the smallest impact of the authenticity and integrity, it is very difficult to be used in existing buildings. They are used to fill new hollow walls, to mix with the concrete or other materials in the process of creating the product, which usually correspond to smaller parts of the building such as architectural details, etc. but not to the façade walls which are responsible for the EE improvement.

The aerogel based thermal plasters or renders have the biggest potential in the application in existing buildings, especially cultural heritage buildings because of their soft texture and flexibility in applying on different surfaces (Ganobjak, 2019). (Castro-Diaz et al., 2022). According to the criteria for protection of historical buildings, aerogel plasters have a mild impact on their authenticity, but it is important that they are compatible with the chemical composition of the original materials, and can be easily removed without damaging them with no need for additional fastening that would damage the original material (Carty, 2017). The application of the new material will not only improve the energy efficiency and sustainability of the building but also it will protect it from climate conditions and expand its lifespan. Due to the composition and method of application, aerogel plasters are available in different textures and colors and they can perfectly mimic the existing materials making it difficult for distinguishing, while the original material remains preserved (see Fig. 3 and 4).

a) b)

Figure 3 - Old renaissance building façade, a) original material before aerogel plaster application; b) after aerogel plaster application

a) b)

Figure 4 - Old natural concrete façade, a) original material, before aerogel application; b) after aerogel plaster application

6. CASE STUDY – IMPROVING ENERGY EFFICIENCY OF BUILDINGS PROTECTED AS CULTURAL HERITAGE

The architecture of 20th century, known as Modernist architecture, represents an important cultural heritage for the City of Skopje. According to the construction standards of that time, the buildings were built in the absence of thermal insulation materails, which resulted in bad thermal comfort, high costs for heating, cooling and maintenance, degradation and decay. Those building need to be properly renovated according to today's energy efficiency standards. On the other hand, the architecture that is considered as a cultural heritage must not undergo changes that would change its authentic appearance. In order to solve the problem with the energy efficiency and thermal confort in Modernist buildings, and in the same time to minimaze the impact on their authensity after the renovation process, two types of facade nanomaterials are analysed. In this paper, a dynamic software simulation of the existing state of a selected Modernist building is made, and the analyzed materials are used as improved scenarios. The application of aerogel based thermal plaster on the facade walls is defined as scenario 1, while the application of nano ceramic coating is defined as scenario 2. The selected "case study" is a Modernist building, considered as cultural hertage, which facade is designed entirely in natural concrete, known as "beton-brut“ (Fig.5).

a) b) c)

Figure 5 – Modernist building complex - student dormitory in Skopje a) Whole complex of the four blocks - front view b) Case study block “B” – front view c) Case study “block - B”- entry view

6.1. Selecting facade nanomaterials

The State of the art of nanomaterials in the building sector was first investigated, especially in terms of energy efficiency. Additional complication of the research problem is the factor of preservation of the authentic appearance of the building which leads to an extensive research process, where through a detailed systematic review of the scientific literature, a selection of the most appropriate nanomaterials has been made to improve energy efficiency, sustainability, and also protect the authenticity of buildings. From all the researched nanomaterials two types of nanomaterials were chosen for the simulation: thermal plaster based on nano silica aerogel and thermal coating based on nano ceramic microspheres. Both materials have their advantages and disadvantages, however, compared to other analyzed materials, they are estimated to be the most appropriate in solving the problem and creating minimal impact based on the following established criteria: thermal conductivity, toxicity and environment damage, cultural heritage protection and thickness).

The research showed that aerogel based thermal plaster has a low coefficient of thermal conductivity λ ranging from 0.028-0.014W/mK (Stahl, 2012), thanks to the porous nano structure (Karol and Tomasz, 2015). In the buildings renovated with this type of plaster, energy savings could be over 50% (Carty, 2017). According to the criteria for protection of cultural heritage (authenticity, integrity, reversibility and compatibility) aerogel plasters have a moderate impact on the authenticity of buildings, but it is important that they are compatible with the chemical composition of the original materials, which can be easily removed without damaging them and there is no need for additional fastening that would damage the original material. They have great flexibility in applying uneven surfaces, architectural details and insulating thermal bridges. Due to the composition and method of application, aerogel plasters perfectly mimic the texture of natural concrete and it is difficult to distinguish (Fig. 6), while the original material remains preserved under the mortar. The cost of the aerogel is still high, which prevents its intense spread in construction.

The nano coating has an indeterminate coefficient of thermal conductivity λ, which can be roughly calculated or measured on the building itself after application. From the studied literature, λ varies around 0.001-0.003 W/mK. The nano coating has an extremely small thickness of 0.0003 m, and therefore the coefficient λ does not play the main role, but the processes of many complex mechanisms in the nano structure of the coating, which are included in the so called factor f_{TS} . Based on the mechanisms of action, the f_{TS} factor varies and is different for each material. Through several laboratory experiments and *in situ* measurements, a calculation software (Calculus) for calculating the f_{TS} factor for different coating materials has been developed. Based on the measurements of buildings renovated with nano ceramic coating, energy savings can be up to 30%. In terms of cultural heritage preservation, the nano coating corresponds very well to the set criteria, without impacting the authentic appearance, thanks to its transparency. (Fig. 6) The cost of the nano coating is lower than aerogel plaster, but higher than conventional coatings and paints (Bumann, 2010).

a) b) c) d)

Figure 6 – Original materials vs. nanomaterials application a) Exposed rough concrete wall b) Wall with applied aerogel plaster as imitation of rough concrete c) Aacrylic plaster finished wall, d) Same wall after the application of nano ceramic coating

6.2. Energy simulaition and results

6.2.1. Methodology

A dynamic software simulation of the energy performance of case study building which is student dormitory (Fig. 6) is made using BIM integrated soft wares Energy Plus and Open Studio. The dormitory has a complex plan of four equal towers. In this paper, only one tower, named as “block - B" is analyzed. Fig. 12 shows the characteristic floor plan and its division into five thermal zones. The building is zoned into a total of 62 thermal zones. The project temperature for the stair’s zones is 20°, for the room’s 21°, for the toilet's 24° and in the basement 15°. The block has net area of 5 520 m² and net volume 15 346 m³, a heated area of 5 002 m² and a heating volume of 13 792 m³ with a capacity of 304 tenants. The glazed area of the facade is 1 268 m². The building is supplied with heat through district heating network (130/70° water) and stored in a thermal substation with a capacity of 578 980 kcal/h. It is distributed through a central hot water pump with forced circulation to the radiators in each zone. Sanitary hot water is prepared from a boiler with a capacity of 4 000l, with combined heaters. The cooling and ventilation of the building are natural, except for the bathrooms in the rooms, where the ventilation is mechanical. The building is heated from 15th of October till 15th of April. Climate data are read simultaneously by the Hydro meteorological Institute in Skopje, which enables accurate calculations in real non-stationary conditions.

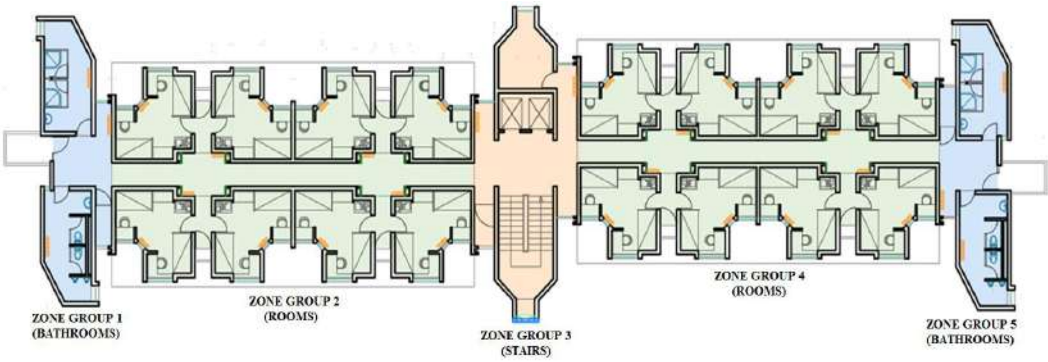

Figure 6 – Characteristic floorplan of the selected building and thermal zones division

Table 2 shows the materials of the building envelope and their thermal properties of the current situation and the added materials and their properties in scenarios 1 and 2. In the current state the windows are made of aluminum profiles with single glass with $U_w = 5.61$ W/m^{2}K. In the improved scenarios the windows are made of six chamber aluminum profiles and two layer low emission glass with $U_w = 1.2$ W/m^{2}K. The nano ceramic coating (Table 1) does not give a specific value of the coefficient λ, but the thermal conductivity is calculated by including the f_{TS} factor for each envelope material. f_{TS} (e.g. f_{TS} for reinforced concrete is 0.55; perlite concrete – 0.40; gypsum mortar – 0.35; ceramic tiles – 0.40). The thermal conductivity for each element of the envelope is calculated in Calculus and the values are then entered into Energy Plus.

The simulation obtained the following results for all three scenarios: heat consumption; electricity consumption for heating; consumption of electricity from electrical appliances and equipment; electricity consumption for lighting; energy consumption for hot sanitary water; CO_2 emissions; indoor air humidity and temperature in each zone; surface internal and external temperatures of the walls; energy losses from infiltration, ventilation, windows and opaque surfaces for each zone; U values of all structural elements of the envelope. The results that show the biggest impact of the applied materials in the improved scenarios are presented in this paper.

Table 2 – Envelope materials properties (current state, scenario 1 and scenario 2)

Envelope	**Material properties**					
	Materials	***λ (W/mK)***	***c (J/kgK)***	***ρ (kg/m³)***	***d (m)***	***μ [-]***
Façade wall type 1 (Current state)	plastic wallpaper	0.2	1250	700	0.002	7000-50000
	gypsum	0.16	830	784.9	0.005	6-10
	perlite concrete	0.25	1000	800	0.04	60-100
	reinfroced concrete	2.6	1000	2500	0.2	80-130
Scenario 1	aerogel plaster	0.028	990	156	0.06	4-5
Scenario 2	ceramic coating	f_{TS}	/	290-410	0.0003	2
Façade wall type 2 (Current state)	ceramic tiles	1.3	840	2300	0.01	200
	perlite concrete	0.25	1000	800	0.04	60-100
	reinfroced concrete	2.6	1000	2500	0.2	80-130
Scenario 1	aerogel plaster	0.028	990	156	0.06	4-5
Scenario 2	ceramic coating	f_{TS}	/	290-410	0.0003	2
Façade wall type 3 (Current state)	gypsum plaster	0.54	1000	1500	0.015	6-10
	reinfroced concrete	2.6	1000	2500	0.2	80-130
Sceanrio 1	aerogel plaster	0.028	990	156	0.06	4-5
Scenario 2	ceramic coating	f_{TS}	/	290-410	0.0003	2
Façade wall type 4 (Current state	reinfroced concrete	2.6	1000	2500	0.2	80-130
Scenario 1	aerogel plaster	0.028	990	156	0.06	4-5
Scenario 2	ceramic coating	f_{TS}	/	290-410	0.0003	2
Ground floor slab structure type 1 (Current state)	carpet	0.08	1230	0.27	0.005	/
	self-leveling mass	1.4	1050	2200	0.035	50-70
	reinfroced concrete	2.6	1000	2500	0.16	80-130
Scenario 1 and 2	eps	0,031	1450	15-40	0,1	60
Ground floor slab structure type 2 (Current state)	ceramic tiles	1.3	840	2300	0.01	200
	cement mortar	1.4	1050	2100	0.04	15-35
	reinforced concrete	2.6	1000	2500	0.16	80-130
Scenario 1 and 2	eps	0,031	1450	15-40	0,1	60
Flat roof type 1 (Current state)	basalt tiles	2	1000	2447	0.04	20-30
	sand	0.58	840	1800	0.02	/
	cement mortar	1.4	1050	2100	0.04	15-35
	vapour barrier	0.16	1460	1121.29	0.0095	100000
	aluminium foil	203	940	2700	0.001	/
	bitumen coating	0.17	1460	1100	0.004	5000
	perlite concrete	0.25	800	1000	0.08	60-100
	glass wool	0.032	840	30	0.04	1-5

Envelope	Material properties					
	Materials	*λ (W/mK)*	*c (J/kgK)*	*ρ (kg/m³)*	*d (m)*	*μ [-]*
	reinforced concrete	2.6	1000	2500	0.08	80-130
Scenario 1 and 2	eps	0,035	1030	10-200	0,2	1-5
	plywood	0.12	1800	1000	0.01	50-70
Flat roof type 2 (Current state)	gravel	0.81	840	1700	0.06	/
	vapour barrier	0.16	1460	1121.29	0.0095	100000
	aluminium foil	203	940	2700	0.001	/
	bitumen coating	0.17	1460	1100	0.004	5000
	perlite concrete	0.25	800	1000	0.08	60-100
	glass wool	0.032	840	30	0.04	1-5
	reinforced concrete	2.6	1000	2500	0.08	80-130
Scenario 1 and 2	eps	0,035	1030	10-200	0,2	1-5
	plywood	0.12	1800	1000	0.01	50-70

6.2.2. Heating energy consumptions and CO_2 emissions

Energy simulations showed that the building biggest energy consumption is for district heating. In real conditions, the average consumption of energy for heating is 190 kWh hourly, 4 553 kWh daily and 138 478 kWh monthly (Table 3), i.e. 1 661 736 kWh annually. That is 227 kWh/m², which is over 25% higher than the consumption of an average building (170 kWh/m²). Scenario 1 showed a reduction of thermal energy by 52%, i.e. the average consumption is 91 kWh hourly, 2 177 kWh daily and 66 237 kWh monthly (Table 3), i.e. 794 841 kWh annually. That is 109 kWh/m², which is a relatively low consumption for buildings of this type. Scenario 2 showed a decrease of 23%, i.e. the average consumption is 147 kWh hourly, 3 538 kWh daily and 107619 kWh monthly (Table 3), i.e. 1 291 428 kWh annually. That is 176 kWh/m², defining the building in the average consumers. Figure 7 shows the graphic of monthly energy consumption for heating in kWh for the three conditions, where it can be concluded that scenario 1 has the lowest heating energy consumption, which is lower that scenario 2 by 30% and lower than the current state by 50%.

The total electricity consumption of the current situation is 53 kWh hourly, 1 275 kWh daily and 38 796 kWh monthly, i.e. 465 556 kWh annually or 64 kWh/m^2. The total electricity energy consumption is divided into: heating electricity (if the district heating system cannot reach the design temperature, electrical heating is activated); electricity for appliances, hot water and for lighting.

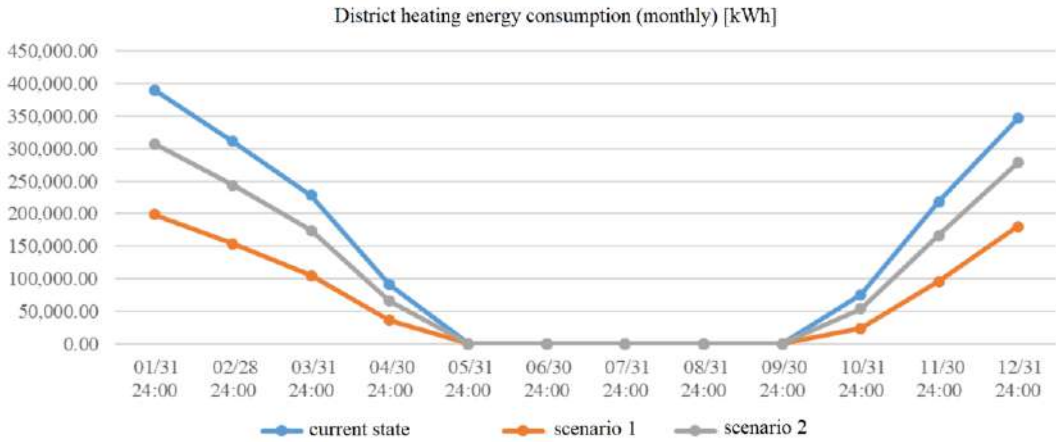

Figure 7 – Comparisons of the district heating energy consumption of the current state and both scenarios

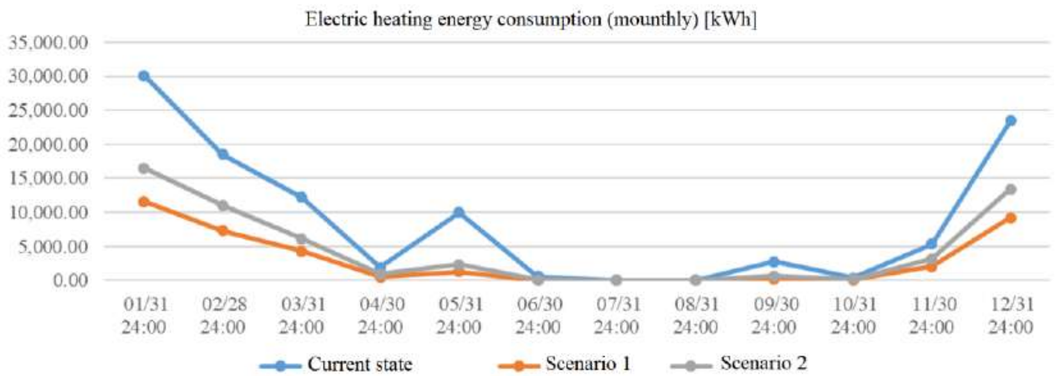

Figure 8 – Comparisons of the electric heating energy consumption of the current state and both scenarios

Table 3 shows the average monthly consumption of different electricity for the current state and both scenarios. The simulations showed that in the improved scenarios only the electricity for heating changes. Electricity consumed for lighting, sanitation and electrical appliances remains the same. In scenario 1 the total average electricity consumption is reduced by 15%, i.e. is 45 kWh hourly, 1 080 kWh daily and 32 875 kWh monthly, i.e. 394 502 kWh per year or 54 kWh/m^2, and in scenario 2 it is 47 kWh hourly, 1 138 kWh daily and 34 624 kWh monthly, i.e. 415 490 kWh annually or 57 kWh/m^2, which is by 11% lower than the existing one (Table 2).

The average electricity consumption for heating in the current state is 12 kWh hourly, 288 kWh daily, 8 762 kWh monthly, i.e. additional heating use is 105 144 kWh annually or 14 kWh/m^2. Scenario 1 shows a drastic reduction of heating electricity by 65%, i.e. 4 kWh hourly, 100 kWh daily and 3 036 kWh monthly, i.e. 36 339 kWh annually or 5 kWh/m^2. Scenario 2 showed a reduction by 51%, i.e. 6 kWh hourly, 149 kWh daily and 4,524 kWh monthly, i.e. 54 285 kWh annually or 7 kWh/m^2 (Table 3). Fig. 8 shows the graphics of the monthly electricity consumption, from which can be concluded that scenario 1 has the lowest consumption, i.e. by 33% lower than scenario 2 and by 65% lower than the current state.

The pollution factor is also included in the simulation, i.e. the CO_2 emissions of the building. Fig. 9 shows the graphic of monthly CO_2 emissions that the building releases in the current state and both improved scenarios) In real conditions, the building emits an average of 144 kg of CO_2 hourly, 3 456 kg daily, and 105 125 kg monthly (Table 3). The highest emission of 572 kg hourly was recorded in December. According to the standards, this building has high CO_2 emission, i.e. in winter season the emissions reaches over 500 kg per hour. The average annual CO_2 emission is 1 261 500 kg. If the limit of 500 000 kg per year is exceeded, it is considered as highly polluting facility, which indicates that the building is highly CO_2 emissive.

