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Transformation of Urban Spaces: The Impact of Green Roofs in Košice, Slovakia

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Abstract: The creation of the greenIZOLA Experimental Center results from a long-term collaboration between the Faculty of Civil Engineering, Technical University of Košice, and the construction company, IZOLA Košice, s.r.o. The project focuses on a four-story administrative building with four terraces and services, asphalt roads, and warehouses located in the industrial part known as Nad Jazerom, in Košice, Slovakia. This study examines the benefits of green roofs as a case study in green transformation processes. Green roofs have multiple benefits. In addition to reducing energy demands for heating and cooling through better insulation properties, green roofs can improve stormwater management and local water balances by mitigating water runoff and increasing local evaporation. They can reduce energy demands, improve stormwater management, and enhance biodiversity. The research involved comparing pre- and post-establishment data with simulations. The roof was divided into three test segments for temperature measurements throughout the year. External climatic parameters were monitored using a weather station and a pyranometer. Long-term temperature monitoring in the individual roof layers was also conducted. This data was crucial for validating the building energy demand simulation models, assessed using the SimStadt platform. The results showed a 15–40% reduction in U-values with different types of greening. The findings could encourage more widespread implementation of green roofs in Slovakia and Eastern Europe.

Keywords: green roof; energy; simulation; transformation; building

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1. Introduction

Rapid economic growth is causing greater urbanization in many cities. The demand for the construction of new buildings and the development of cities is happening at the expense of vegetation. A key requirement for a city in green transition processes is to be able to respond to change and do so with intrinsic agility across both digital and physical aspects of its operating model [1]. Cities are packed with materials like asphalt and concrete that store heat and do not allow water through. This causes the rapid and sudden runoff of rainwater, overheating of cities, climate change that causes periods of heat and flooding, and overheating of buildings, which must then be actively cooled. By applying elements of green infrastructure to cities, we can mitigate the adverse effects of urbanization and thus improve the environment. Such elements include rain gardens, artificial wetlands, retention ponds, vegetated alleys, green roofs, and walls.

Many countries have implemented green roofs in both new and existing buildings due to their social, environmental, and economic advantages. The concept was designed to encourage the growth of vegetation on the top of the building and provide benefits for the building and the surrounding area. Each component of such a roof, such as the vegetation, growth medium, filter layer, drainage layer, and waterproofing resistant to root overgrowth, has its role in the composition. Green roofs are often designed as extensive, for their smaller substrate thickness of 80–150 mm and minimal maintenance. Semi-intensive roofs are designed with a substrate thickness of 150–300 mm and need to be watered, especially in hot and dry months. With intensive green roofs, the selection of vegetation is more diverse, due to the greater thickness of the substrate, from 300 mm or more, but such a roof also requires more maintenance [2].

Green roofs have been used for thousands of years in various regions (in both warm and cold climates). The first such grass roofs were located above caves, where the vegetation and soil on the roof were used for agricultural, residential, and ceremonial purposes. We consider the Hanging Gardens of Babylon (Hanging Gardens of Queen Semiramis), which were built around 500 BC, to be the most famous and sophisticated ancient green roofs. Subsequently, roof gardens were a common part of larger houses and palaces in ancient Rome. In countries with a cold climate, green roofs were also used on houses, now known as sod houses. The vegetation composition of the roof was used as a type of insulating material to reduce heat loss from the inside to the outside [3]. At the beginning of the 20th century, there were new developments in architecture that led to great progress in the field of roof greening [4]. Green roofs began to be actively applied in construction based on their benefits (Figure 1). In addition to the aesthetic beautification of the roof, the vegetation structure enables the roof to retain water and thus slow down the flow of water into the sewer. The captured water is then gradually evaporated through the process of evapotranspiration, creating a cooling effect on the surroundings and the building. The parts of the green roof layers protect the waterproofing layer in several ways. They stabilize the temperature, thereby reducing damage to the layer caused by expansion and contraction during alternating extreme temperatures, and they protect against UV radiation damage and mechanical damage caused by hail and human causes. At the same time, the roof can absorb noise, clean the air due to the vegetation, and increase local biodiversity.