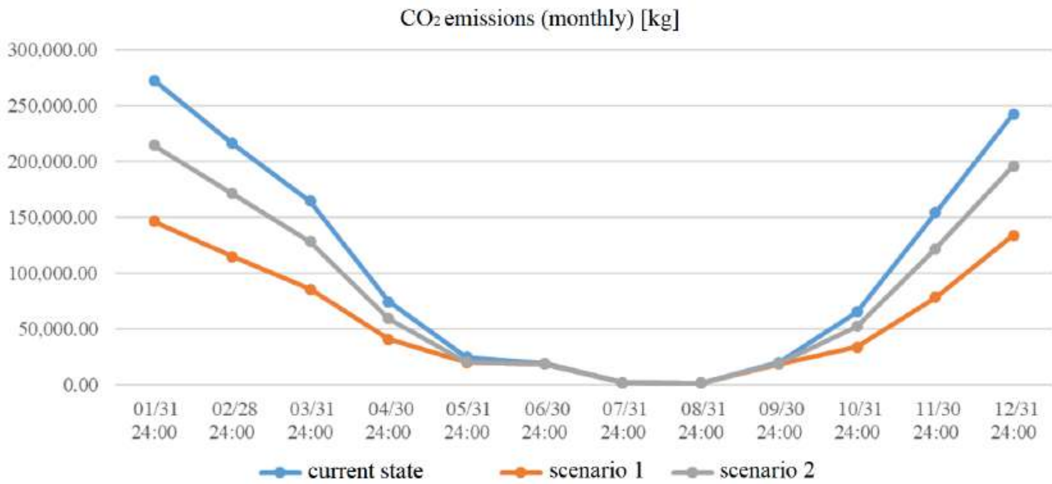

Figure 8 – Comparisons of the monthly CO_2 emissions between the current state and both scenarios

Scenario 1 showed lowest CO_2 emissions with an average of 80 kg hourly, 1 916 kg daily and 58 273 kg monthly, i.e. 699 332 kg annually (Table 3). Emissions in scenario 1 are reduced by 45% compared to the current state. Scenario 2 showed an average emission of 11 kg hourly, 768 kg daily and 84 194 kg monthly, i.e. 1 010 328 kg annually (Table 3). In scenario 2, the emissivity is reduced by 20% compared to the current situation. Fig. 5 shows the graphs of the monthly CO_2 emissions for the three conditions. It can be concluded that scenario 1 has the lowest emissivity with 150 000 kg, scenario 2 with 220 000 kg, and in current state the building emits over 250 000 kg. Scenario 1 has a lower emissivity compared with Scenario 2 by 30% and by 45% compared with the current state.

Table 3 – Average values for heating and electricity energy consumption and CO_2 emissions

Energy consumption and emissions	**Current state**			**Scenario 1**			**Scenario 2**		
	hour	***month***	***year***	***hour***	***month***	***year***	***hour***	***month***	***year***
District heating energy consumption [kWh]	190	4553	138478	91	2177	66237	147	3538	107619
Heating electricty consumption [kWh]	12	288	8762	4	100	3036	6	148	4 524
Sanitary water electricity consumption [kWh]	10	251	763	10	251	7631	10	251	7631
Electricity consumption from appliances [kWh]	21	498	15152	21	498	15152	21	498	15152
Electricity consumption from lightening [kWh]	9	215	6536	9	215	6536	9	215	6536
Total electricity consumption [kWh]	53	1 275	38796	45	1081	32875	47	1138	34624
CO_2 emissions [kg]	144	3 456	105125	80	1916	58273	115	2768	84194

6.2.3. U values of the envelope

Based on the existing data for the structural element's materials of the building envelope, the U values of the current state are calculated, and after that compared with the optimal recommended U values according to today's Rulebook for energy performances of buildings as well as with the simulated U values in the improved scenarios, shown in Table 4.

From Table 4 it can be concluded that there are large differences between the allowed and existing values, as well as the newly acquired values in the improved scenarios, especially in the facade walls. Facade walls in the current state have very high U coefficients, they are made only of rogh exposed concrete without any external protection layers and they have the largest share in reducing the total transmission losses through the envelope. All types of facade walls show a significant decrease in U values, especially in scenario 1, compared to the current (U value of facade wall type 1 in the current state is 2.33 W/m^2K, in scenario 1 - 0.38 W/m^2K and in scenario 2 - 1.54 W/m^2K). This indicates the fact that the improvement of the overall energy performance of the building greatly depends on the thermal insulation of the envelope, especially the exterior facade walls.

Table 4 – U values of the structural elements of the building envelope

Envelope	*U values (current state) [W/m²K]*	*U values (scenario 1) [W/m²K]*	*U values (scenario 2) [W/m²K]*	Max. allowed U values [W/m²K]
Façade wall type 1	2.33	0.38	1.54	0.35
Façade wall type 2	3.93	0.41	2.75	0.35
Façade wall type 3	2.53	0.39	1.66	0.35
Façade wall type 4	4.41	0.42	3.10	0.35
Ground floor slab structure type 1	2.97	0.27	0.27	0.35
Ground floor slab structure type 2	2.55	0.29	0.29	0.35
Slab structure type 3	3.22	0.40	2.74	0.30
Flat roof type 1	0.51	0.13	0.13	0.25
Flat roof type 2	0.50	0.13	0.13	0.25
Windows	5.99	1.4	1.4	2.00

6.2.4. Financial analysis

Finally, financial analysis of the energy consumption costs for district and electrical heating of the current state and both scenarios are made, graphically shown in Fig. 10. From the analysis it can be concluded that the costs in the current state are higher by 35% comparing to Scenario 1 and by 18% to Scenario 2. Scenario 1 has lower costs by 22% from Scenario 2. The highest costs are observed during winter months, while the smallest during summer, which indicates the great need for heating in winter, but also the fact that the dormitory doesn't work in summer.

These analysis show the important role of the thermal insulation not just in improving the energy efficiency of the building by reducing its energy consumption and transmission losses, but also in reducing the financial costs for building maintenance.

6.2.5. Conclusion of the Case Study

Based on the conducted analyzes, it can be concluded that Modernist architecture in Skopje is an endangered cultural heritage whose energy efficiency, sustainability, emissivity and costs need to be improved. From the investigated nanomaterials, the aerogel plaster (scenario 1) and the nano ceramic coating (scenario 2), are materials that leave a minimal impact regarding the authenticity of the buildings. The dynamic energy simulations for the current situation and the two improved scenarios, showed that in the district heating energy consumption analysis, scenario 1 has lower consumption than the current state by 52%, and scenario 2 by 23%. Electricity consumption for heating in scenario 1 is lower by 65%, and scenario 2 by 51% compared to the current state. Scenario 1 has lower CO_2 emissions by 45%, and Scenario 2 by 20% compared to the current state. Finally, the financial costs of the current state are higher by 35% compared to Scenario 1 and 18% compared to Scenario 2. From the energy simulations it can be concluded that Scenario 1 gave better results in terms of thermal insulation properties and energy efficiency, but Scenario 2 has less impact on the authentic appearance of the selected case study building.

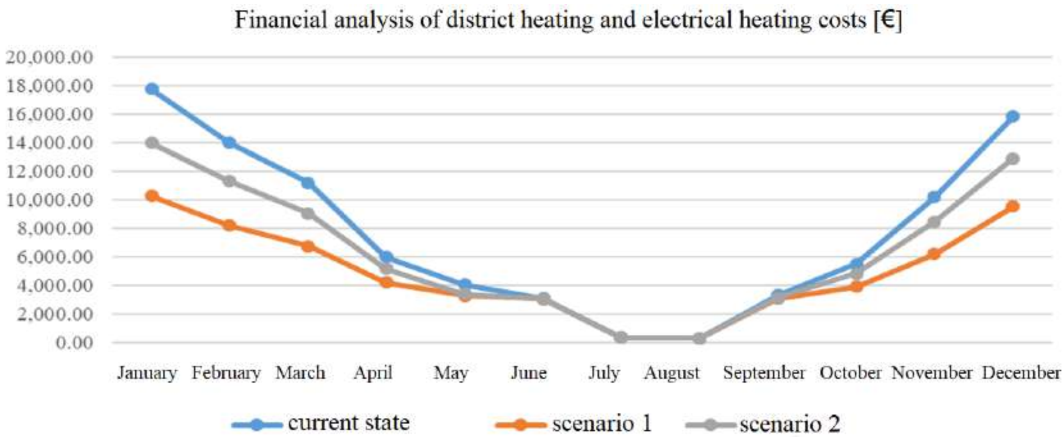

Figure 10 – Comparisons of the cost analysis between the current state and both scenario

7. DISCUSSION AND CONLUSION

Improving the energy efficiency and sustainability of the building stock is critical for meeting EU climate targets. Circular economy (CE), especially in the building sector, strive to reduce the pollution, extend the building's lifespan, reduce the material waste and favour the use of long-lasting building materials and products. Adopting the CE principles in building sector can reduce the quantity of materials used for the renovation of existing buildings, improve their energy performance and sustainability and minimize harmful emissions embodied in building materials.

This lecture aims to show the potential that different aerogel based materials have, because of their excellent thermal properties, low embodied energy and different products and methods of application in the building sector. The analyses of different types of aerogel materials bring the conclusion that the aerogel plaster is the most convenient product according to all of the established criteria. By applying the aerogel thermal plaster, the EE of the of the building will be improved, along with the thermal comfort, sustainability and lifespan. Also, by applying the thermal insulation from the outside, thermal bridges will be eliminated and the façade will be protected from external influences, preventing premature aging and carbonization of the original materials.

By keeping the authenticity, integrity, reversibility and compatibility of the historical building in the process of renovation, together with improvement of the thermal comfort which leads to cutting the buildings emissions for heating and cooling, aerogel thermal plaster application has a great potential in EE, CE and cultural heritage renovation criteria and practices.

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DESIGN OF BUILDINGS WITH PASSIVE HOUSE STANDARD

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Abstract

The biggest challenge of the 21st century in construction sector is how to use energy and other non-sustainable resources more efficiently and how to reduce waste, pollution and environmental degradation at once. New construction concepts, new construction materials in combination with facilities for energy productions from renewable resources allow creating new sustainable buildings.

The Passive House Standard is a voluntary, performance-based standard for energy efficiency in buildings, focusing on reducing heating and cooling demand to a minimum while maintaining high indoor comfort. Designing buildings according to this standard involves a comprehensive approach that includes architectural form, orientation, insulation, airtightness, and mechanical ventilation with heat recovery.

The building envelope directly affects the building energy consumption. In order to define the time dependent thermal losses through the building envelope, a computer simulation is recommended at the beginning stages of design planning. This lecture presents the numerically achieved results for the influence of the type and the position of the thermal insulation of the building on the heat loss and energy consumption of the building.

Keywords: *Passive House Standard, thermal insulation, building envelope, heat transfer, energy consumption*

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1. INTRODUCTION

As the global construction sector faces increasing pressure to reduce energy consumption and mitigate climate change, energy-efficient building design has emerged as a central focus of sustainable development strategies. Buildings are responsible for approximately 36% of greenhouse gas emissions and 40% of energy use in the European Union, making them one of the largest contributors to environmental degradation (European Commission, 2021). In response to these challenges, the Passive House Standard—also known as Passivhaus—offers a rigorous and scientifically grounded approach to reducing the energy demand of buildings without compromising indoor comfort, health, or functionality.

Developed in the early 1990s by Dr. Wolfgang Feist and the Passive House Institute (PHI) in Germany, the Passive House concept is based on a set of strict performance criteria, including ultra-low space heating and cooling demand, high airtightness, and minimal primary energy consumption. Rather than relying on conventional heating and cooling systems, passive houses maintain a stable and comfortable indoor environment through passive design strategies such as superinsulation, thermal bridge-free construction, high-performance windows, and mechanical ventilation with heat recovery.

What sets the Passive House Standard apart from other green building frameworks is its quantitative, performance-based nature. All design aspects must be modeled and verified using the Passive House Planning Package (PHPP) to ensure compliance. The result is a building that consumes up to 90% less energy for heating and cooling compared to conventional buildings, while providing consistent indoor temperatures, excellent air quality, and significant long-term cost savings.

This lecture explores the key principles, design strategies, materials, and benefits of passive house construction, as well as its role in advancing sustainable architecture. By examining both the technical and practical dimensions of Passive House design, the paper aims to demonstrate its relevance as a high-impact solution for energy-efficient and climate-resilient buildings in both new construction and retrofit contexts.

2. PRINCIPLES OF PASSIVE HOUSE DESIGN

The Passive House Standard represents one of the most effective solutions for achieving ultra-low-energy buildings without compromising comfort. Through a combination of insulation, airtight construction, heat recovery ventilation, and strategic design, passive houses demonstrate that it is possible to drastically reduce energy use while enhancing occupant well-being. A building to meet the Passive House Standard must adhere to specific performance criteria:

- Annual heating and cooling demand: ≤ 15 kWh/m²a
- Primary energy demand (including domestic appliances): ≤ 60 kWh/m²a
- **Airtightness**: ≤ 0.6 air changes per hour at 50 Pa pressure (n50)
- **Thermal comfort**: No significant overheating (>25°C for more than 10% of the occupied time)

To meet these targets, passive house design is based on five fundamental principles (Figure 1):

- High-Performance Insulation

High levels of insulation are applied continuously around the building envelope, including walls, roofs, and floors. The goal is to minimize heat loss in winter and reduce heat gain in summer. Insulation materials with low thermal conductivity (λ-value) are chosen to achieve a U-value typically below 0.15 W/m²K.

- Thermal Bridge-Free Construction

Thermal bridges are areas in the building envelope where heat is transferred at a faster rate. Thermal bridges must be avoided or minimized. Special attention is paid to corners, wall-roof connections, and window installations to ensure continuity of insulation and prevent condensation and energy loss.

- Airtight Building Envelope

An airtight construction is essential to control ventilation and avoid uncontrolled air leakage, which leads to energy loss. The airtightness is verified through a blower door test. Materials such as membranes, tapes, and seals are used to ensure continuity of the air barrier throughout the envelope.

- High-Performance Windows and Glazing

Windows in a passive house must be triple-glazed with low-emissivity (low-e) coatings and insulated frames to minimize heat loss. They also play a critical role in solar gain, especially in cold climates. Proper orientation and shading devices are used to optimize solar benefits and avoid overheating.

- Mechanical Ventilation with Heat Recovery (MVHR)

A balanced mechanical ventilation system with heat recovery is essential in passive houses. The MVHR unit extracts heat from outgoing stale air and transfers it to incoming fresh air, maintaining indoor air quality and thermal comfort with minimal energy input.

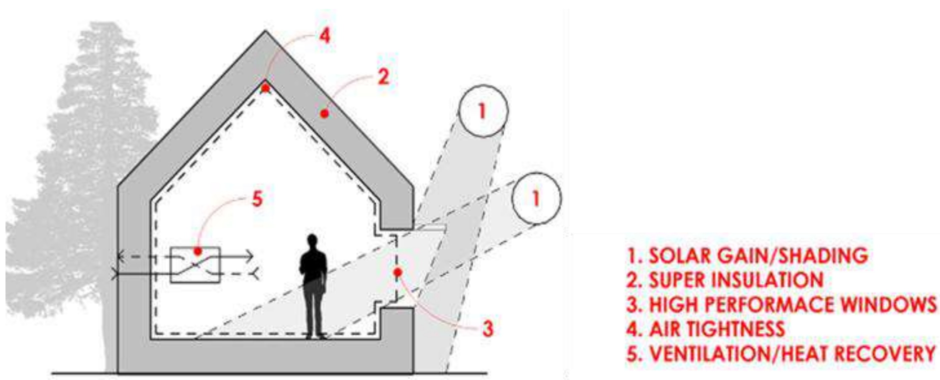

Figure 1 - Five principles of Passive House design

3. DESIGN CONSIDERATIONS AND STRATEGIES

Achieving passive house certification requires an integrated design process involving architects, engineers, and energy consultants from the early stages. Several strategies must be carefully considered:

- Site Selection and Building Orientation

The building should be positioned to maximize solar exposure, particularly on the south-facing facade in the northern hemisphere. Proper orientation reduces heating demand and improves daylight availability (Figure 2).

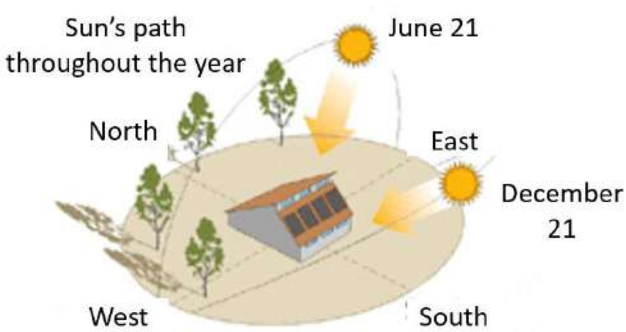

Figure 2 - Building orientation for Passive House design

- Compact Building Form

A compact form (low surface-to-volume ratio) minimizes exposed surface area, reducing heat loss. Simple geometries with fewer external corners and articulations are more efficient from an energy standpoint (Figure 3).

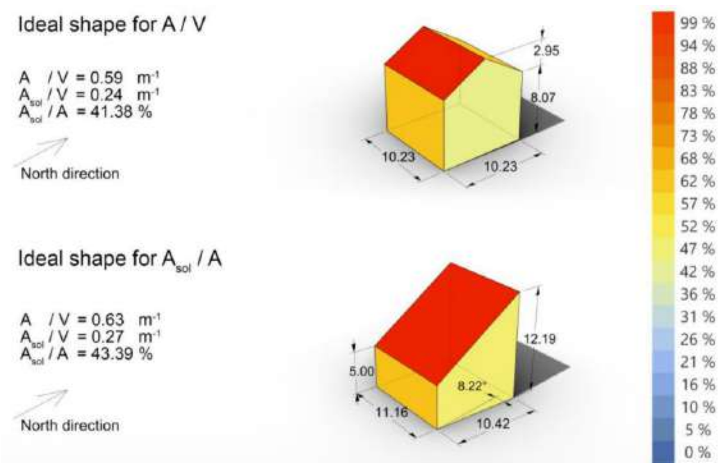

Figure 3 - Top: ideal shape for surface-area-to-volume ratio; bottom: shape optimised simultaneously for both indicators, A/V and Asol/V (Hajtmanek et al., 2023)

- **Optimized Window Placement**

South-facing windows are prioritized for solar gain, while north-facing windows are minimized to reduce heat loss. East and west windows are carefully managed to avoid glare and overheating.

- **Shading and Solar Control**

Overhangs, shutters, blinds, and vegetation are used to prevent summer overheating. Dynamic shading systems may be employed for adaptive comfort and daylight control.

- **Thermal Mass Integration**

Although not required, thermal mass (e.g., concrete floors or internal masonry walls) can be beneficial in moderating indoor temperatures by absorbing and releasing heat slowly.

4. MATERIALS AND CONSTRUCTION SYSTEMS

Selecting appropriate materials and construction systems is crucial for meeting passive house criteria:

- **Wall systems**: Timber frame with high-performance insulation, insulated concrete forms (ICFs), or masonry with external insulation systems.
- **Insulation**: Materials such as mineral wool, cellulose, wood fiber, or expanded polystyrene (EPS) are used, with thicknesses ranging from 200 mm to 400 mm, depending on the climate zone.
- **Windows**: Certified passive house windows with thermal breaks and triple glazing are a prerequisite.
- **Roof and floor assemblies**: Well-insulated and carefully detailed to avoid thermal bridges.

Attention to construction quality and airtightness detailing during execution is critical. Contractors must be trained in passive house construction methods to achieve the required performance standards. Materials are selected based on performance and sustainability. Examples of wall assemblies for Passive House Construction are given in Table 1.

Table 1: Example Wall Assemblies for Passive House Construction

Wall Type	U-Value (W/m²K)	Typical Insulation Thickness
Timber frame + cellulose	0.12	300 mm
Masonry + EPS	0.14	250 mm
CLT + mineral wool	0.15	300 mm

Some typical wall assemblies include:

- Timber-frame with cellulose or mineral wool insulation
- Masonry walls with external insulation systems (ETICS)
- Cross-laminated timber (CLT) in modern passive buildings

5. CERTIFICATION AND TOOLS

Buildings can be certified under the **Passive House Institute (PHI)** or **PHIUS (Passive House Institute US)** depending on the region. Certification involves:

- Design modeling using the **Passive House Planning Package (PHPP)** or other approved tools.
- Construction oversight and quality assurance.
- Blower door testing to confirm airtightness.
- Commissioning of mechanical systems.

The PHPP is a reliable, spreadsheet-based tool used to simulate energy balance and optimize the design parameters to ensure compliance with passive house requirements.

6. BENEFITS, CHALLENGES AND LIMITATIONS

Designing buildings to the Passive House Standard offers several long-term benefits:

- **Drastic reduction in energy consumption**, often up to 90% less than conventional buildings.
- **High indoor air quality** due to continuous ventilation with filtered air.
- **Thermal comfort** with consistent indoor temperatures year-round.
- **Durability and resilience**, especially in the face of future energy crises or climate change.
- **Operational cost savings** through reduced utility bills.
- **Contribution to climate goals** by lowering carbon emissions from the building sector.

While initial investment costs may be slightly higher, the life-cycle costs are significantly lower due to reduced energy use and maintenance.

Despite its advantages, passive house design faces some challenges:

- **Higher upfront costs**, especially for components like triple-glazed windows and MVHR systems.
- **Limited contractor experience** in some regions.
- **Design limitations** due to the need for compact forms and specific orientation.
- **Climate dependency**, requiring adaptation of the standard for very hot or humid regions.

These limitations can be addressed through proper training, incentives, and growing market demand, which is gradually driving down costs and increasing availability of passive house components.