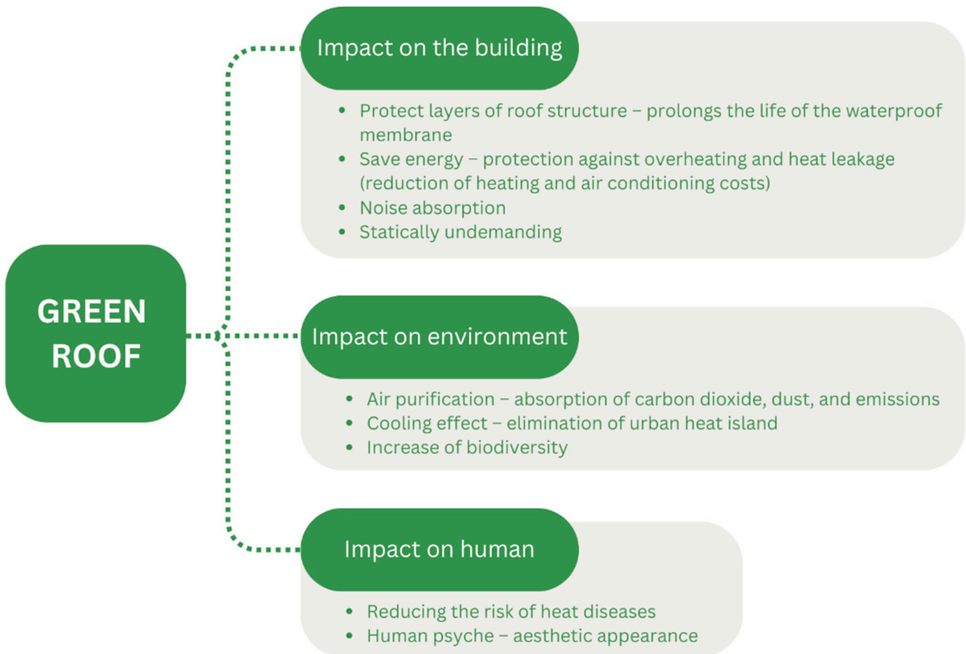


Figure 1. The benefits of green roofs and their division into three sections.

1.1. State of the Art of Green Roofs (International)

Currently, green roofs are very popular and widespread. Some countries are offering strong initiatives to apply rooftop vegetation on both new and existing buildings to achieve multiple benefits. Toronto has mandated the application of a green roof on 20–60% of the total roof area if the building has a floor area greater than 2000 m^2. In Copenhagen, a green roof should be applied to all new roofs with a slope of less than 30°. In New York, if a green roof is applied to 50% or more of the roof area, the owner can get an annual tax credit. In Minneapolis, a 50% credit in stormwater fees is available for green roof applications. Germany has been supporting the application of green roofs for a long time; for example, in Esslingen, users will receive compensation of 50% of the cost of a green roof, and in Darmstadt, users will receive 5000 Euros for its application [5].

In recent years, green roofs have received a lot of attention, as they provide various benefits in several areas. Due to the need to understand the interaction of green roofs with the construction of the building, various research studies are being carried out around the world. Experiments are carried out in laboratories under controlled conditions and in situ (in the field), where the structure is exposed to external weather conditions and internal ones from building operations. The measured data is used for simulation models (validation of models) in order to be able to evaluate the influence of the vegetation layer on the structure already in the pre-implementation phase.

Bevilacqua from the University of Calabria [6] investigated the energy properties of green roofs by simulating an extensive green roof with the transient dynamic code, TRNSYS, using real measured data on experimental roofs (uninsulated green roof, insulated green roof, and reference roof). They performed simulations in continuous operation and intermittent operation of the building. It was shown that the non-insulated green roof can reduce the peak cooling power by 4 kW and the need for cooling energy by 43.8% in the spaces under the roof. In the case of an insulated green roof, the peak power in winter decreased by approximately 2 kW and the energy saving for heating by 28.2%.

Graffin et al. [7] analyzed temperature data from black (EPDM), white (EPDM with high membrane reflectance), and green (vegetation) roofs. The roofs were equipped with instruments to collect information on temperatures, roof heat flow, and outdoor climate conditions. The most extreme daily temperatures through all the seasons were on the black roof. The temperature peaks of the white roof membrane were 17 °C cooler in summer than the black one. The average rate of heat loss in winter on the green roof was 34% lower than on the black roof, and the summer heat gain was 84% lower than on the black roof.

Arkar et al. [8] investigated the thermal response of light-extensive green roofs with a mineral wool growth medium in latent heat accumulations by using in situ measurement. It turned out that in winter, the heat loss of the green roof was smaller than the heat loss of the reference roof at night, on the coldest days, where the difference was up to 40%.

Issa et al. [9] in Texas investigated the effect of soil type, moisture content, and the presence of a vegetation layer on heat transfer through the roof. They used two types of soil—uniform sand and local clay loam. It turned out that the thermal conductivity of the clay loam did not increase gradually with soil moisture, as it did for sand. They concluded that better conditions for heat transfer are achieved when sand and clay vegetated roofs are irrigated at a depth of 10 mm per day than at twice the rate in the Texas climate.

Green roofs play a crucial role in promoting circularity and enhancing the resilience of cities against environmental and socio-economic challenges. They are nature-based solutions that utilize existing building spaces to support the greenIZOLA project's vision for a greener Slovakia. A multidisciplinary approach is necessary in transforming buildings into green structures, including life cycle analysis, water retention, and energy simulations. Local in situ experiments are essential for validating simulation programs and optimizing green roof designs specific to the location and building type.

These findings have significant implications for future research in the field of green roofs and their impact on sustainability solutions. They highlight the need for a multidisciplinary approach and local experiments to optimize green roof designs and promote their widespread adoption. The insights gained from this research represent an opportunity for scientific development and multidisciplinary connections in Slovakia within the field of construction with a vegetation layer.

1.2. State of the Art of Green Roofs in Slovakia

The history of green roofs in Slovakia does not go far back and has its bright and dark cases. In cases such as the "commercial and residential house" of Theodor Ringo and Rudolf Szel in Žilina and Vila Dr Vore in Nitra with vegetated terraces, the execution turned out well. The Nitrian villa was even mentioned in a Dutch publication about modern villas in Europe and America. However, there were also cases that could be described as "attempted operation failed" errors. As an example, a green roof was implemented above the parking garage on the Ťahanovce housing estate in Košice. The green roof was created with uncertified materials and an unproven system. After the implementation, there were several complications, degradation, and the loosening of joints and deformation in the expansion joints. Therefore, roof reconstruction was needed. System solutions with certified materials were used during the reconstruction. Currently, investors, designers, and contractors have learned from the mistakes of the past and are designing functional green roofs. They are often included in the design of new buildings, including administrative buildings, apartment buildings, and family houses. The user can receive a financial contribution for the application of a vegetation roof as a result of rainwater management (as a water retention measure) or as a subsidy from the restoration plan.

From the point of view of research on green roofs, Slovakia is only at the beginning. In recent years, two experimental roofs have been built in Slovakia. One was realized in Košice by the TUKE Faculty of Civil Engineering and the other in Žilina by the ŽUŽ Faculty of Civil Engineering.

1.2.1. Experimental Vegetation Roof UNIZA

Over the course of 2020, four green roof compositions from various manufacturers were realized on the roof of the ŽUŽ Faculty of Architecture. Currently, there are already six samples of green roofs in place. Each composition is made in duplicate; one serves to monitor temperatures and the other to measure the retention capacity of the roof (sample). Compositions of green roofs differ in the use of different filters, drainage layers, or mineral wool to retain water. The measurements confirmed that the green roof reduces the temperature of the covering by approximately 35 °C in the summer, and the phase shift of the temperature oscillation is approximately 2.5 h in the transitional period and up to 3–4 h in the summer. The monitored sample reduced the water runoff by up to 83% with a higher amount of precipitation, above 30 mm. At lower totals during the summer, the composition was able to retain the total falling rainwater [10,11].

1.2.2. Experimental Vegetation Roof with Biodiversity Potential in Košice

In 2019, preparations began for the application of an experimental roof with biodiversity potential in Košice. The idea of the research was to compare the heat–moisture response of an extensive roof with different substrate thicknesses and a reference roof. The test terrace was divided into three test segments for the purpose of in situ experiments. Above the waterproofing layer of the roof, the experimental parts are divided into an extensive vegetation roof with a substrate thickness of 120 mm (TS I.), a reference roof finished with a gravel layer of 60 mm (TS II.), and an extensive vegetation roof with a substrate thickness of 240 mm (TS III.) [12] (Section 2.1. Case Study: greenIZOLA project an urban mixed-usage building in Košice).

During the measured period in summer, it was found that the surface temperature of the waterproofing with the vegetation layer was reduced by 14 °C at a substrate thickness of 120 mm, and 21 °C at a substrate thickness of 240 mm compared to the reference roof. During summer rainfall, retained water in the test segments affects the lowering of temperatures in the individual layers. During the winter months without snow, when the outside temperature reached −9 °C, the surface temperature on the waterproofing of the reference roof was −8.3 °C. In the case of the vegetation segments, this value was close to 0 °C. In the event of snow, temperatures stabilized in all the segments [13].

2. Materials and Methods

In our investigation, we used research methods and analytical procedures based on a systemic-constructivist approach and research principles. A main hypothesis for the greenIZOLA project was formulated: We propose that a direct relationship exists between the quality of life experienced by residents and the environmental quality of their workplaces, specifically buildings. In the presented part of the project, we state that the implementation of a green roof will lead to a reduction in rainwater runoff from the roof, have a significant impact on reducing the building's heat demand, and the thermal transmittance U will be lower. This relationship is further influenced by the degree of green infrastructures incorporated in both the inner and outer spaces. Our hypothesis is grounded in the understanding that both the work environment and urban space significantly impact individuals' well-being and productivity. In addition, the presence of green spaces has a substantial effect on climate change.