7. CASE STUDY FOR ACHIEVING THE PASIVE HOUSE STANDARD

Appropriate planning, anticipation of all the steps and taking into account the exact entry parameters is an extremely important during the design and the calculation procedure of the passive houses. The entry data that has to be defined as first are: type and purpose of the building; internal design temperature (20ºC); number of inhabitants; calculation method (monthly or annual method); location (climate conditions); existence of surrounding buildings (Bahr et al., 2012). The next step is determination of: areas and their functions; U-values of the different parts of the building envelope; emission balances, thermal bridges; as well as energy demands for heating and cooling defined in Standards.

The basic assessment criteria whether the building meets the standard "passive house" or not, are as follows: specific energy demands for heating /cooling (Q_{SH} / Q_{SC}) [≤15kWh/(m^{2}a)], or alternative: heating/cooling load (HL)/(CL) [≤ 10W/m^2]; air impermeability [η_{50} ≤ 0.6 h^{-1}]; specific primary energy demand (Q_{SP}) [≤ 120 kWh/(m^{2}a)] (Andreev, 2013). In addition to these basic criteria, there are several criteria which are also important, especially from the economical aspect and the exploitation costs of the building, such as: frequency of overheating of the building ($h\varphi$) [≤ 10%]; the ability of the ventilation system to distribute the required quantity of heat (P_H) and the emission of CO_2.

This lecture deals with the influence of some of the basic parameters on the evaluation criteria for Passive House standard. The orientation of the passive house and the thickness of the thermal insulation of the roof, ground and in façade walls were varied and the influence of these four parameters was analyzed.

In order to obtain complete analysis there is a need to track and vary some more parameters, as: percentage and position of the glazed surfaces on the facade; the type of the window glass; the type of the window frames; the position of the windows in the wall; shading from structural elements; an additional shading in summer; the size and number of solar panels for hot water; the technical solutions for the use of sanitary hot water. All these parameters were subject of the complete research (Andreev, 2013), but only the effects of the window parameters are presented in this paper.

The calculations are based on the methods of thermodynamics, using Macedonian MKS EN and DIN standards, and program packages PHPP 2007, HEAT2 and NOVOLIT.

7.1. Basic data of the analyzed building

The macro location of the building falls in the eastern part of Macedonia, at an altitude of 600m and is located on a plateau (Andreev, 2013). The front facade of the building is pure southern orientation, and the entrance is on the north side. The architecture of the house has been taken from the famous house of Franz Freundorfer (Figure 4). The building is located in “ideal” conditions in order to make further variations and parametric analysis. The building consists of the ground-floor rooms, first floor and under roof space.

The ground floor is intended for daily living, while the first floor is designed for sleeping and resting. The under roof space is designed to accommodate mechanical equipment. For the analysis, the construction materials used in this paper differ from the ones in the original building, and are specific to the construction market in Macedonia.

Façade walls with thickness of 50 cm are equal on all sides of the building and their composition is: gypsum cardboard sheets on metal sub construction d=12,5 mm; rock wool d=50mm with λ=0,045 W/(mK), gypsum plaster d=17mm with λ=0,510 W/(mK), masonry blocks from “Itong” d=250 mm with λ = 0,160 W/(mK), gypsum lime mortar d=17mm with λ = 0,700 W/(mK), 5 mm glue for thermal insulation, thermal insulation d=150 mm with λ=0,024 W/(mK), glue and smoothing mass 5mm, 3mm final mortar.

Figure 4. Ground floor and first floor of the building

The roof structure is reinforced concrete slab MB30, with two eaves and pent house on all sides of the building. The composition of the roof is: gypsum cardboard sheets on metal sub construction d=12,5 mm; rock wool d=50mm with λ=0,045 W/(mK), reinforced concrete slab MB30 d=100mm with λ=2,3 W/(mK), thermal insulation d=150mm with λ=0,024 W/(mK), sheath of wooden boards d=22mm with λ=0,24 W/(mK), 3 mm vapor barrier, double stripping for clay cover sheaths. The ground floor was placed directly on earth and around the building a route horizontal intermediate plate from extruded polystyrene was set. The composition of the floor was: floating floor base 30 mm, rock wool 20 mm with λ=0.038 W/(mK), 350 mm reinforced concrete slab MB30 with λ = 2.3 W/(mK), 340 mm thermal insulation with λ = 0.038 W/(mK), 8 mm waterproofing layer with λ = 1.2 W/(mK), concrete foundation 100 mm.

The windows are selected from the list of certified passive house windows (Arasteh et al., 2007) as follows: frame W Internorm-passiv Fixverglasung with distancer 'Thermix'; Glass INTERPANE - iplus 3E (4:/14/4/14/:4 Argon 90%). During the process of defining the surfaces, despite their purpose, the following values and information are defined: thermal envelope/Unit (line of balance) and Net useful (treated) area (TFA - Treated Floor Area). The calculation of the areas covered: all net living areas with heights over 2m, areas with heights from 1m to 2 m were calculated with 50%, non leaving areas (basement, machine rooms and storage) with height above 2 m, were calculated with 60%.

7.2. Parametric analysis on the Passive House

The calculation of the passive house was made with the software package PHPP 2007 (Darmstadt, 2012). Dimensions of the insulation, windows and all other elements were defined to meet the criteria for a passive house and in same time to be as close as possible to the limit values for the Passive House (PH) standard. Comparison of the final calculation results with the maximum values defined by the Passive House standard is presented in Table 2.

The calculation results clearly show that the ventilation system can not deliver the necessary heat, so there is a need somewhere in the house to place an additional heating device which will produce an additional 171 W. In the summer period there is no need of cooling compressor, but opening of the windows is required at night. Emissions of carbon dioxide from the heating system is 9 kg/(m^{2}a) while the total emission is 19 kg/(m^{2}a).

Table 2. Comparison of calculation results from PHPP 2007 and standard values

Criteria	Symbol	Unites	Design value	Max. value (standard)	criteria satisfied?
Specific energy heating demand	Q_{SH}	kWh/(m^{2}a)	14	15	Yes
Specific primary energy demand	Q_{SP}	kWh/(m^{2}a)	78	120	Yes
Heating load	HL	W/m^2	10	10	Yes
Cooling load	CL	W/m^2	7	10	Yes
Frequency of overheating	h_φ	%	4	10	Yes

7.3. Impact of windows area

The windows are part of the thermal envelope of the building and therefore their impact on total energy demand is high. It is even more apparent in case of passive houses, because despite the need for good heat insulation properties, the use of energy from the sun in winter is of exceptional importance. To provide the necessary solar gains in house, the solar factor or permeability of the light glazing becomes crucial for overall energy needs, but also the risk of overheating is high in summer. Because of these facts, the windows are a key element in achieving the passive house standard.

For the purposes of this paper and for more detailed analysis of the impact of the glazed surfaces on the energy demands of the building, variations in percentage of the window area separately on each facade and on the whole building were made.

According to the design data, on the south side of the building the total window area is 26,63 m^2, on the north side it is 3,46 m^2, on the east side it is 8,21 m^2 and on the west side it is 6,55 m^2. The total design window area for the entire building is 44,85 m^2.

For the purposes of this analysis, the window area on each façade separately and on the whole building first was increased by step of 25 % up to 100% and then decreased by step of 25 % up to complete elimination of the windows. In all these cases the following parameters were analyzed:

- specific energy demand for heating (Q_{SH}),
- specific energy demand for cooling (Q_{SC}),
- specific energy demand for primary energy (Q_{SP}),
- heating load (HL), cooling load (CL),
- thermal energy to be submitted through the ventilation system (PH),
- frequency of overheating (h_{φ}) and
- emission of carbon dioxide (CO_2).

For each of the analyzed variations the calculation results were obtained by the computer program PHPP 2007. Some of the results are presented in: Table 3 for south orientation of the windows, Table 4 for the east orientation of the windows and Table 5 for the whole building.

Table 3. Effects of window's area variations on the south facade

Criteria	Q_{SH}	Q_{SC}	Q_{SP}	HL	CL	P_H	h_ϕ	CO_2^{QSH}	CO_2^{QSP}
	kWh/(m²a)	kWh/(m²a)	kWh/(m²a)	W/m²	W/m²	W	%	kg/(m²a)	kg/(m²a)
Prescribed value	15		120	10	10	/	10	/	/
Designed	13,93	9,36	77,74	10,06	6,76	1524	3,62	8,88	19,35
Without	18,41	6,58	81,16	8,90	3,18	1348	0	9,67	20,13
75% less	21,88	6,96	84,95	10,03	3,19	1519	0	10,53	21,00
50% less	19,45	8,09	82,64	10,12	4,21	1532	0	10,00	20,47
25% less	16,54	8,94	79,99	10,10	5,46	1530	0,62	9,40	19,87
25% more	11,74	9,47	75,94	10,02	8,08	1517	8,83	8,46	18,94
50% more	10,05	9,39	74,61	9,97	9,32	1510	12,61	8,16	18,64
75% more	8,51	9,22	73,41	9,92	10,74	1502	14,12	7,88	17,80
Double	7,35	9,01	72,53	9,86	12,08	1494	15,40	7,68	18,16

Table 4. Effects of window's area variations on the east facade

Criteria	Q_{SH}	Q_{SC}	Q_{SP}	HL	CL	P_H	h_ϕ	CO_2^{QSH}	CO_2^{QSP}
	kWh/(m²a)	kWh/(m²a)	kWh/(m²a)	W/m²	W/m²	W	%	kg/(m²a)	kg/(m²a)
Prescribed value	15		120	10	10	/	10	/	/
Designed	13,93	9,36	77,74	10,06	6,76	1524	3,62	8,88	19,35
Without	13,98	6,57	77,58	9,77	4,59	1480	0	8,84	19,32
75% less	14,63	7,00	78,25	10,04	4,80	1521	0	9,00	19,47
50% less	14,45	7,81	78,13	10,06	5,44	1524	0,41	8,97	19,44
25% less	14,19	8,59	77,94	10,06	6,09	1524	1,16	8,92	19,40
25% more	13,67	10,09	77,55	10,06	7,42	1523	5,51	8,83	19,31
50% more	13,42	10,80	77,37	10,05	8,08	1522	11,97	8,79	19,27
75% more	13,18	11,48	77,19	10,04	8,75	1521	13,21	8,75	19,23
Double	12,94	12,14	77,02	10,04	9,41	1520	12,98	8,71	19,19

Table 5. Effects of window's area variations on all four facades of the house

Criteria	Q_{SH}	Q_{SC}	Q_{SP}	HL	CL	P_H	h_ϕ	CO_2^{QSH}	CO_2^{QSP}
	kWh/(m²a)	kWh/(m²a)	kWh/(m²a)	W/m²	W/m²	W	%	kg/(m²a)	kg/(m²a)
Prescribed value	15		120	10	10	/	10	/	/
Designed	13,93	9,36	77,74	10,06	6,76	1524	3,62	8,88	19,35
Without	18,97	1,13	81,31	9,74	0,48	1225	0	9,70	20,17
75% less	23,78	1,92	86,77	9,94	0,80	1496	0	10,95	21,41
50% less	20,92	5,39	83,94	9,99	2,58	1517	0	10,30	20,77
25% less	17,16	7,97	80,49	10,06	4,67	1524	0	9,51	19,98
25% more	11,48	10,25	75,82	10,08	9,00	1527	12,74	8,43	18,91
50% more	9,70	10,67	74,47	10,09	11,09	1528	14,48	8,12	18,60
75% more	8,21	10,89	73,35	10,08	13,37	1527	22,67	7,86	18,35
Double	7,15	11,05	72,57	10,08	15,57	1526	26,79	7,68	18,17

The calculation results showed that the energy demand for heating is most sensitive to changes in the percentage of window area on the south facade. When the window area on the south facade is increased, the Specific energy demand for heating is reduced and opposite. All other facades have negligible effect, and the north facade has negligible, but opposite effect (Figure 5). The energy demand for cooling is most sensitive to changes in the percentage of window area on the east facade.

When the window area on the east facade is decreased, the Specific energy demand for cooling is reduced and opposite. All other facades have less, but not negligible effect (Figure 6).

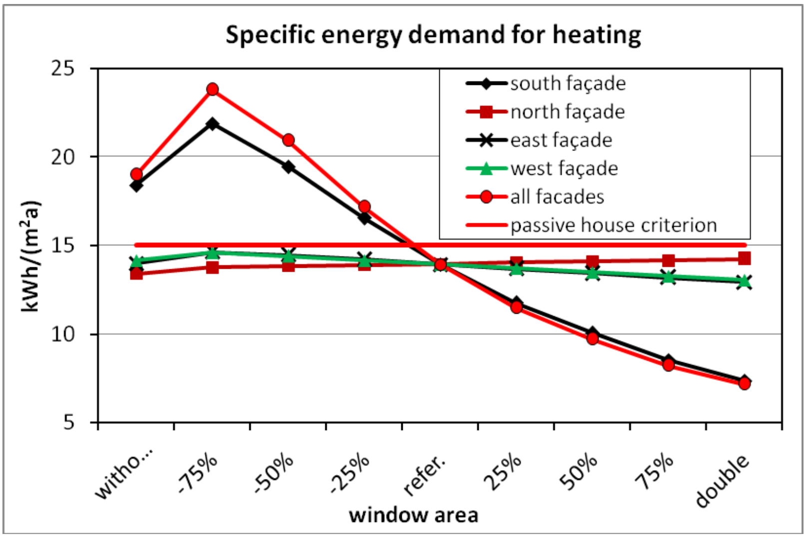

Figure 5. Effects of window's area variations on Specific energy demand for heating

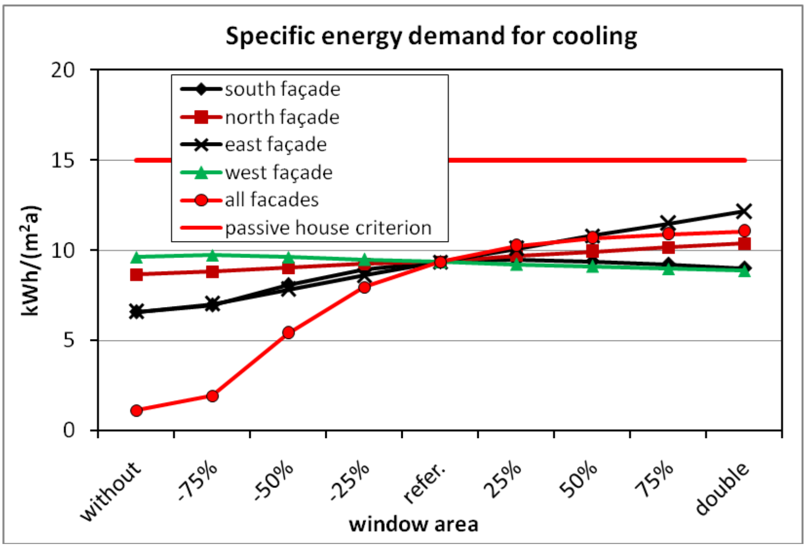

Figure 6. Effects of window's area variations on Specific energy demand for cooling

7.4. Influence of windows frames and type of glass

In addition to variations of window area on different facades of the building, the type of glass and the type of the frame were varied and the results of the analysis are presented in this paper. For that purpose combinations of frames and glass which are characteristic for the building tradition in North Macedonia were used. It was assumed that the built in windows were made identically as for windows of passive house, which means thermal bridges were eliminated. The following combinations were analyzed:

- Windows with wooden frame d = 48 mm (U_f=2,50 W/m^{2}K), glazed with single glass (U_g=5,80 W/m^{2}K and g=0,87) ;
- PVC frame windows with d=72 mm (U_f=2,20 W/m^{2}K), with double glazed glass 4+12 (air) +4 (U_g=2,90 W/m^{2}K and g=0,77)
- PVC frame windows with d=98 mm (U_f=1,60 W/m^{2}K), with double glazed glass 4+16 (90 % argon)+4, PVC spacer with thermal bridges factor ψ=0,05 W/(mK) (U_g=1,20 W/(m^{2}K) and g=0,60).

For that purpose the computer program PHPP 2007 was used and the calculation results are presented Table 6.

Table 6. Influence of the window's frame and the type of glass

Criteria	Q_{SH}	Q_{SC}	Q_{SP}	HL	CL	P_H	h_ϕ	CO_2^{QSH}	CO_2^{QSP}
	kWh/(m^{2}a)	kWh/(m^{2}a)	kWh/(m^{2}a)	W/m^2	W/m^2	W	%	kg/(m^{2}a)	kg/(m^{2}a)
Prescribed values	15		120	10	10	/	10	/	/
Design values	13,93	9,36	77,74	10,06	6,76	1524	3,62	8,88	19,35
Single glass with wooden frame	91,62	23,63	164,6	37,38	9,46	5663	1,56	28,74	39,21
PVC frame with double glazed glass	53,29	18,51	120,9	24,35	8,46	3689	1,52	18,77	29,23
PVC frame with double glazed glass with argon	30,58	12,82	95,37	15,81	6,63	2394	0,92	12,91	23,38

7.5. Building orientation influence

The orientation of the building plays an extremely important role in the final balance of energy gains and losses, because windows with south orientation contribute to reduction of the energy demand for heating, while windows on the north side have no contribution to gains, but in opposite - the losses are increased. However, during summer, the southern windows contribute to overheating of the building and hence to energy demands for cooling the building. To prevent overheating there are effective and relatively inexpensive measures for summer shading.

The windows on the east and west sides of the building make significant contribution to the needs for heating of the building in winter, but they are unsuitable for use in the summer because seriously contribute to overheating. The measures for their shading are either extremely expensive or not effective. The orientation of the walls has no impact on energy balance, due to the large thickness of insulation in them.

The influence of orientation of the house, presented in this paper, is based on analysis of several parameters. For that purpose the initial orientation of the house was rotated by steps of 30° clockwise and the results of PHPP 2007 for each of the defined positions of the house are presented in the Table 7.

Table 7. Building orientation influence on achievement the Passive House standard

Description	Specific energy demands			Load		Frequen. of overheat.	CO_2 emision	
	heating	cooling	primary energy	heating	cooling		without equipem.	Total
Symbol	Q_{SH}	Q_{CS}	Q_{SP}	HL	CL	h_{φ}	CO_2^{Qsh}	CO_2^{Qsp}
Unites	kWh/(m²a)			W/m²		%	kg/(m²a)	
Prescribed values	15		120	10	10	10	/	/
Design values	13.93	9.36	77.74	10.06	6.76	3.62	8.88	19.35
Rotation 30°	14.57	11.22	78.33	10.22	7.87	6.11	9.01	19.49
Rotation 60°	16.34	14.93	79.96	10.46	8.56	12.97	9.39	19.86
Rotation 90°	18.26	17.20	81.78	10.65	10.03	11.90	9.80	20.28
Rotation 120°	20.02	16.68	83.47	10.75	8.96	9.89	10.19	20.66
Rotation 150°	21.41	14.99	84.84	10.78	7.55	4.10	10.51	20.97
Rotation 180°	22.92	13.85	86.36	10.94	6.61	1.83	10.85	21.32

7.6. Influence of thermal insulation thickness

For the purposes of this analysis, the thickness of the insulation in all elements first was increased by 25% from the initial design value until doubling the thickness was reached, and then decreased by 25% until complete elimination of insulation was reached. The results of PHPP 2007 for each variation are sorted and presented in Table 8. The calculations were also made for individual variations, as well as with the same ratio of increase and decrease of the insulation (25%) (facade walls, floor and roof). The results for façade walls are presented in Table 9.

The influence of the thermal insulation thickness variations on specific energy demand for heating is presented in Figure 7 and the influence of the variation of the thermal insulation thickness on specific primary energy demand is presented in Figure 8.

Table 8. Influence of thermal isolation thickness in building envelope

Description	Specific energy demands			Load		Freq. of overheat.	CO_2 emision	
	heating	cooling	primary energy	heating	cooling		without equipem.	Total
Symbol	Q_{SH}	Q_{CS}	Q_{SP}	HL	CL	h_{φ}	CO_2^{Qsh}	CO_2^{Qsp}
Unites	kWh/(m²a)			W/m²		%	kg/(m²a)	
Prescribed values	15		120	10	10	10	/	/
Design values	13.93	9.36	77.74	10.06	6.76	3.62	8.88	19.35
No isolation	310.67	0.00	415.63	97.44	0.00	0.00	86.08	96.54
Decreased 75%	57.55	12.27	125.62	24.04	5.13	0.00	19.83	30.29
Decreased 50%	30.27	12.03	95.04	15.58	6.19	0.62	12.84	23.30
Decreased 25%	19.48	10.63	83.43	12.04	6.57	2.15	10.18	20.65
Increased 25%	10.67	8.33	74.56	8.80	6.87	4.54	8.15	18.63
Increased 50%	8.59	7.53	72.62	7.92	6.95	5.20	7.70	18.18
Increased 75%	7.17	6.90	71.35	7.28	7.00	5.81	7.41	17.89
Increased 100%	6.16	6.40	70.47	6.78	7.05	6.96	7.21	17.69

Table 9. Influence of thermal isolation thickness in facade walls

Description	Specific energy demands			Load		Freq. of overheat	CO_2 emision	
	heating	cooling	primary energy	heating	cooling		without equip.	Total
Symbol	Q_{SH}	Q_{CS}	Q_{SP}	HL	CL	h_{φ}	CO_2^{Qsh}	CO_2^{Qsp}
Unites	kWh/(m²a)			W/m²		%	kg/(m²a)	
Prescribed values	15		120	10	10	10	/	/
Design values	13.93	9.36	77.74	10.06	6.76	3.62	8.88	19.35
No isolation	59.35	16.35	127.71	25.30	6.97	0.53	20.30	30.77
Isolation 50mm	29.91	13.02	94.67	15.70	6.84	1.43	12.75	23.22
Isolation 100mm	20.73	11.21	84.75	12.56	6.79	2.56	10.48	20.95
Isolation 150mm	16.40	10.10	80.24	11.00	6.77	3.21	9.45	19.92
Isolation 250mm	12.35	8.83	76.18	9.44	6.75	3.90	8.52	19.00
Isolation 300mm	11.26	8.44	75.12	9.00	6.74	4.11	8.28	18.75
Isolation 350mm	10.47	8.14	74.36	8.66	6.74	4.27	8.10	18.58
Isolation 400mm	9.86	7.90	73.79	8.40	6.73	4.40	7.97	18.45

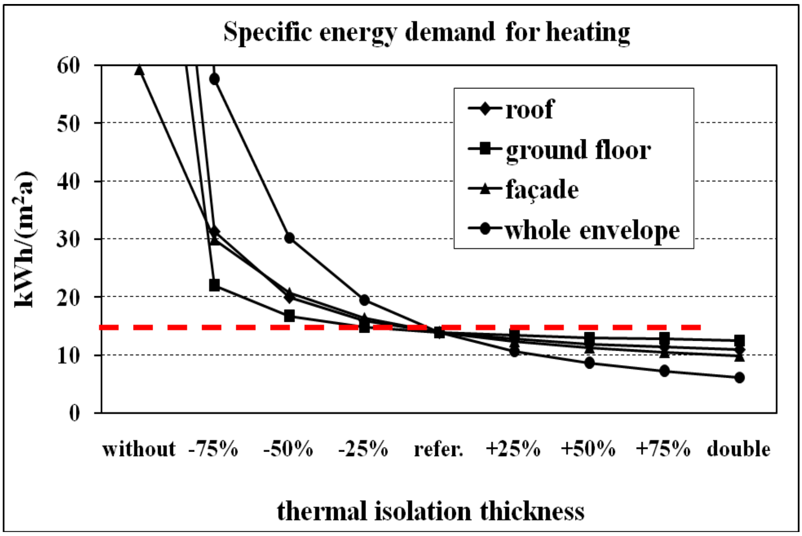

Figure 7 - Influence of thermal insulation thickness on specific energy demand for heating

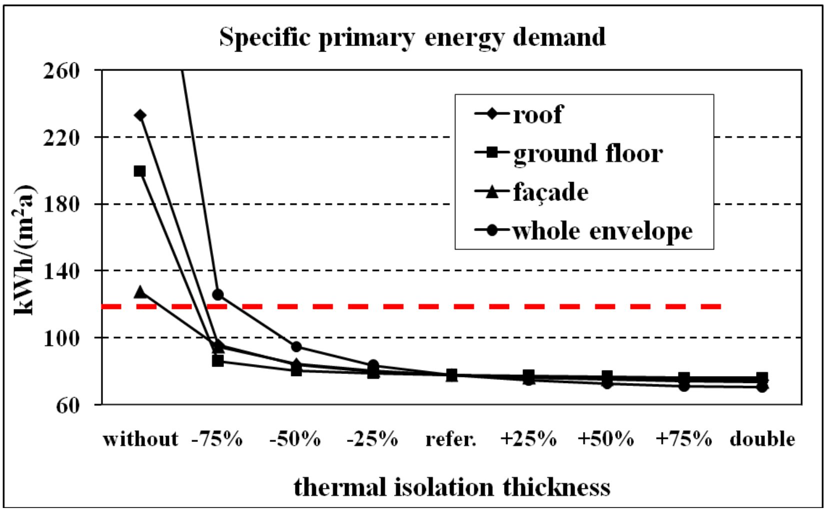

Figure 8 - Influence of thermal insulation thickness on specific primary energy demand

7.7. Conclusions of the Case Study

With the radical changes in urban development, i.e. in the way the buildings are designed, constructed and renovated, significant impact can be made in the reduction of energy needs and the use of renewable energies, and thus in creating a sustainable future for the buildings and cities.

The orientation of the building has direct impact on the energy balance of the passive building. The results show that the building orientation of ± 30° has minimal impact on the demand for energy for heating or the most up to 5%. Further rotation of the building shows far greater impact on energy demand for heating with a growth of about 7% for every additional 30° rotation. The reason for this change is to reduce the exposure of the windows to the southern sun rays, thus reducing solar heat gains.

The orientation of the building has a great impact on energy demand for cooling. The reason for this is the exposure of significant area of windows on the south side to the sun rays, when it is rotated by more than ± 30°. Accordingly, the extended rotation to the north side, i.e. for rotations of more than ± 120° a decrease of energy demand for cooling appears. The rotation of the building to ± 30° from the north-south orientation makes small and insignificant impacts on energy demand for cooling, and thus over the necessary financial means to achieve the Passive House standard. Larger deviations have a serious impact on energy demand for cooling. Good insulation in walls doesn't allow cooling of the building during the night but therefore requires more energy to cool the building.

The orientation itself has a profound effect on overheating the building. Unlike the energy needs for heating and cooling, even the slightest deviation on axis from north-south, the increase in overheating is high. For deviations up to ± 30 °, an increase in the frequency of overheating is even 50%. Maximum frequency of overheating is reached when deviations from the north-south axis are between ± 60 ° and ± 90° and can reach overheating of 2.2 times greater than projected ones. Therefore, it is necessary to apply measures for summer shading on windows (eaves that protect from the summer sun and allow winter sun lighting, various blinds and even deciduous trees).The emission of CO_2 is proportional to the increase in energy consumption for heating / cooling and total primary energy. The CO_2 emissions can vary due to the orientation of the building up to 22% (out of the energy consumed without household appliances) or up to 10% (of total energy consumed).

In order to better understand the influence of the changes in the thickness of the insulation, many combinations have been analyzed in this paper, such as different thickness of the thermal isolation in the roof; to the ground, in the façade walls and in the whole envelope. By analyzing the results it is obvious that the slightest impact on energy demand for heating has insulation in the floor slab, and the most effective is the insulation of the facade. Increasing the thickness of the insulation more than it is recommended (i.e. an increase of the U-value of elements) has no major contribution to the reducing of the energy demands and represents an economically non profitable investment.

In opposite, the reduction of the insulation of the elements drastically affects energy demand for heating, so that the least cuts in insulation within any of the building elements will pass the limit 15 kWh/(m^2a). Opposite of the energy demands for heating, the thermal insulation of the building envelope has insignificant impact on energy demand for cooling. The thermal insulation of the building envelope makes almost no impact on energy demand for cooling.

Contrary to expectations, the overheating decreases with decreasing the insulation and increases with increasing the insulation. This is due to the fact that with reduction of the insulation, the thermal capacity of the elements is proportionally decreased and in case of less insulation the cooling of the building grows faster during the nights. And vice versa the greater insulation prevents nighttime cooling of the building, which contributes to higher overheating. The emission of CO_2 is proportional to the increase of energy consumption for heating / cooling.

The orientation of the building plays an extremely important role in the final balance of profit and loss, because the southern orientation of windows contribute to reducing energy demand for heating, while windows on the north side have no contribution to gains, but the opposite - the losses are increased. The analysis confirmed that the greatest impact on the energy demand for heating has the window area located on the south side of the building. It appears that the design should anticipate as large window area with this orientation as it is possible. However, during summer, the southern windows contribute to overheating of the building and hence the energy demand for cooling increases. To prevent overheating there are effective and relatively inexpensive measures for summer shading.

The windows on the east and west sides of the building make significant contribution to the needs for heating of the building in winter, but they are unsuitable for use in the summer because seriously contribute to over-heating. The measures for their shading are either expensive or not effective. The orientation and the size of the windows have impact on energy balance, of the building that very seriously should be taken for consideration at the planning and design stage of the building.

The frequency of overheating mostly depends on the type of glazing of the windows. By reducing the solar factor the overheating is reduced, but the energy demand for heating is increased and vice versa.

From the analysis results it could be concluded that windows are one of the most important elements in achieving the Passive House standard. The choice of glazing is extremely important and it should satisfy all the prescribed criteria for glass for passive house.

Emission of carbon dioxide (CO_2) is proportional to the increase in energy consumption for heating / cooling and total primary energy.

8. CONCLUSION

The Passive House Standard represents one of the most effective solutions for achieving ultra-low-energy buildings without compromising comfort. Through a combination of insulation, airtight construction, heat recovery ventilation, and strategic design, passive houses demonstrate that it is possible to drastically reduce energy use while enhancing occupant well-being. As energy regulations become stricter and the urgency of climate action intensifies, the passive house approach offers a proven pathway for sustainable building development. By embracing this standard, architects, engineers, and policymakers can contribute meaningfully to a low-carbon, resilient future in the built environment.

The radical changes in urban development, related to the way the future buildings will be designed and built, will have an essential influence on reducing the energy consumption as one of the most important factors for sustainable development. Globally, the strategy expressed by "energy triad" (Trias energetica 20:20:20) was set and requirements to be met up to 2020 are: 20% reduction of energy consumption, 20% reduction of CO_2 emissions and 20% increase of renewable energy use. Nearly 40% of the total energy consumption in Europe is consumed in buildings, 67% of it in residential buildings and only 33% in commercial buildings. Hence, this paper refers to the analysis of residential buildings under Macedonian climate conditions.

Passive buildings represent the highest standard in the energy efficiency of buildings. They guarantee extremely low energy needs, which can be fully meet with relatively small alternative energy sources (sun, water, wind, waste, etc..). It will help to decrease the environmental impact of the building sector, in same time it gives opportunity for full independence from the most exploited sources of energy that are used so far and hence, the concentration of CO_2 in atmosphere could be reduced drastically.

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IMPLEMENTATION OF CIRCULAR ECONOMY IN CONSTRUCTION SECTOR - STATE OF THE ART

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Abstract

A Circular Economy-CE is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products for as long as possible. CE has been gaining popularity because it helps to minimize emissions and consumption of raw materials, open up new market prospects and principally, increase the sustainability of consumption and improve resource efficiency. Construction is one of the critical sectors in the transition to a Circular Economy due to its contribution to resource depletion, waste, and emissions. Despite its acknowledged limitations, the construction sector has been the focus of policies and regulations to improve its sustainability and circular economy capabilities. This study presents the State of the Art on circular economy implementation in the construction sector in the European Union. The analysis identified a growing number of publications since 2019, that can be divided into four areas: Resource and Waste Management, Sustainable Development Goals, Green Public Procurement, and Circular Economy.

Keywords: *Construction sector, Linear economy, Circular economy, State of the art, 3 Horizon model, Enablers*

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1. INTRODUCTION

Circular Economy is transition to an economy where resource consumption is in balance with the Earth's capacity to naturally regenerate those resources. The future of our economy, and especially the built environment, must recognize the fact that the model of endless exploitation does not work within the limits of our limited resources. While rapid reductions in carbon emissions and resource utilization must take priority over undirected economic growth, the circular economy can offer the opportunity to grow within our carbon budgets and planetary boundaries. Circular Economy (CE) is defined in contradistinction to the traditional linear economy. CE aims to tackle global challenges such as climate change, biodiversity loss, waste, and pollution by emphasizing the design-based implementation of the three base principles of the model: designing out waste and pollution, keeping products and materials in use, and regenerating natural systems."

Achieving a circular economy requires a fundamental system-level change in our economy. All levels of government, industry and civil society will have to come together behind the common goal of moving from our current extractive and wasteful linear economy to a regenerative, circular one. We are at a turning point. We can continue to try to adapt business as usual and make minor improvements to a failing system, or we can make fundamental changes at the system level and create a resilient, collaborative and forward-looking construction sector that is fit for the future. Our current linear economy and focus on economic growth maintain levels of carbon emissions and resource use that exceed our planetary boundaries.

So far, our efforts to separate the economy from these influences have largely failed, compared to the impact needed. The circular economy is an important piece of the puzzle for solving the challenges we face. Our current system is contributing to climate and biodiversity crises. To have any chance of solving these interconnected crises, we must shift to a new way of thinking, working and delivering; the circular economy must be part of the equation, to minimize the use of virgin resources in the built environment and maximize reuse at higher value.If there are bullets in the text, they should appear like this:

2. THREE HORIZONS MODEL

The Three Horizons Model-THM (Figure 1) is a way of structuring our thinking about the transition towards an emerging future, giving us a simple tool to handle the complexity of multiple facets of change happening at the same time, and over time. It acts as a roadmap to resolve tensions between incremental change and radical transformation and shows how to move from a linear to a circular economy (UKGBC, 2022).

Horizon 1: The current dominant system, or business-as-usual. Thinking within this horizon means managing existing realities for the system to remain successful. The Three Horizons Model assumes that this system is no longer fit for purpose under emerging conditions and will need to adapt and/or decline.

Horizon 2: The innovations that help us transition from our current system (Horizon 1) towards the emerging future (Horizon 3), by showing us that a new system is possible.

Note that these innovations might not always be supporting the emerging future (H2+) but can manifest the current system in new ways (H2-). Careful evaluation of which Horizon they support is paramount.

Horizon 3: The emerging future of a radically different world and vision to aspire to that should become the new business-as-usual over time.

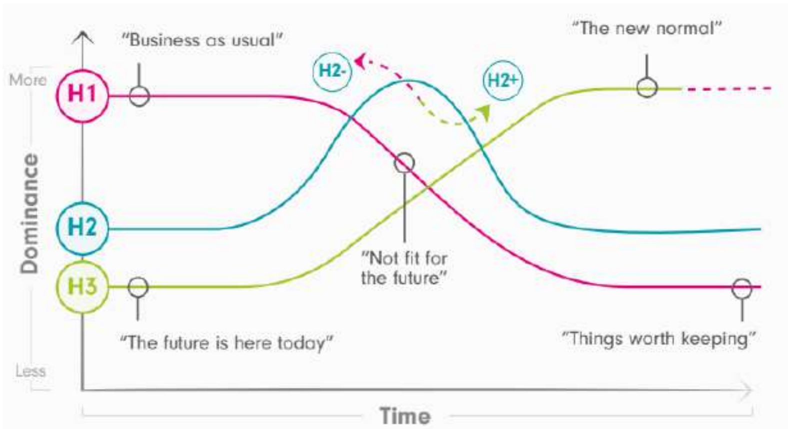

Figure 1 - The Three Horizons model as roadmap to Circular Economy

In a complex world, each of these horizons is needed to create meaningful change by bringing these different perspectives together in a constructive way to face the challenges ahead. The built environment industry's current "business-as-usual" approach is an extractive and is presented by "use and dispose" principals (Horizon 1- linear economy). The circular built environment is incorporated in Horizon 3.

To achieve this emerging future and vision of a regenerative, circular economy, a set of strategic objectives provides a tangible trajectory in environmental, social and economic terms.

Environmental:

- Planetary boundaries are not exceeded,
- The true value of raw non-regenerative materials is reflected in their price (balance tips in favor of secondary materials),
- Zero carbon trajectory.

Social:

- Mindset shift in high-income nations – consumption behavior and high-consumption lifestyles,
- Less demand for 'new' things,
- Low-resource lifestyles,
- Established routes for sharing resources and information,

- Fairer distribution of resources we use,
- Holistically take on our role as stewards of the built environment.

Economic:

- Reliant on regenerative, renewable, and inclusive resource flows,
- Urban development supports localized loops (e.g. knowledge, space, and tools needed to maintain, reuse, upcycle and recycle materials locally and regionally),
- Creation of new sustainable market opportunities such as secondary materials market as well as the market for eco-designed products,
- Focus on a thriving economy beyond GDP growth.

3. CIRCULAR ECONOMY IN BUILD ENVIRONMENT-STATE OF THE ART

The built environment plays a crucial role in economic progress and social welfare. Nonetheless, the construction industry imposes dreadful environmental impacts and is responsible for almost 33% of greenhouse gas emissions, 40% of waste generation, and 40% of materials consumption (Hossain et al., 2018). In response to these figures, the European Commission launched the first Circular Economy Action Plan (ECEAP) in 2015, which holds particular promise for achieving multiple Sustainable Development Goals (SDGs), including SDGs 6 on energy, 8 on economic growth, 11 on sustainable cities, 12 on sustainable consumption and production, and 13 on climate change. A new Circular Economy Action Plan (CEAP) was adopted in 2020 with more concrete measures on reducing the pressure on natural resources and creating sustainable development. Circular Economy (CE) action plans have put a major focus on the construction and real estate sector and building activities by developing strategies and policies to promote more efficient utilization of natural resources like primary raw materials (ore, minerals, biomass, fossil energy carriers) and waste hierarchy of reduce-reuse-recycle. Above all, recent endeavours for delivering more concrete measures also include the development of new standardisation activities like CEN/TC 350/SC 1 and ISO 59004.

The application of CE principles in building design (adaptability, durability and waste reduction and high quality management according to European Commission (2020) and use is mainly focused on new buildings where circularity can be embedded and facilitated since the early design stage and consequently throughout the whole life cycle of a building and its components and materials. Conversely, circularity in the context of existing buildings is not so far defined. Moreover, the multitude of definitions of a circular economy, and more specifically circularity in the built environment, does not contribute to a coherent systematic approach. The focus in this regard is currently limited to viewing those as potential material banks where components and materials can be recovered, reused or recycled for new constructions while optimizing their use is rarely discussed. Still, recovered materials from existing building face a critical barrier from aspect of their technical compatibility and quality appraisal which put their direct reuse in question, the reason why they end up down-cycled engaging extra resources and energy flows. Besides, the majority of research on Circular Building (CB) has mainly addressed techniques for measuring and assessing lifecycle outcomes of buildings and their materials or innovative materials for circularity, as well as on recycling construction and demolition waste (CDW)

(Adams et al., 2017). On the other hand, less has been said regarding the design aspect of circularity integration in buildings (e.g. design for disassembly (DfD), design for adaptability (DfA), etc.) and the role of building professionals and supply chain elements in embodying the CE principles into the building sector.

In other words, existing practices and concerns give a major focus to the CE principle of "closing the loop" which assumes intensified reuse and upcycling of materials and components (Figure 2).

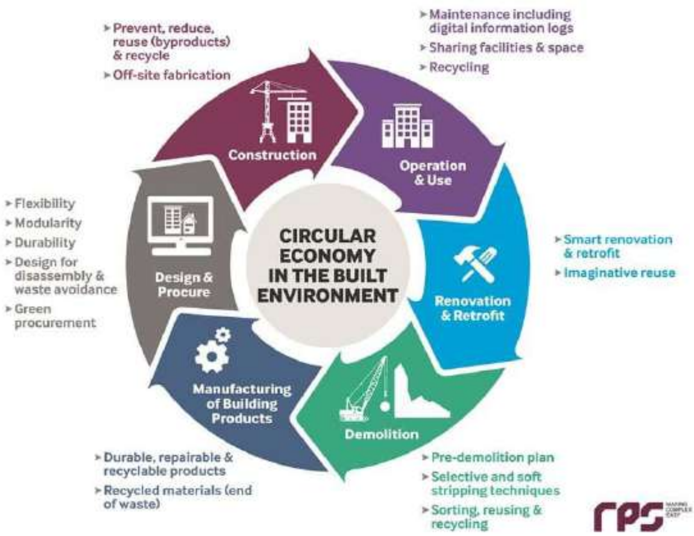

Figure 2 – Circular Economy in the build environment

Meanwhile, CE principle of "Slowing the loop" that suggests increasing building and product longevity by preserving their value, quality, and efficiency to the highest possible extent has received less attention so far. This can be justified by the remaining influence of the prevailing construction and design culture during the last decades of viewing buildings as temporal products of limited life service and predefined destiny – Demolition. Another key principle of CE that is rarely addressed by existing strategies frameworks is "Narrowing the loop" that relies on using fewer resources per product. This principle is inspired from nature's processes that mainly use a limited chemical palette often consisting of six elements: carbon, hydrogen, oxygen, nitrogen, phosphorus and sulphur, while industrial manufacturers follow a different approach seeking out rare and toxic elements to reach the desired functional properties. Narrowing the loop delivers conditions for recycling by allowing efficient and facilitated material separation and recovery.

Moreover, several tools have been developed to support the decision making of designing buildings for circularity as well as accessing some aspects of their circularity.

However, many of these tools serve the same purpose with slight differences in terms of goal and scope. The majority of the frameworks of these tools were developed to focus on specific aspects of circularity without considering other important aspects such as supporting products and materials choice by only substantiating material-related indicators based on their environmental impacts (e.g. aspects of health, non-toxic composition) and reuse and recycling potential such as Materials Passports (MP), Circular Materials Platforms, Material Circularity Index (MCI) (EMF, 2015) and material flow analysis (MFA) tools.

However, these tools failed to address a comprehensive circularity conception and led to a loss of criticality when used individually since they did not appraise all the other important design aspects e.g. building composition and connectivity between elements. This is because circularity values come up when specified intrinsic properties (material and product characteristics) cross with relational properties (building design and use characteristics). For example, a building can be made of 100% of circular materials and products but still, those being unreachable for replacement or maintenance make the building system non-circular.

Multiple sustainability rating tools were used to assess circularity considering it as an added value to sustainability. LCA-based tools such as SimaPro, ReCiPe, Open LCA are widely used for sustainability assessment of buildings. However, the use of LCA tools in the context of circularity assessment assumes the end-of-life options resulting in more comprehensive assessments. Yet, these tools only addressed the environmental results without other aspects.

Similarly, LCC-based tools are used to address the economic aspect of circularity in buildings and investigate the feasibility of circular solutions and conduct financial impact analysis of circular business models. Still, LCA and LCC methods are considered time-consuming and complex to base design choices on (Cambier et al., 2020). They also rely on many inaccessible data. S-LCA or Social Life Cycle Assessment is a relatively recent type of LCA which has been investigated as an endeavour to complement the triple bottomline of sustaibility (environmental, economic and social aspects) towards a common framework of sustainability. However, S-LCA has been rarely investigated to calculate the social and socio-economic impacts of products circularity.

Some frameworks provide strategies to implement circularity through practical guidelines and successful practices supporting the concept of learning by doing. A prominent example is the circular design guide put forward by the Ellen McArthur foundation. The guide consists of a series of methods based towards actions and aiming at building up a circular mind-set and reframing questions to get started with the circularity challenge. The value of this guide lies in experiencing, exercising and training through multiple methods to transform designers into being intuitive about circularity. This is because design practice is largely based on experience and less on tools (Cambier et al., 2020).

More recent tools have been developed in the spectrum of the CE such as Circular Building Assessment Prototype (CBA) developed by the European Union (EU) project of BAMB, Circularity Calculator (IDEAL&CO, 2021) and Building Circularity Index. These tools introduce rating systems to calculate a circularity score aiming at objectifying the circularity performance of a building or a building element. However, they are criticised for their lack of participatory and practice-oriented approach which is fundamental to meet the need to appraise the impact of rating tools on the design process.

Moreover, there is no clear between the outcome of these tools and the actual environmental impact of the investigated solution. The Level(s) framework developed by the European Commission introduced a more inclusive approach towards circularity in this regard. The consideration of circularity in Level(s) is mainly featured in macro-objective 2 - resource efficiency and circular material lifecycles - which consists of lifecycle tools namely:

- Bill of quantities, materials with their functional performance and service life planning.
- Design for adaptability and design for disassembly.

These life cycle tools are not indicators by themselves. Still, they are important to determine several other indicators such as:

- Indicator 1.2 - Life cycle global warming potential and
- Indicator 2.3 - Construction and demolition waste.

Each scenario has different impacts in terms of input and output flows along a building's lifecycle. The evaluation of lifecycle scenario tools enables comparisons in terms of resource efficiency allowing to define advantages and barriers for each and identify potential trade-offs. However, the realisation of trade-offs between different scenarios which make more sense in real life is not clearly identified.

Although Level(s) provides guidelines for doing simplified, detailed or optimization studies, it delivers a less concrete framework for circular design strategies such as design for adaptability which is limited to simple checklists. Moreover, the market uptake of Level(s) is still limited and a stong position still has to be found in the playing field of international frameworks such as LEED and BREEAM and national frameworks.

The multiple aspects addressed by the different types of tools and the similarities among the majority of objectives point out the need of creating complementarity among these tools rather than establishing new ones from scratch. Still, the majority of existing tools are developed so far to support design decisions and perform comparative analysis but not to create solutions and strategies to implement circularity in buildings bearing in mind that the role of design is not merely at the initial planning process but rather persisting along the life cycle of products and services and remains relevant at any point.

To ensure a full benefit of circular strategies implementation, the supply chain management and monitoring should be key. The issues of process circularity have been posed by multiple scholars and practitioners taking into consideration the complexity of the process. This includes ensuring an efficient information flow among partners and stakeholders (Cambier et al., 2020).

In this regard, the need for matchmaking tools to connect verified stakeholders is surfaced. Also, a smooth process calls for legal support and guiding policies that ensure compliance with circular strategies.

The emergence of Building Information Modelling (BIM) has created new opportunities to improve process efficiency and productivity. Among the several applications of BIM for the construction industry, authors have recognized its influence on building sustainability, mainly on decision support, material information storage, managing the building end of life scenarios and waste minimization (Akanbi et al., 2019). Despite the great opportunity to link BIM with circular economy principles, it is still a growing topic with few related investigations. BIM has been widely integrated into some circular-related fields, as automated LCA, LCC or sustainability assessment (Carvalho et al., 2020). The role of BIM for circular thinking concerns the capability to accumulate lifecycle multi-disciplinary information about a building, together with the possibility of process automation.

The application of circularity strategies in the buildings sector is still hindered by the lack of innovative business models that ensure implementation without comprising economic viability and value capture by market actors. The most common archetypes discussed in the literature are either oriented towards Product-Service Systems (PSSs) or recycling practices (Sassanelli & Terzi, 2019). However, they mainly target companies belonging to specific industries (particularly electric and electronic products).

Moreover, most of the existing knowledge is based on theoretical or/and analytical studies that often do not involve companies or common stakeholders but rather deliver theoretical concepts merely serving as suggestions to companies and policy makers. Besides, best practices are oriented towards large investments and therefore too complex to be adaptable by Small and Medium Enterprises (SMEs). With very few examples implementing CE into practice, the practical transformation from a linear business model into a circular one is still the main research gap in terms of consolidated circular practices steering companies towards improving the circularity of their products or services and incentivizing policies to subsidize those.

4. CONCLUSION

The built environment is a complex system made up of globally connected supply chains and established processes. The complexity of this system makes it challenging to adapt to meet the needs to fix our current crises. Moreover, existing infrastructure supports the current way things are done while differing and diverging visions for the future can make the direction of travel unclear. Therefore, the transition to a circular economy cannot be achieved with some simple alterations to the status quo but will require a fundamental systems-level change in our economy and cross-industry collaboration.

The Three Horizons framework is a model of systems change along short, medium and long-term timelines, which help us to work out how to prioritise our actions now and in the future. This report has examined the current state of the industry from a systems perspective (H1), identifying some practical industry enablers that are currently emerging

(H2) and must be implemented to set us on the necessary path to achieve a regenerative circular economy (H3).

The eight industry enablers (Figure 3) can support this much-needed shift, acting as tipping points toward a circular future by overcoming key barriers and unlocking circular opportunities. Supported by stakeholder actions, they propose achievable solutions, bringing us closer to an emerging new way of doing business in the built environment.

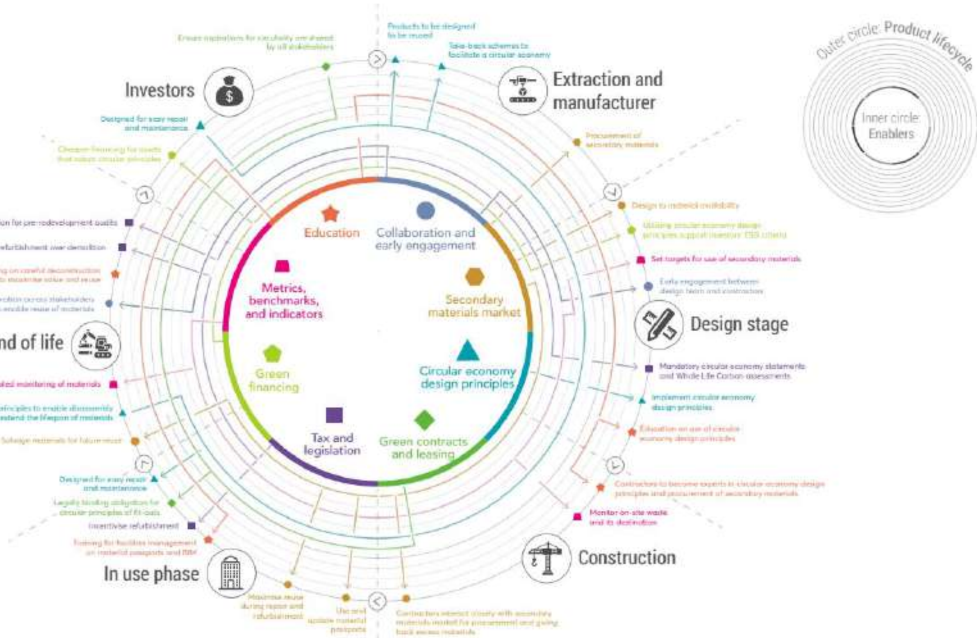

Figure 3 - Industry enaablers (UKGBC, 2022)

Many of the solutions are already out there. Green contracts and leases are available to be implemented, take-back schemes of construction products are being offered, and circular economy design principles are more regularly being implemented in recent architectural designs. Many are already pioneering a more collaborative approach with contractors being increasingly consulted at the early stages of the design. Other solutions, such as reuse hubs and material passports are in their infancy and will require concerted industry efforts to develop and become mainstream. As a call to action, this report outlines a set of policy and industry actions for all levels of the value chain to rally behind these enablers and deliver the necessary pieces of the puzzle so they can become the new business-as-usual in a circular built environment. Transitioning to a circular economy will be a crucial element in tackling the ecological and climate crises.

Facing the increasing concerns about the negative environmental impacts of buildings, governments and general society worldwide have been seeking more efficient and sustainable constructions. Hence, the Circular Economy (CE) emerged as a new paradigm of innovative practice with potential application to the construction industry besides other economic sectors. Following the European Circular Economy Action Plan (ECEAP), multiple efforts have been made to apply circular thinking to construction practices and include resource circularity into sustainability frameworks, such as Level(s). However, despite the endeavors, there is still a lack of a standard tool that fully implements the circularity potential, classifies buildings accordingly, and assesses the realization level of the ECEAP.

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OPPORTUNITIES FOR INVOLVING CIRCULAR ECONOMY IN CONSTRUCTION SECTOR

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Abstract

The construction sector, a major contributor to global resource consumption and waste generation, offers significant opportunities for implementing circular economy principles to reduce resource consumption, minimize waste, and enhance sustainability. By adopting strategies such as material reuse, design for disassembly, modular construction, and recycling of building components, the sector can shift from a linear to a circular model. The 10R model encourages a shift from the traditional linear "take-make-dispose" economy to a regenerative system that designs out waste and pollution. The 10R strategies form the foundation of the circular economy framework, promoting sustainable resource management across various sectors. These strategies aim to minimize resource input, waste, emissions, and energy leakage by extending the lifecycle of products and materials. This paper provides an overview of the conceptual basis of the circular economy and 10R strategies and their interconnections, highlighting how they can be applied to construction sector. Successful case studies on circular buildings involving steel, concrete, and timber demonstrate the practical potential of circular approaches, highlighting the importance of innovation, collaboration, and supportive policies in driving this transition.

Keywords: *circular economy, construction sector, 10R strategy, steel, concrete, timber*

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1. INTRODUCTION

Pollution, the overuse of natural resources, and the generation of waste are deeply interconnected issues that pose significant challenges to achieving sustainability. The extraction and exploitation of natural resources, such as fossil fuels, minerals, and water, often result in pollution through emissions, habitat destruction, and chemical contamination. This unsustainable use of resources depletes ecosystems and reduces the Earth's capacity to regenerate itself. At the same time, the waste generated by human activity, especially non-biodegradable and hazardous waste, contributes to land, air, and water pollution, further straining the environment.

Sustainability aims to break this destructive cycle by promoting the responsible use of natural resources and reducing pollution and waste. This involves shifting from a linear economic model, where resources are taken, used, and discarded, to a circular model that emphasizes reuse, recycling, and regeneration. Sustainable practices encourage the design of products that last longer, use fewer raw materials, and are easier to repair or recycle. By minimizing waste and managing pollution, societies can preserve natural resources for future generations and protect the ecosystems that support life. In essence, addressing pollution and waste through sustainable resource management is key to creating a healthier, more resilient planet.

Clean technologies, green infrastructure, and policy measures such as emissions regulation and waste management are vital tools in aligning economic activity with environmental protection. Underpinned by a transition to renewable energy and materials, the circular economy is a resilient system that is good for business, people, and the environment.

In our current economy, we take materials from the Earth, make products from them, and eventually throw them away as waste – the process is linear. In a circular economy, by contrast, we stop waste being produced in the first place. We must transform every element of our take-make-dispose system: how we manage resources, how we make and use products, and what we do with the materials afterwards (Figure 1).

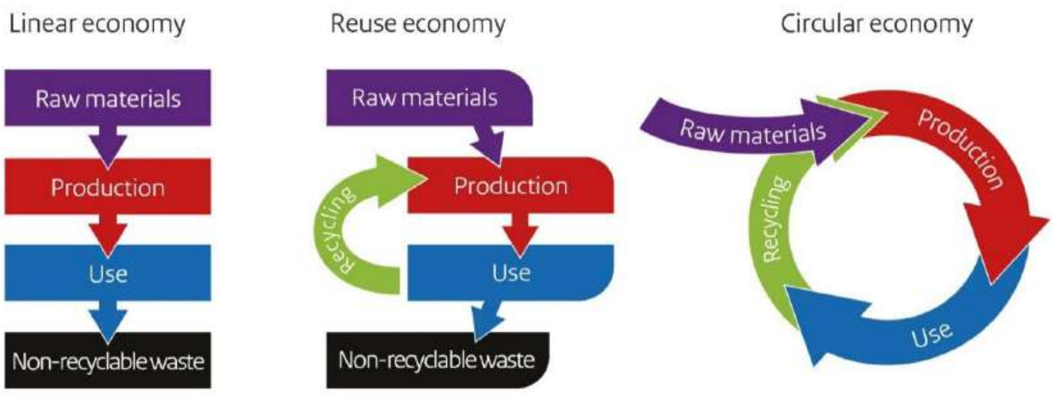

Figure 1 - Transition from Linear to Circular economy (https://www.government.nl/topics/circular-economy/from-a-linear-to-a-circular-economy)

The circular economy gives us the tools to tackle climate change and biodiversity loss together, while addressing important social needs. It gives us the power to grow prosperity, jobs, and resilience while cutting greenhouse gas emissions, waste, and pollution.

Unlike the traditional linear economy, which follows a "take-make-dispose" model, the circular economy seeks to create a closed-loop system where materials are constantly repurposed, minimizing environmental impact and promoting sustainability.

2. CIRCULAR ECONOMY AS SYSTEMS SOLUTION FRAMEWORK

A widely accepted and foundational definition of the circular economy is provided by the Ellen MacArthur Foundation. According to this foundation, “Circular economy is a systems solution framework that tackles global challenges like climate change, biodiversity loss, waste, and pollution”.

The circular economy is based on three principles, driven by design:

- Eliminate waste and pollution
- Circulate products and materials (at their highest value)
- Regenerate nature

The circular economy tackles climate change and other global challenges, like biodiversity loss, waste, and pollution, by decoupling economic activity from the consumption of finite resources (Ellen MacArthur Foundation). It is a system where materials never become waste and nature is regenerated. In a circular economy, products and materials are kept in circulation through processes like maintenance, reuse, refurbishment, remanufacture, recycling, and composting.

The circular economy system diagram, known as the **butterfly diagram**, illustrates the continuous flow of materials in a circular economy. There are two main cycles, the technical cycle and the biological cycle. In the technical cycle, products and materials are kept in circulation through processes such as reuse, repair, remanufacture and recycling. In the biological cycle, the nutrients from biodegradable materials are returned to the Earth to regenerate nature (Figure 2).

The **Butterfly Diagram by the Ellen MacArthur Foundation** is not just a graphic, it's a powerful conceptual tool for understanding the systemic changes needed to shift from a linear "take-make-dispose" economy to a circular, regenerative economy. It emphasizes designing out waste, keeping products and materials in use, and regenerating natural systems. By understanding and applying the principles represented in the Butterfly Diagram, businesses, governments, and individuals can contribute to a more sustainable and resilient economic model.

The Butterfly Diagram is a visual representation of the Circular Economy system. It illustrates the continuous flow of materials in two distinct but interconnected cycles: the biological cycle and the technical cycle. These cycles work together to maintain the value of products, materials, and resources in the economy for as long as possible, and to minimize waste.

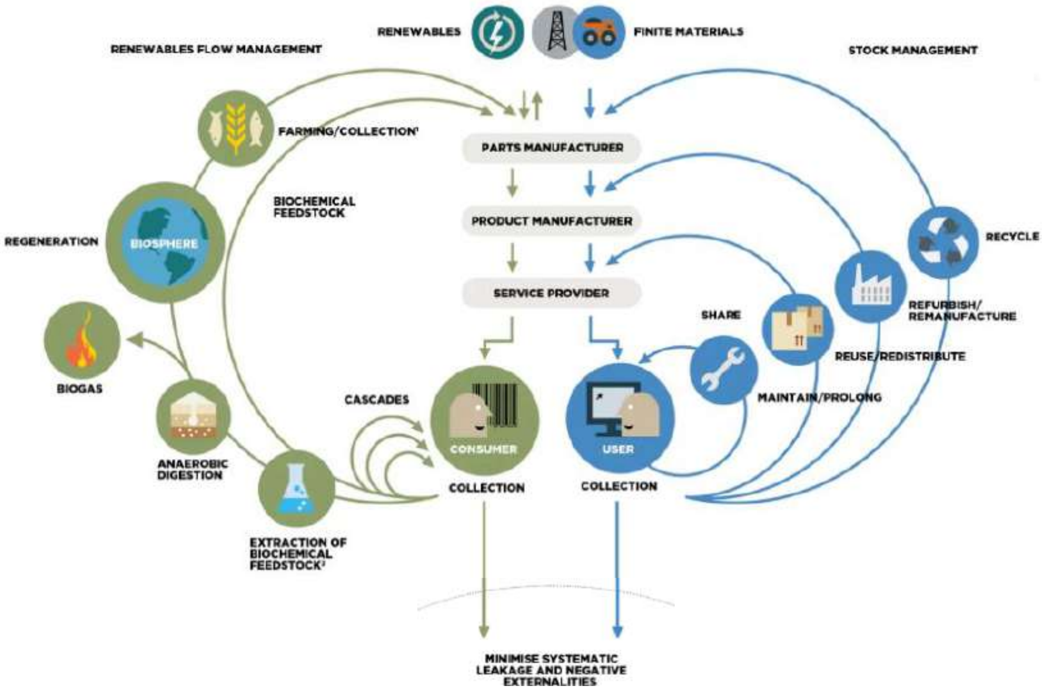

Figure 2 - Butterfly diagram for Circular Economy system (Ellen MacArthur Foundation)

The Butterfly Diagram is split into two "wings" resembling a butterfly, each representing one of the fundamental loops of the circular economy.

- **The Biological Cycle (Left Wing)**

The biological cycle includes materials that can safely re-enter the natural environment after use. These are biodegradable materials typically derived from renewable resources such as food, wood, cotton, or other organic matter. This cycle supports regenerative systems, such as agriculture and forestry.

The flow of materials in this cycle involves several key stages:

✓ **Biological Feedstock**: Sourced from renewable resources (e.g., plants, animals).

✓ **Cascades**: Materials are used several times before becoming waste, such as using cotton rags for insulation after they can no longer be used as clothing.

✓ **Anaerobic Digestion/Composting**: Organic waste is processed to extract energy and nutrients.

✓ **Restoration of Nature**: Nutrients are returned to the soil to regenerate natural systems, completing the cycle.

The key principle in the biological cycle is "safe return" designing products so that they decompose and enrich ecosystems without harming them.

- **The Technical Cycle (Right Wing)**

The technical cycle applies to non-biodegradable materials, such as metals, plastics, and synthetic chemicals, which should be kept in the economy through reuse and recycling rather than being discarded.

This cycle involves several circular strategies, including:

- ✓ **Maintenance and Prolongation:** Keeping products in use longer through repair and servicing.
- ✓ **Reuse and Redistribute:** Extending the life of products by giving them to new users (e.g., through resale or donation).
- ✓ **Refurbishment and Remanufacturing:** Reconditioning or rebuilding products to original or improved specifications.
- ✓ **Recycling:** Recovering materials from used products for manufacturing new items.

Unlike the biological cycle, which relies on decomposition, the technical cycle emphasizes "closed-loop systems" retaining the maximum value of materials and minimizing the need for virgin resources.

- **The Inner vs. Outer Loops**

An essential concept in the Butterfly Diagram is the idea of inner vs. outer loops. Inner loops (like maintenance and reuse) retain more value and consume less energy compared to outer loops (like recycling). The closer the loop to the center of the butterfly, the better it is for efficiency and sustainability.

For example, reusing a whole product is more resource-efficient than recycling its components, or refurbishing a device is generally better than melting it down for raw materials.

The Butterfly Diagram also implicitly acknowledges the need for **enabling systems**, such as:

- ✓ Product design that supports longevity, modularity, and recyclability.
- ✓ Reverse logistics to retrieve used products.
- ✓ Business models such as leasing, sharing, and service-based models.
- ✓ Policy frameworks that support circular practices.
- ✓ Consumer behavior oriented toward sustainability.

Although the two cycles are distinct, they are not isolated. Designing for material separation ensures that each component ends up in the correct loop.

2.1. The 10R Framework of the Circular Economy

The 10R strategy is a pivotal element of the circular economy, providing several sustainability advantages (see Fig. 3). This approach involves designing out waste by implementing a waste-free system which concentrates on high-quality products and materials that are optimised for disassembly and utilization (Rahman et al., 2021)

The goal is to optimise resource yields by obtaining the highest possible utility of products, components, and materials in both technical and biological cycles (Bag et al., 2021). Products are designed to be of highest use for a long time before being disassembled and reused or recycled, minimizing waste, and decreasing the reliance on virgin materials. As a result, businesses can achieve triple bottom line sustainability benefits that include economic, social, and environmental advantages (Rahman et al., 2021).

The **10R framework** is a structured hierarchy of strategies used to implement the principles of the circular economy. It guides businesses, governments, and individuals in shifting from the traditional linear model—take, make, dispose—toward a regenerative system where resources are kept in use for as long as possible.

By following the 10R strategy, businesses can reduce their environmental impact, create new opportunities for growth and cost savings, promote the circular economy, and drive innovation. By adopting a sustainable future, businesses can play their role in lessening reliance on virgin materials and resources, contributing positively towards a sustainable future. The 10Rs represent ten strategies ranked by their potential to retain value and reduce environmental impact, with the first few being the most desirable and impactful (Fig. 3).

Refuse (R0) – Avoid using unnecessary products or materials in the first place. This could mean refusing single-use plastics or avoiding products with excessive packaging.

Rethink (R1) – Rethink how products are used or offered. This often involves business model innovation, such as product-as-a-service, shared use, or multifunctional design.

Reduce (R2) – Use fewer resources by increasing efficiency or reducing consumption. This includes designing products that require less material or encouraging minimalist consumption.

Reuse (R3) – Extend the life of products by reusing them for the same or different purposes. This could involve second-hand markets, donation, or repurposing items.

Repair (R4) – Fix faulty products instead of discarding them. Promoting repair helps extend product lifespan and reduces the need for new materials.

Refurbish (R5) – Restore old products to good working condition, often by replacing or upgrading components. This is common with electronics and furniture.

Remanufacture (R6) – Rebuild products using a mix of used and new parts to bring them back to like-new condition. This strategy is widely used in industries such as automotive and machinery.

Repurpose (R7) – Use a product or its parts for a new function without processing it extensively. An example might be turning old tires into playground surfaces.

Recycle (R8) – Process materials to obtain raw materials that can be used to make new products. While important, recycling typically consumes more energy and value than strategies earlier in the hierarchy.

Recover (R9) – Extract energy from waste that cannot be reused or recycled, such as through incineration with energy recovery. This is considered the last resort before disposal.

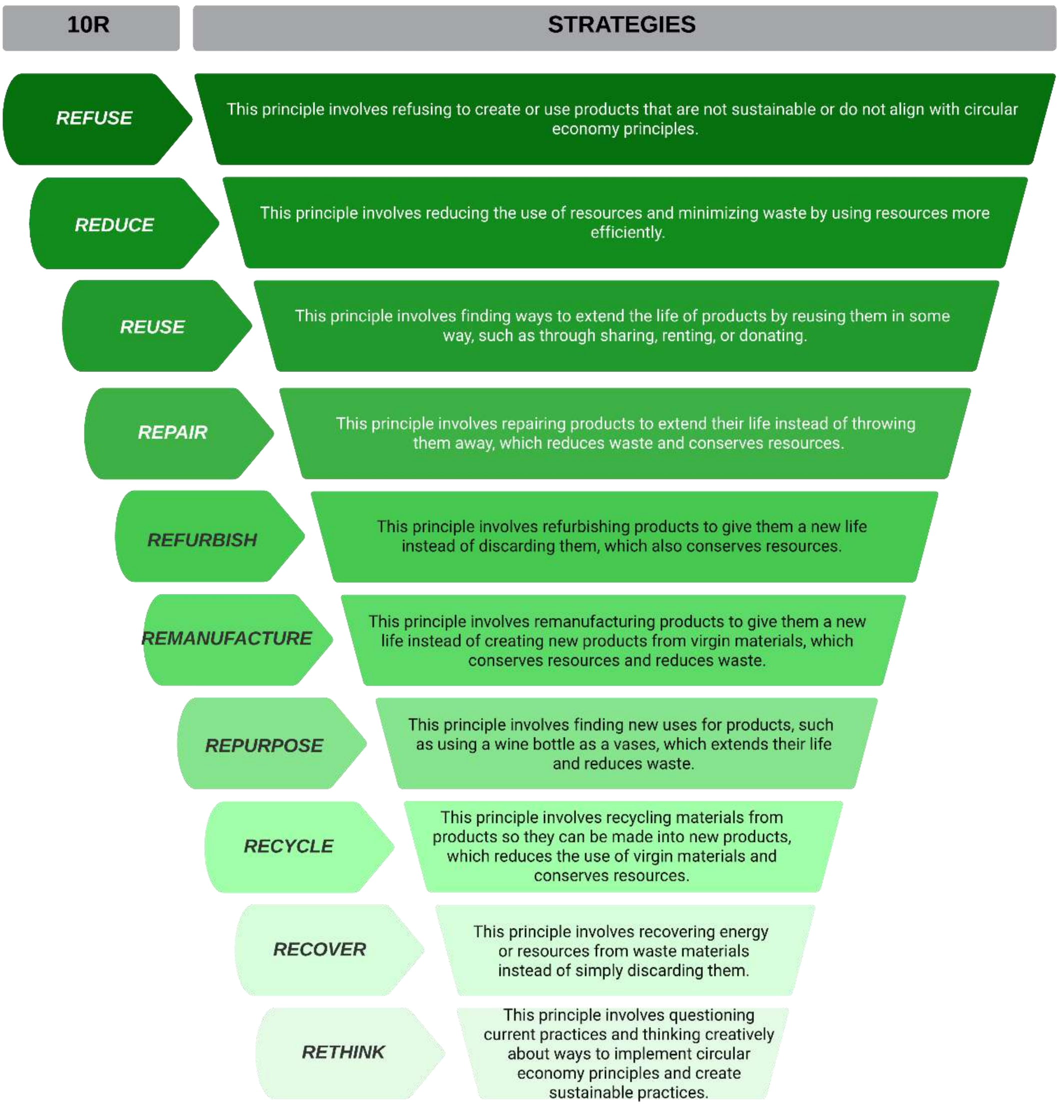

Figure 3 - 10R Strategy (Rotting et al., 2017)

3. ENVIRONMENTAL IMPACTS OF THE BUILT ENVIRONMENT

Buildings and infrastructure, encompassing everything from residential, commercial and industrial buildings to roads, bridges, and utility systems, are essential for modern life. However, their development and operation are major contributors to global environmental degradation. From their construction through operation to demolition, buildings and infrastructure contribute significant energy use, carbon emissions and material depletion. Addressing these impacts from a sustainability perspective is essential to mitigating environmental degradation and fostering a healthier and more resilient planet.

The built environment, and the infrastructure have far-reaching impacts on natural ecosystems, resource consumption and climate change. Their environmental impacts span multiple phases: extraction of raw materials, construction, operation, maintenance, and eventual demolition or repurposing. The cumulative effects touch nearly all aspects of the natural environment (Fig.4).

The construction sector is one of the world's largest consumers of raw materials. It accounts for 50% of global raw material consumption, but in same time it accounts for 40% of total global energy consumption and 30% of global water usage. According to the International Energy Agency (IEA) and UN Environment Programme report for 2021 (UNEP, 2021), buildings are responsible for approximately 39% of CO_2 emissions and they are responsible for over one-third of global greenhouse gas emissions. Much of this impact comes from operational energy consumption, such as heating, cooling, lighting, and appliance use. However, the embodied energy in building materials (the energy required to extract, manufacture, transport, and install them) is increasingly recognized as a critical environmental concern. Processes related to production, transport and the use of building materials, in particular, cement, concrete and steel, account for an ever-growing CO2 footprint of buildings.

Construction activities also generate huge amounts of waste. In many countries, construction and demolition (C&D) waste accounts for over one-third of total solid waste generated. Most of this waste ends up in landfills, where it contributes to land degradation and methane emissions. While some countries have made progress in recycling concrete, asphalt, and steel, a significant portion of material still goes unrecovered due to poor design for disassembly and lack of infrastructure for material reuse.

Urban sprawl and infrastructure expansion often lead to: deforestation and loss of biodiversity, fragmentation of ecosystems, soil erosion and degradation. The conversion of natural land into urban areas not only destroys wildlife habitats but also reduces the Earth's natural carbon sinks. Impervious surfaces like asphalt and concrete also increase surface runoff, contributing to flooding and water pollution.

Buildings and construction activities consume large amounts of freshwater, particularly in concrete mixing, dust suppression, and equipment cooling. Moreover, improper waste disposal and chemical runoff from construction sites can contaminate water bodies and storm water runoff from urban infrastructure can carry pollutants like oil, heavy metals, and microplastics into rivers and oceans.

Dense urban areas with abundant concrete and asphalt absorb and retain heat, leading to the urban heat island (UHI) effect, where cities are significantly warmer than surrounding rural areas. This contributes to: increased energy consumption for air conditioning, worsening air quality due to trapped pollutants and health issues such as heat stress and respiratory problems.

Environmental Impact Pathways of Buildings and Infrastructure are presented on the diagram in Figure 4.

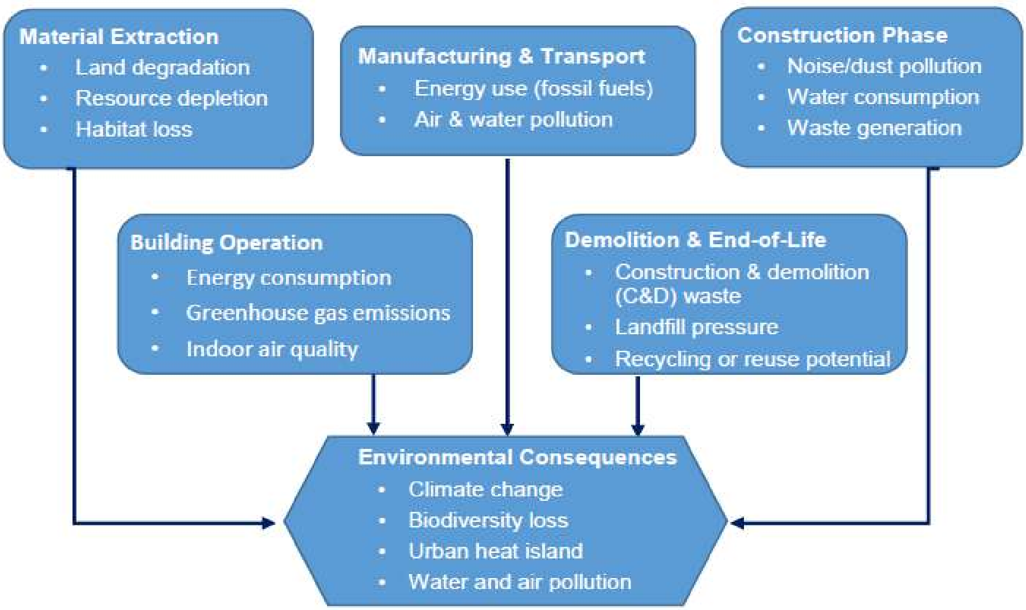

Figure 4 - Environmental Impact Pathways of Buildings and Infrastructure

In response to these challenges, the construction industry is shifting towards sustainable building practices, which aim to reduce negative environmental impacts while enhancing efficiency and occupant well-being. Key strategies include:

- Energy-efficient design. By involving passive solar design, insulation, energy-efficient windows, and HVAC systems, the operational energy needs could be reduced.
- Sustainable materials. The use of recycled, low-carbon, or locally sourced materials reduces environmental footprints and supports circular economy goals.
- Green certifications. Programs like LEED (Leadership in Energy and Environmental Design) and BREEAM help measure and encourage sustainability in building projects.
- Renewable energy integration. Solar panels, wind turbines, and other renewable technologies can significantly reduce reliance on fossil fuels.
- Infrastructure planning is also shifting toward low-impact development,

prioritizing public transport, green spaces, and compact city designs that reduce the need for sprawling land use and minimize resource consumption.

Adopting a lifecycle approach to buildings, from design and construction to use and eventual deconstruction, is central to sustainability. This approach evaluates a building’s environmental impacts over its entire lifespan, encouraging strategies such as design for disassembly, modular construction, and reuse of building components. These principles are tied to the circular economy, which seeks to minimize waste and keep materials in use for as long as possible.

4. CIRCULAR ECONOMY IN CONSTRUCTION SECTOR: KEY PRINCIPLES, OPPORTUNITIES AND STRATEGIES

A circular economy in construction represents a transformative shift from traditional linear construction practices to more sustainable, resource-efficient approaches. Instead of the conventional “take-make-dispose” model, the circular economy emphasizes designing buildings and infrastructure with the entire life cycle in mind, especially the end-of-life phase. This approach aims to minimize waste, reduce environmental impact, and maximize the value of materials and components by enabling reuse, recycling, and adaptability.

The key principles of Circular Economy in construction are:

1. **Use of Recycled and Renewable Materials**

   Incorporating recycled concrete, reclaimed wood, recycled steel, or bio-based materials (like hempcrete) helps reduce the extraction of virgin resources.

2. **Design for Disassembly and Reuse**

   Buildings are designed so components (like steel beams, façade panels, flooring) can be easily taken apart and reused elsewhere, rather than demolished and discarded.

3. **Modular Construction**

   Prefabricated and modular designs enable easier upgrading, relocation, or reuse of building elements.

4. **Material Passports**

   These are digital records of materials used in a building, making it easier to reuse or recycle them at the end of the building’s life.

5. **Adaptive Reuse of Existing Structures**

   Repurposing old buildings for new functions rather than tearing them down extends the lifecycle of both materials and structures.

6. **Waste Minimization On-Site**

   Efficient project planning and lean construction practices reduce material waste during the construction process.

Applying circular economy principles to construction can deliver long-term environmental, economic, and social benefits. It fosters innovation, reduces dependence on raw materials, and aligns the built environment with broader sustainability goals. As urbanization accelerates and resource pressures increase, embracing circular design is not just a responsible choice, it is an essential step toward a resilient and regenerative future.

Central to this vision are several strategic design principles. One key strategy is the use of modular and prefabricated components, which not only simplify construction processes but also facilitate future dismantling and relocation. Modular buildings can be expanded, reconfigured, or dismantled with minimal disruption, facilitating the reuse of entire units and individual parts. This flexibility significantly extends the life of materials and reduces the demand for raw resources.

Another important principle is design for disassembly (DfD). This concept involves planning buildings from the outset so that their parts can be easily separated and recovered at the end of their useful life. DfD considers how connections are made, the sequencing of materials, and labeling systems, enabling efficient deconstruction without damaging valuable elements. This process supports the recovery of components in high-quality condition, increasing the potential for reuse and reducing construction and demolition waste.

Material selection also plays a key role. The circular construction model prioritizes sustainable, recyclable and bio-based materials that have a lower environmental impact and can be reintegrated into production cycles. Examples include recycled steel, reclaimed wood, biodegradable insulation and natural fiber composites. Salvaging bricks, steel, wood and other components from demolition sites not only reduces waste, but also preserves the embodied energy in these materials. Urban mining, the extraction of valuable resources from existing buildings, has become a promising area of growth. The materials obtained in this way not only help conserve limited resources, but also support a healthier indoor environment and reduce carbon emissions.

Better planning and tracking of resources throughout a building's life cycle is enabled by technologies such as Building Information Modelling (BIM). Policy frameworks, green procurement requirements and certification systems (e.g. LEED, BREEAM) further encourage the adoption of circular practices.

While challenges such as regulatory barriers, market demand and logistical complexity remain, the transition to a circular economy in construction is gaining momentum. With coordinated efforts from policymakers, industry stakeholders and designers, the construction sector can play a vital role in building a more sustainable, circular future.

Applying the key principles of the circular economy in construction sector brings significant benefits, such as:

- Reduces environmental footprint and landfill waste
- Lowers material and lifecycle costs
- Enhances resilience and long-term value of buildings
- Encourages innovation in building design and materials

The six principles of the circular economy in construction sector can provide the expected benefits only if they are incorporated into a well-developed circular business model based on the 10R strategy (Fig. 5).

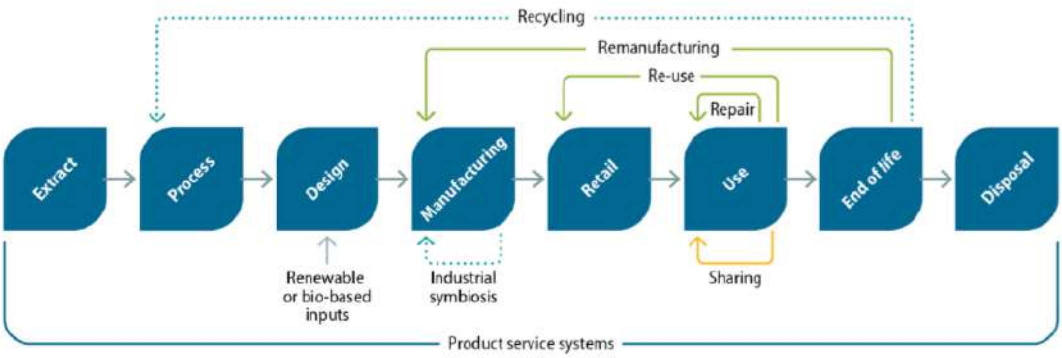

Figure 5 - Typology of Circular Business Model in construction sector

5. IMPLEMENTING CIRCULAR ECONOMY IN THE CONSTRUCTION SECTOR: FOCUS ON STEEL, CONCRETE, AND TIMBER STRUCTURES

Common materials like concrete, steel, and glass are energy-intensive to produce and often sourced through mining or quarrying, which disrupt ecosystems and deplete non-renewable resources. The continued demand for these materials puts pressure on finite resources and accelerates environmental degradation.

To effectively integrate circular principles in the construction sector, it is essential to understand the specific opportunities and challenges associated with different structural materials, especially the most commonly used ones, such as steel, concrete and wood.

5.1. Steel Structures

Steel is one of the most recyclable construction materials. The opportunities that make it highly suitable for circular applications are:

- **Design for Disassembly (DfD):** Steel structures cen be designed with demontable connections. The components can be bolted rather than welded, allowing for easy disassembly and reuse in future projects.
- **Standardization and Modularity:** Standardized steel elements enable easy replacement, reuse, and integration into new structures.
- **Recycling:** Steel retains its properties after recycling, making it ideal for closed-loop recycling systems.
- **Urban Mining:** Decommissioned steel structures can be systematically dismantled, and components can be reused or recycled.

Parallel to opportunities there are few challenges, as:

- Ensuring structural integrity and meeting modern codes for reused elements.

- Tracking material history and quality, which can be addressed using digital tools like BIM and material passports.

5.1.1. Case Study: The Circular Building, London

The Circular Building, developed for the 2016 London Design Festival, exemplifies circular construction through its fully reusable components and modular steel frame (Fig.6). The project was a collaboration between Arup, The Built Environment Trust, Frener & Reifer, and BAM (https://www.steelconstruction.info/Circular_building), aiming to demonstrate how buildings can be designed for complete disassembly and material reuse.

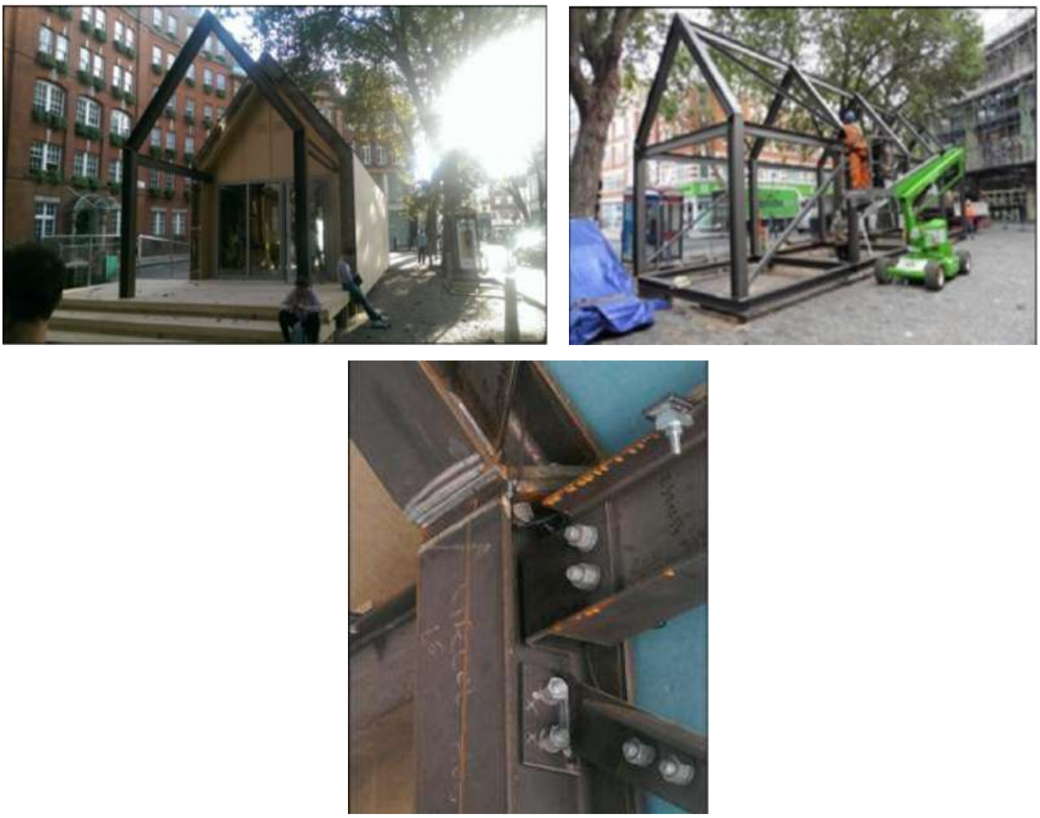

Figure 6 - Circular building, London, erection of steel frame, and structural connection detail

The circular strategies are implemented in all phases of the building's life-cycle:

1. Design Phase

- Circular Economy Integration: The design prioritized the use of reclaimed materials, with the building's size and form adjusted to accommodate available steel off-cuts from other projects.

- Modular Construction: Standardized steel components were used to facilitate easy assembly and future disassembly.
- Digital Material Tracking: Each component was tagged with a QR code linked to a digital Building Information Modeling (BIM) system, detailing material specifications and assembly instructions to aid in future reuse.

2. Construction Phase

- Dry Assembly Techniques: The structure was assembled using bolts and screws instead of welding or adhesives, allowing for straightforward disassembly without damaging components.
- Efficient On-Site Assembly: The modular design enabled rapid construction with minimal waste, as components were prefabricated and fitted together on-site.

3. Operational Phase

- Temporary Installation: The building served as a temporary exhibition space during the London Design Festival, showcasing sustainable construction practices.
- Educational Demonstration: Visitors could scan QR codes on building components to learn about their origins, materials, and potential for reuse, promoting awareness of circular construction.

4. Deconstruction Phase

- Planned Disassembly: After the festival, the building was systematically dismantled in the reverse order of assembly, guided by the BIM system and component tagging.
- Material Reuse: All components were recovered without damage and stored for future use in other construction projects, demonstrating the feasibility of material circularity.

5. Reuse and Legacy

- Component Repurposing: The reclaimed steel components have been earmarked for use in future construction projects, reducing the demand for new materials and associated environmental impacts.
- Influence on Industry Practices: The project has served as a model for integrating circular economy principles into building design, influencing subsequent projects to adopt similar strategies.

Demonstration projects like The Circular Building play a crucial role in educating stakeholders and promoting the adoption of circular construction practices. Incorporating modular design and dry assembly techniques facilitates easy deconstruction and material reuse. Utilizing BIM and component tagging enhances transparency and efficiency in both construction and deconstruction phases. Prioritizing the use of reclaimed materials and planning for their future reuse contributes to sustainability and resource efficiency.

5.2. Concrete Structures

Concrete poses more challenges in circular applications due to its monolithic nature and lower recyclability compared to steel or timber. The opportunities for concrete are:

- **Concrete Recycling:** Crushed concrete can be used as aggregate for new concrete or road sub-base material.
- **Precast Modular Elements:** Prefabricated concrete components can be designed for disassembly and reuse.
- **Carbon Capture in Concrete:** Emerging technologies allow for CO_2 to be captured and stored in concrete during production.
- **Adaptive Reuse:** Instead of demolition, concrete buildings can be refurbished or repurposed, preserving embodied energy.

The challenges for the concrete reuse are:

- Dismantling reinforced concrete is labor- and energy-intensive.
- Quality control of recycled aggregate can be variable.
- Cement production remains highly carbon-intensive, requiring innovation in low-carbon binders (e.g., geopolymer concrete).

5.2.1. Case Study: Super Circular Estate (SCE) Project, Kerkrade, Netherlands

The Super Circular Estate (SCE) project in Kerkrade (Fig. 7) stands as a pioneering initiative in circular concrete construction (https://www.uia-initiative.eu/en/news/super-circular-estate-project-journal-no-5-municipality-kerkrade). It involved the deconstruction of a 10-story apartment building and the subsequent reuse of its concrete components to construct new housing units, aiming to minimize waste and promote material circularity. The aim of the construction of the three new houses was to construct them using at least 95% of reused materials that are re-sourced from the donor building. Foundation has been made out of circular concreate (aggregate for the concrete have been acquired by crushing the existing concreate structure and only 7% of new cement has been added during production of concrete for the foundation).

Main loadbearing structure of the two houses has been directly reused from the existing building by cutting 3D concrete modules from the existing structure, while the main loadbearing structure of third house has been made of circular concreate (aggregate and cement for the concrete, only 5% of new cement has been added during production of concrete for the structural walls).

Partitioning walls have been directly reused from the exiting building as well as wooden frames for doors and kitchen cabinets have been directly reused and finally, façade has been constructed out of parts using crushed concrete pieces from the existing building brick, cut off elements, and recycled concrete.

The circular strategies are implemented in all phases of the building's life-cycle:

1. **Design Phase**
   - Design for Disassembly (DfD): The original building was not initially designed for disassembly. However, the SCE project retroactively applied DfD principles by carefully planning the deconstruction process to maximize material recovery.
   - Stakeholder Collaboration: An interdisciplinary team, including architects, engineers, and contractors, collaborated to identify reusable components and plan their integration into new constructions.
   - Material Assessment: A thorough audit was conducted to assess the quality and suitability of existing concrete elements for reuse, ensuring structural integrity and compliance with current building standards.
2. **Construction Phase**
   - Selective Deconstruction: Instead of traditional demolition, the building underwent selective deconstruction. Concrete elements, such as slabs and panels, were carefully removed to preserve their usability.
   - Component Processing: Recovered concrete elements were cleaned, tested, and, where necessary, modified to fit new design specifications. This process ensured that the materials met safety and performance requirements.
   - Integration into New Structures: The processed concrete components were then incorporated into the construction of new housing units within the same area, demonstrating a closed-loop material cycle.
3. **Operational Phase**
   - Monitoring and Evaluation: The newly constructed units were monitored to assess the performance of reused materials over time, providing valuable data on durability and occupant satisfaction.
   - Community Engagement: Residents were informed about the sustainable aspects of their homes, fostering awareness and appreciation for circular construction practices.MDPI
4. **Deconstruction Phase (Future Planning)**
   - Design for Future Disassembly: The new structures were designed with future disassembly in mind, incorporating features that would facilitate the easy removal and reuse of components at the end of their lifecycle.
   - Material Documentation: Detailed records of the materials used, including their origin and properties, were maintained to aid future deconstruction and recycling efforts.

The SCE project successfully demonstrated that concrete components from deconstructed buildings could be effectively reused in new constructions, reducing the demand for virgin materials. By reusing existing materials, the project significantly reduced construction waste and associated carbon emissions, contributing to more sustainable building practices. While initial costs were higher due to the labor-intensive deconstruction process, the long-term benefits included material savings and reduced environmental remediation expenses.

Figure 7- Hoisting of elements and two 3D units for the construction of two circular houses (Type A left and Type B middle). The structure for the third house (Type C) has been made of recycled concrete.

The methodologies developed during the SCE project serve as a model for similar initiatives, highlighting the potential for broader application of circular construction principles in the industry.

The Super Circular Estate project exemplifies how thoughtful planning and collaboration can transform traditional construction practices, paving the way for a more sustainable and resource-efficient built environment.

5.3. Timber Structures

Timber is a renewable material with strong potential in circular construction, especially with the rise of engineered wood products like cross-laminated timber (CLT). The circular process throughout the entire life cycle of a timber building is shown in Figure 8.

The opportunities for implementing the circular economy in construction of timber buildings are:

- **Reusability and Bio-based Design:** Timber elements can be easily dismantled and reused with minimal processing.
- **Carbon Storage:** Wood stores carbon throughout its lifecycle, contributing to carbon neutrality.
- **Design for Flexibility:** Timber lends itself well to modular design, allowing for future modifications or reuse of components.
- **Biodegradability**: End-of-life timber products can be composted or used in bioenergy systems (with care to avoid treated wood).

The challenges for circular timber structures are:

- Durability and fire resistance must be managed carefully in reused timber.
- Preservatives and adhesives may affect recyclability or biodegradability.
- Market demand and regulations for reused wood may be limited in some regions.

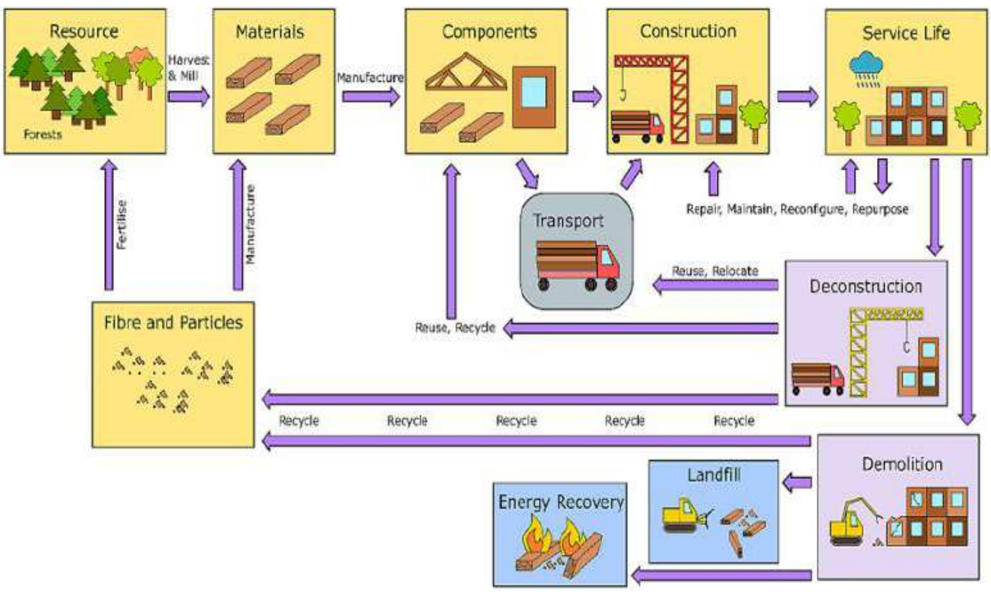

Figure 8 - Circular process throughout the entire life cycle of a timber building

5.3.1. Case Study: Pikku-Finlandia (Little Finlandia), Helsinki, Finland

Pikku-Finlandia is a temporary timber building constructed as an events venue during the renovation of the iconic Finlandia Hall in Helsinki. Designed with circular economy principles, it exemplifies sustainable timber construction through its use of natural materials and a design that facilitates disassembly and relocation.

Pikku-Finlandia was designed as a temporary replacement events facility during the three-year renovation of the landmark Finlandia Hall (https://pub.norden.org/nord2023-031/6-circular-construction-projects-support-platforms-and-tools). The project was organised by Aalto University, the City of Helsinki, and Finlandia Hall in the autumn of 2019. The design used whole untrimmed tree trunks as load-bearing columns, thus minimising processing costs and impacts. The 2000 m^2 Pikku-Finlandia has four multifunctional halls, a gallery, and a cafe (Fig. 9).

Three of the multifunctional halls can be combined into one large area together with the lobby. This flexibility allows the building to fulfil a variety of functions and meet a variety of needs. Following the renovation, the building will be disassembled and moved to a new location and continue its life serving another function, such as a school or day-care centre for example, for at least the next 50 years. In this way, this circular, low-impact building not only uses natural, non-hazardous recyclable materials, but can also be moved, reused, and adapted as needed.

The circular strategies are implemented in all phases of the building's life-cycle:

1. Design Phase

- Natural Material Utilization: The design incorporated whole, untrimmed tree trunks as load-bearing columns, minimizing processing and preserving the natural aesthetics of the timber.Nordic Publishing
- Modular Design: The building was conceived with modular components to allow for easy disassembly, relocation, and reassembly, aligning with circular construction principles.
- Multi-Functionality: Pikku-Finlandia was designed to accommodate various functions, including events, exhibitions, and gatherings, enhancing its utility and lifespan.

2. Construction Phase

- Efficient Assembly: The use of prefabricated timber elements facilitated a swift and efficient construction process, reducing on-site waste and labor.
- Minimal Environmental Impact: The construction process emphasized low-impact methods, utilizing sustainable materials and techniques to minimize the building's ecological footprint.

3. Operational Phase

- Temporary Venue: Pikku-Finlandia served as a temporary events venue during the Finlandia Hall's renovation, hosting various cultural and public events.

- Public Engagement: The building's unique design and sustainable construction attracted public interest, raising awareness about circular construction practices.

4. Deconstruction Phase

- Planned Disassembly: Upon completion of its temporary function, Pikku-Finlandia was designed to be disassembled efficiently, with components preserved for reuse.
- Relocation and Reuse: The building is intended to be relocated and repurposed, potentially serving as a school or daycare center, thereby extending its lifecycle and utility.

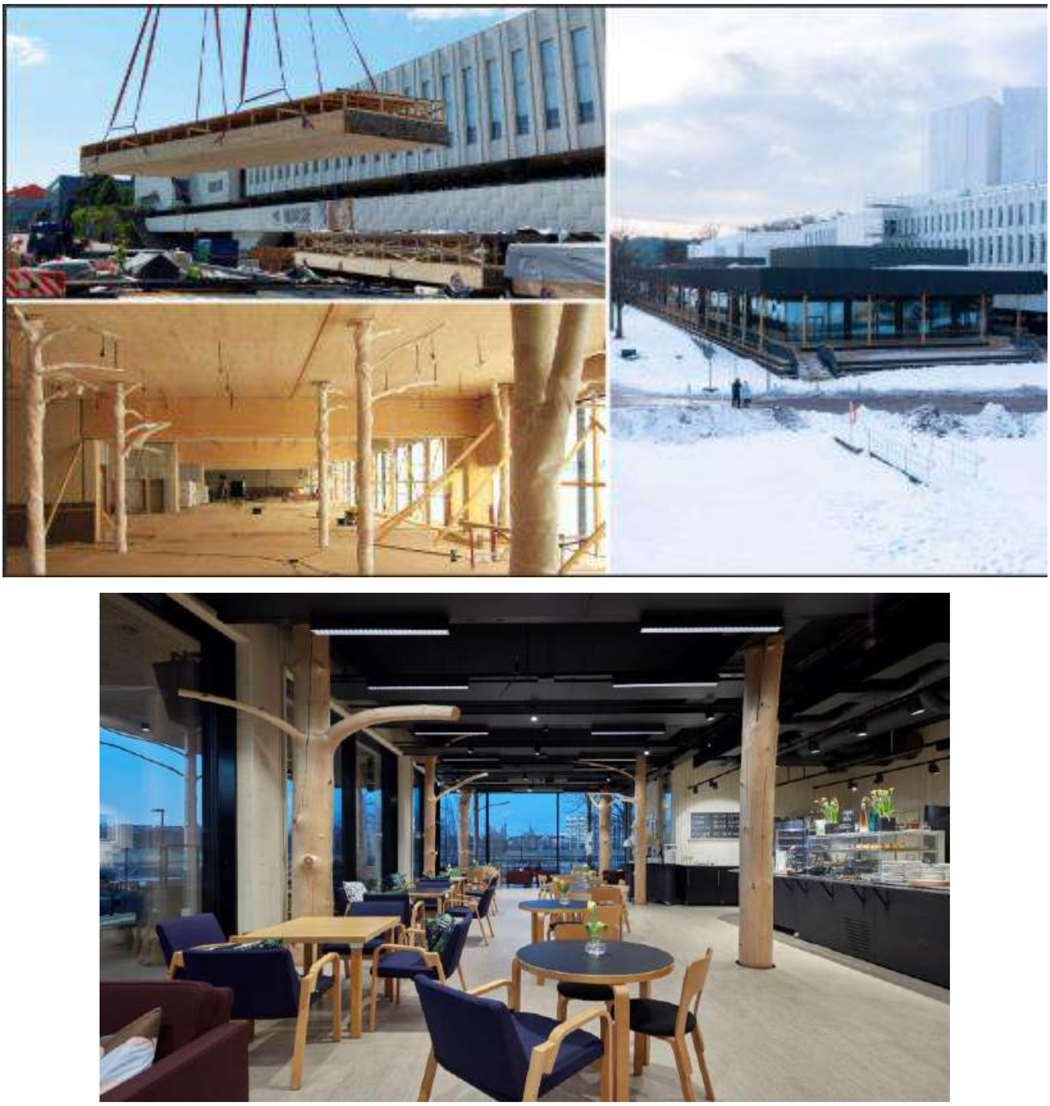

Figure 9 - Circular building Pikku-Finlandia (Little Finlandia) in Helsinki, Finland

Pikku-Finlandia exemplifies how buildings can be designed from the outset for easy disassembly and relocation, promoting material reuse and reducing waste. The use of whole tree trunks and natural materials underscores the potential of timber in sustainable construction. The building's modular design and multifunctionality demonstrate how structures can adapt to different uses over time, aligning with circular economy principles.

Pikku-Finlandia serves as a model for circular timber construction, showcasing how thoughtful design and sustainable practices can create buildings that are not only functional and aesthetically pleasing but also environmentally responsible.

6. CONCLUSION

The environmental footprint of buildings and infrastructure is vast but not irreversible. By rethinking how we design, construct, and manage our built environment, we can significantly reduce these impacts. The transition to sustainable, circular, and low-impact construction and urban development is critical to achieving global climate and biodiversity goals.

The circular economy offers numerous benefits that make it an attractive solution for promoting sustainability and reducing waste. These benefits include environmental sustainability, economic opportunities, and social benefits. By adopting circular practices, stakeholders can minimise the environmental impact of production and consumption, stimulate innovation and economic growth, create job opportunities, improve resource access and affordability, and enhance community resilience (Gardeti, 2019).

One of the significant environmental benefits of implementing circular economy principles is that it can lead to a reduction in greenhouse gas emissions. By promoting the reuse of existing products and materials, the circular economy can curtail the need for extracting natural resources, reducing the associated carbon footprint.

Additionally, by minimizing the use of virgin materials, the circular economy can help conserve natural resources and protect vital ecosystems such as soil, air, and water bodies. Moreover, circular practices and processes can lead to significant energy savings by reducing the need for resource extraction, manufacturing, and transportation of new products.

Another environmental benefit of the circular economy is that it can help to limit waste generation and reduce pollution. Circular economy practices such as recycling and remanufacturing can divert waste from landfills and incineration, thus promoting resource efficiency. This, in turn, can help protect ecosystems, limit biodiversity loss, reduce landscape and habitat disruption, and contribute to the global effort to combat climate change (Gardeti, 2019).

By adopting these principles, the circular economy can create a sustainable economic system that meets the needs of current and future generations while minimizing its environmental impact.

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BUILDING ENEVELOPE INFLUENCE ON ENERGY EFFICIENCY OF BUILDING STRUCTURES

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Abstract

The biggest challenge of the 21st century in construction sector is how to use energy and other non-sustainable resources more efficiently and how to reduce waste, pollution and environmental degradation at once. New construction concepts, new construction materials in combination with facilities for energy productions from renewable resources allow creating new sustainable buildings. The building envelope directly affects the building energy consumption. In order to define the time dependent thermal losses through the building envelope, a computer simulation is recommended at the beginning stages of design planning. This paper presents the numerically achieved results for the influence of the type and the position of the thermal insulation of the building on the heat loss and energy consumption of the building.

Keywords: *thermal insulation, building envelope, heat transfer, energy consumption*

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1. INTRODUCTION

Energy efficiency in buildings is a fundamental component of sustainable development, aiming to reduce energy consumption, minimize environmental impact, and improve indoor comfort. The design and operation of energy-efficient buildings are guided by several core principles and supported by a range of technical and operational measures.

The main principles of energy efficiency of buildings are:

1. Thermal Insulation: Proper insulation in walls, roofs, and floors reduces heat transfer, maintaining comfortable indoor temperatures and minimizing heating and cooling demands.
2. Air Tightness and Controlled Ventilation: Ensuring a building is airtight prevents unwanted air leakage. Combined with mechanical ventilation systems with heat recovery (MVHR), this maintains air quality while minimizing energy loss.
3. Passive Design: Utilizing natural resources such as sunlight, wind, and shade to regulate temperature and lighting. This includes proper building orientation, window placement, thermal mass, and shading devices.
4. High-Performance Glazing: Installing double or triple-glazed windows with low-emissivity (low-E) coatings to reduce heat loss and solar gain.
5. Energy-Efficient Systems: Using high-efficiency HVAC systems, water heating systems, and lighting fixtures to lower operational energy use.
6. Renewable Energy Integration: Incorporating solar panels, solar thermal systems, or other renewable energy sources to supply part of the building's energy demand.
7. Smart Building Technologies: Implementing intelligent control systems for lighting, heating, and cooling to optimize energy use based on occupancy and external conditions.

Measures that enable the realization of the basic principles of energy efficiency are:

1. Energy Audits: Conducting a comprehensive assessment of the current energy performance to identify areas for improvement.
2. Retrofitting Existing Buildings: Upgrading insulation, windows, and mechanical systems in older buildings to meet modern energy standards.
3. Use of Energy-Efficient Appliances: Choosing appliances with high energy efficiency ratings (e.g., Energy Star, EU energy label).
4. Building Automation Systems: Installing programmable thermostats, occupancy sensors, and smart meters to control energy consumption in real time.

5. Green Roofs and Walls: Adding vegetated surfaces to improve thermal performance and reduce urban heat island effects.
6. Lighting Upgrades: Replacing traditional incandescent bulbs with LED lighting and maximizing the use of natural daylight.
7. Behavioral Change and User Awareness: Educating occupants on energy-saving practices such as proper thermostat settings, turning off unused devices, and responsible use of heating and cooling.

Implementing these principles and measures contributes not only to reducing energy consumption and greenhouse gas emissions but also to improving indoor environmental quality and lowering operational costs. Energy-efficient buildings play a crucial role in achieving climate goals and transitioning to a more sustainable built environment. The Building Industry, in particular the Residential Sector has great potential for energy savings since building design is the major factor determining the energy use in buildings. Energy efficient design enables substantial savings to be made on the running costs of heating, cooling and lighting, and in same time will minimize greenhouse gas emissions and pollution from the use of fossil fuels.

Any style of building can be designed to be energy efficient and any existing building can improve its energy efficiency. There are many factors that contribute to energy efficient design (Dahksveen et al., 2003). Some must be dealt with in the planning and design process if they are to be incorporated (e.g. orientation of living areas, the building envelope), while others may be added after construction if necessary (e.g. draught-stripping to doors and windows).

The factors that influence the choice of measures to achieve energy efficiency in a building and measures that has to be undertaken, are:

- climate conditions,
- orientation - daytime living areas with large north-facing windows to receive unobstructed winter sun,
- internal planning to create zones which reduce the amount of energy required for heating and cooling,
- windows which are appropriately orientated and sized with protection from winter heat loss and summer heat gain,
- adequate thermal mass (building materials) to stabilize indoor temperatures;
- adequate thermal insulation in roofs, ceilings, walls and floors,
- good draught proofing,
- cross ventilation for summer cooling,
- an efficient hot water system and fittings, located close to user station,
- efficient lighting and appliances, and
- landscape design that assists in modifying the microclimate for more comfortable conditions.

2. THERMAL INSULATION OF BUILDING ENVELOPE

Building envelope is a term used to describe the roof, walls, floors and windows as building elements that directly control the heat gain in summer and heat loss in winter. Thermal insulation and energy efficient windows as a part of the building envelope are the most effective way to improve the energy efficiency of a building and help to improve comfort.

Regardless of the theory of heat transfer, heat flows from warmer to cooler zones until there is no longer a temperature difference. In buildings this means that in winter, heat flows directly from all heated spaces to adjacent unheated attics, garages, basements, and even to the outdoors. Heat flow can also move indirectly through interior ceilings, walls, and floors - wherever there is a difference in temperature. During the cooling season, heat flows from the outdoors to the interior of a boilding. To maintain comfort, the heat lost in the winter must be replaced by the heating system and the heat gained in the summer must be removed by the cooling system.

The appropriate level of insulation that has to be used depends on climate, building construction type, and whether auxiliary heating and/or cooling is used. A well insulated and well designed building will provide year-round comfort, decreasing energy costs (Asiepi, 2009), (AAAMSA Group, 2010).

State and local building codes typically include minimum insulation requirements, as recommended R-values, but to optimize energy efficiency, interaction between the insulation and other building components should be considered as the effectiveness of the insulation material's resistance to heat flow mostly depends on how and where the insulation is installed. Taking under consideration only the R-value and neglecting all other thermal factors, such as: air leakages; thermal bridging; conductivity and thermal mass; as well as the position of the thermal insulation in the building envelope will reduce energy efficiency. If we want to take under consideration all parameters that influence the energy efficiency and to calculate the real energy loss or gain, from or into the buildings, the whole structure has to be analyzed. Numerical procedures based on Finite element method solve this problem with sufficient accuracy (Cvetkovska, 1993), (Filipova, 2010).

3. THERMAL INSULATION AND ENERGY CONSUMPTION

In order to define the influence of the position of the thermal insulation and the U-value of the window on the energy efficiency of building structure, a cross section of one story building (part of a school that was renovated), including the whole envelope: the wall, the window, the floor, the roof, the fondation and the coresponding part of the ground (Figure 1) has been analyzed. Numerical 2D analysis has been performed by using the computer program TERMIKA (Cvetkovska, 1993).

The analysed structure without thermal insulation (Figure 1) comprises of: wall (h=2.6m, outside morter d=5cm, brick d=38cm, inside morter d=4cm); window (h=1.4m, U=3.3 W/m^{2}K); ground floor (concrete slab d=12cm, cement screed d=4cm, terrazzo d=2,5cm); reinforced concrete fondation under the brick wall and roof (ceiling of gupsum board d=2.5cm, wooden elements d=3cm, airspace with variable height and steel sheets).

The interior temperature in the room is T_{in}=+20°C, while the exterior temperature is assumed to be T_{out}=-15°C.

The problem has been treated as two dimensional because in longitudinal direction the building has suficient length (15m).

In order to define the thermal insulation influence on the energy efficiensy of the building, three different cases have been analyzed:

- non-insulated structure (Figure 1a);
- outside wall insulation with 10cm expanded polystyren, floor insulation with 2.5cm expanded polystyren and 20cm mineral wool insulation over the ceiling (Figure 1b);
- inside wall insulation with 10cm expanded polystyren, floor insulation with 2.5cm expanded polystyren and 20cm mineral wool insulation over the ceiling (Figure 1c).

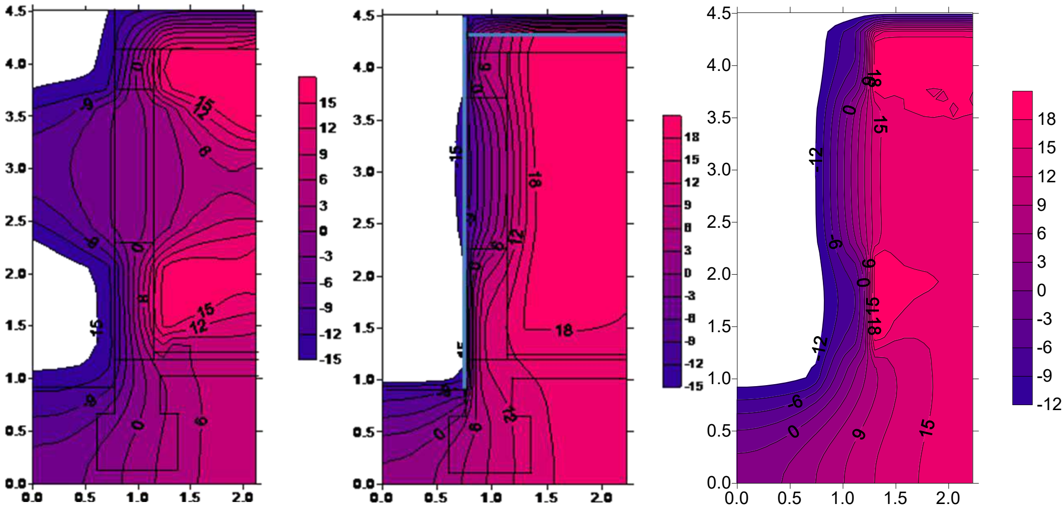
For all three cases three different types of windows with different U-values (U=1.7 W/m^2K, U=2.5 W/m^2K and U=3.3 W/m^2K) are used and the coresponding effect are analysed.

For each case study two different analysis have been performed. First, a stationary analysis has been performed that means the air temperature in the room and the exterior temperature are constant. The aim is to define the influence of the thermal insulation on the formation of the temperature profile in the structure, as well as the possibility of appearance of thermal bridges, but in this case we have no data for the energy loss trough the building envelope, so the real effect of the thermal insulation on the energy efficiency of the building can't be defined. We can't also define the capacity and the time duration of the heating source that is necessary to maintain constant temperature conditions.

The temperature profiles obtained by the steady state analysis are presented in Figures 1a, 1b and 1c. These profiles are close to the results obtained by R-value calculations only for the sections far from the connection wall-beam-floor, wall-ceiling and wall-window, where the heat transfer is one-dimensional. For all other sections the heat transfer is two or three dimensional and the temperature distribution may be defined only by using numerical procedures.

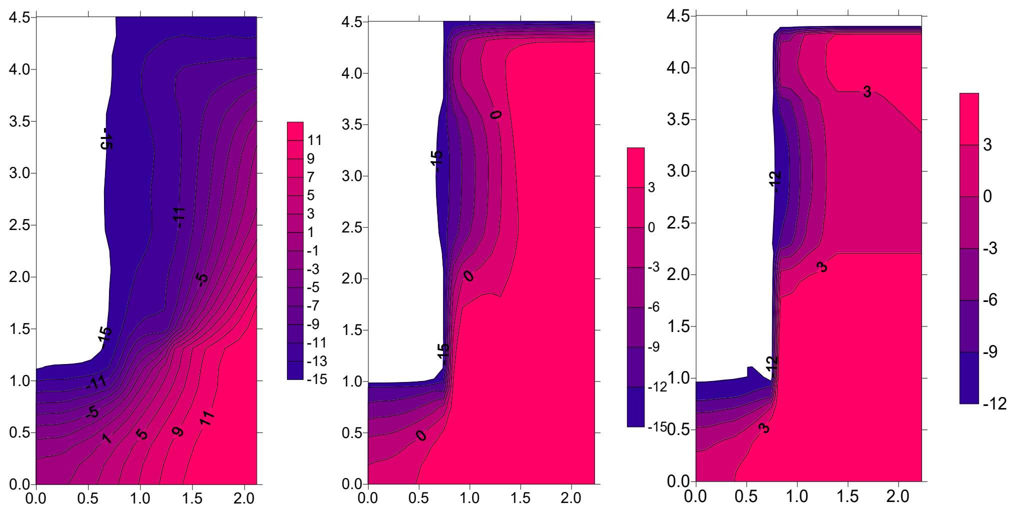
Concerning the temperature profiles presented on Figure 1 it can be concluded that in case without thermal insulation and with old and energy un-efficient windows (U=3.3W/m^2K) low temperatures penetrate deeper in the room, especially in the region of the window. The most favorable case is when the thermal insulation is outside and the old window is replaced with a new one, with thermal coeficient U=1.7W/m^2K (Figure 1b).

In order to define the energy loss trough the building envelope and the capacity and the time duration of the heating source that is necessary to maintain constant temperature conditions (directly conected with the energy consumption of building), transient heat transfer analysis are performed from the moment when the heating in the room is switched off and cooling begins. The analysis lasts up to the moment when the inside temperature reaches zero, or the cooling speed is less then 0.1°C per hour. The temperature profails for the main case studies (without insulation and old window U=3.3W/m^2K, with outside insulation and new window U=1.7W/m^{2}K and with inside insulation and new window U=1.7W/m^{2}K), after the cooling period, are presented on Figure 2.



a) b) c)

Figure 1- Temperature profiles (isotherms in the cross section of the building) in case of constant thermal conditions (T_{in}=20°C, T_{out}=15°C): a) without thermal insulation, U_{win}=3.3W/m^{2}K , b) outside thermal insulation, U_{win}=1.7W/m^{2}K, c) inside thermal insulation, U_{win}=1.7W/m^{2}K

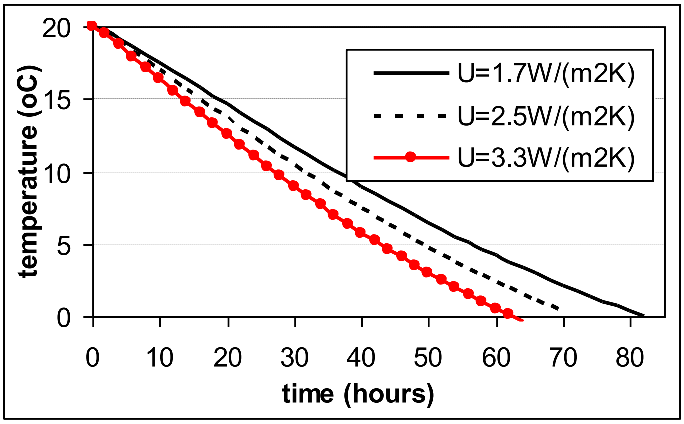


a) t=82 hours *b) t=184 hours* *c) t=153 hours*

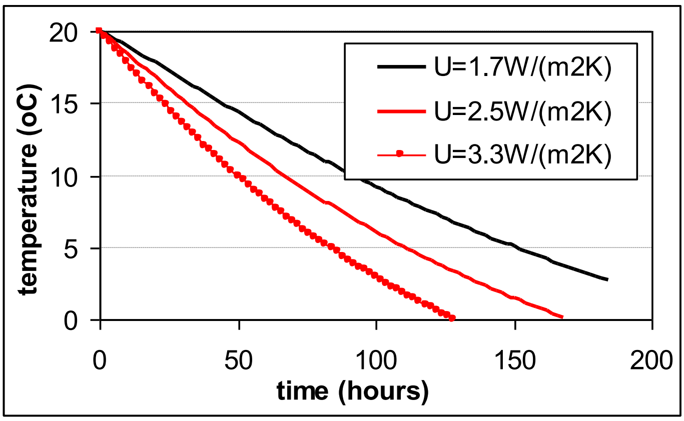
Figure 2- Temperature profiles (isotherms in the cross section of the building) after the cooling period a) without insulation, U_{win}=3.3W/m^{2}K, b) outside insulation, U_{win}=1.7W/m^{2}K, c) inside insulation, U_{win}=1.7W/m^{2}K

From the presented results it can be found out that the thermal insulation and the energy efficient window have sugnificant influence on the heat loss in winter period, and opposite, on heat gain in summer period. If we compare the isoterms in Figure 2a, 2b and 2c, that represent the temperature profils after the cooling period, it can be concluded that in case when there is no insulation and the window has low thermal resistant R (Figure 2a) the temperature in the room is much lower than in the other two cases and the zone around the window is colder than in case when the window is replaced with new one with high thermal resistant (Figure 2b and 2c). When the insulation is inside the room temperature is zero after 186 hours but after 152 hours the temperature profil is the same as in case when the insulation is outside (room temperature is oround 3°C).

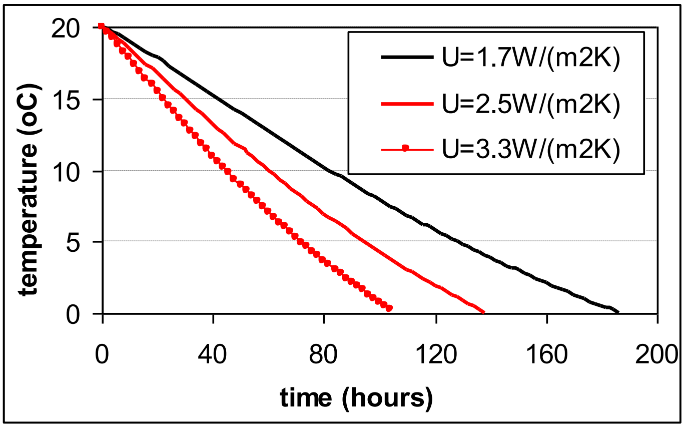
Comparison of the time needed for cooling of the room depending on the existance and the location of the thermal insulation and the U value of the window is given in Figure 3. According to the curves in Figure 3 it can be concluded that the U value of the window has sugnificant influence on the cooling period. The reason for that is the high surface ratio between the window and the whole envelope.



a) without thermal insulation



b) thermal insulation from outside



b) thermal insulation from inside

Figure 3- Comparison of the time needed for cooling of the building, depending on the thermal insulation location and U-value of the window

The insulation and its location obviously influence the time and the level of the structure cooling. Figure 4 presents the cooling time for the three case studies when the thermal coeficient of the window is the same ($U=1.7W/m^2K$). The longest time for cooling of the structure, when the heating is off, is obtained for the case of outside insulation (t>200h), that means in this case the energy loss is the least and the time for cooling to same temperature is almost three times longer than for the case without insulation (t=82h).

When the thermal insulation is placed from inside the cooling period is less then in case when the insulation is outside, but the high surface ratio between the window and the whole envelope is the main reason why the effect of the position of the insulation is not much more expresed.

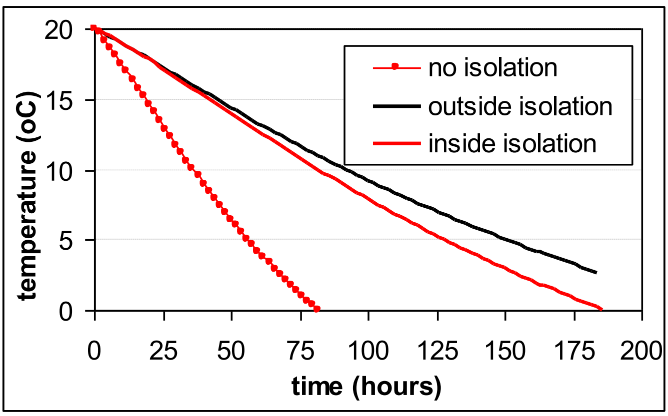


Figure 4 - Comparison of the time needed for cooling of the building, depending only on the thermal insulation location ($U_{window}=1.7W/m^2K$ for all three cases)

4. CONCLUSION

If we want to take under consideration all parameters that influence the energy efficiency of buildings and to calculate the real energy loss, the whole structure has to be analyzed. Numerical procedures based on Finite element method solves this problem with sufficient accuracy.

Thermal insulation placed on the exterior side of the wall is absolutely the best case; it avoids appearance of thermal bridges, provides the longest time for cooling of the buildings when the heating is off and the highest temperatures in the rooms when the cooling is finished.

Energy efficiency end energy loss from buildings is not always treated adequately, although the consequences are well known. All insulated building components need to be designed and built in a way to work as an integral system, which will provide continuous barrier of the heat transfer through the building envelope. In order to obtain the maximal potential of the used materials and measures, coordination of the civil engineers and architects is necessary in all design phases.

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