2.1. Case Study: greenIZOLA Project, an Urban Mixed-Usage Building in Košice

The greenIZOLA project, a result of a long-term collaboration between the Faculty of Civil Engineering and the construction company, IZOLA Košice, s.r.o., aims to transform the site into an industrial zone using construction with a vegetation layer. The project focuses on an office building and its adjacent areas in Košice, located in the industrial part known as Nad Jazerom.

Košice, situated in the northern temperate climate zone, experiences a regular alternation of four seasons and changeable weather with relatively even precipitation distribution throughout the year. The entire land area, approximately 3700 m^2, is mostly built up, with two storage halls, shelters, and an office building. The office building is a four-story reinforced concrete structure with a filigree ceiling and flat roof. The building area is around 624 m^2. It features four terraces (two on the second floor facing west and north, and two on the fourth floor facing south and north). The building envelope consists of Porotherm 20 masonry insulated with thermal insulation, EPS Baumit open Therm, in thicknesses of 140 and 180 mm.

The roof and terraces are constructed as a single-skin roof structure with an inverted layer order. The gradient layer is made of foam concrete, the waterproofing consists of two layers of asphalt strips, and the thermal insulation is made of extruded polystyrene Roofmate, 160 mm thick. The project was gradually formed into eight phases, which were gradually implemented and adapted to current needs. Blue-green infrastructure elements, which have the potential to retain rainwater, are used. It is currently focused on different types of green roofs and green facades, which are implemented in phases (Figure 2):

- 1st Phase—Experimental green roof with biodiversity potential (the southern terrace).
- 2nd Phase—Green roof on the existing shelter with three different growing media (outside the building).
- 3rd Phase—Carport with a green roof (outside the building).
- 4th Phase—Extension on the western terrace (the western terrace).
- 5th Phase—Biodiverse green roof (the northern terrace on the 2nd floor).
- 6th Phase—Different types of green roofs (the northern terrace on the 4th floor).
- 7th Phase—Biosolar green roof (roof of the building).
- 8th Phase—Green facade.

The first phase of the project represents an experimental green roof with biodiversity potential. The southern terrace on the fourth floor was selected for the in-situ experiment. The roof was divided into 3 test segments (see Section 1.2.2, Experimental vegetation roof with biodiversity potential in Košice) with measuring infrastructure for measuring selected physical parameters. The roof was supplemented with thermal insulation based on a PIR board with a thickness of 60 mm and waterproofing based on PVC foil. The vegetation part of the roof was designed as a system solution from the Bauder company, from bottom to top: a protective mat, drainage and accumulation layer, filter layer, and 120 mm- or 240 mm-thick substrate (Figure 3). Both vegetation test segments (TS I. and TS III.) have an area of 17.6 m^2, and the reference test segment (finished with a gravel layer) has an area of 8.96 m^2. The composition of the reference segment consists of a geotextile and a gravel layer (above the waterproofing). Table 1 describes the water-storage properties of the used green roof materials, and Figure 3 shows the procedure for the realization of the experimental roof. During its implementation, temperature sensors, Pt 100 class "A", were installed in the individual layers of the test segment compositions: under the ceiling structure; under the thermal insulation; on the waterproofing layer; and in the substrate (TS I. and TS III.) Moreover, heat flux sensors were placed under the ceiling structure for every test segment. The Ahlborn FMD760 weather station and the Ahlborn FLA 628 S pyranometer were installed on the roof to measure and record external parameters (temperature and relative air humidity, atmospheric pressure, wind speed and direction, solar radiation intensity, amount, and intensity of atmospheric precipitation). The measurements took place in two circuits with one-minute recordings. The first circuit recorded external parameters and the second recorded selected physical quantities and changes over time inside the experimental roof segments. Subsequently, the data are transformed into one-hour averages or sums, according to the requirements.

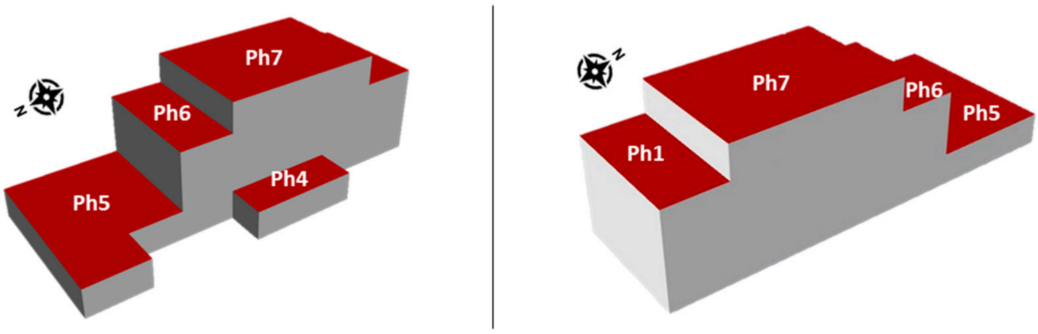


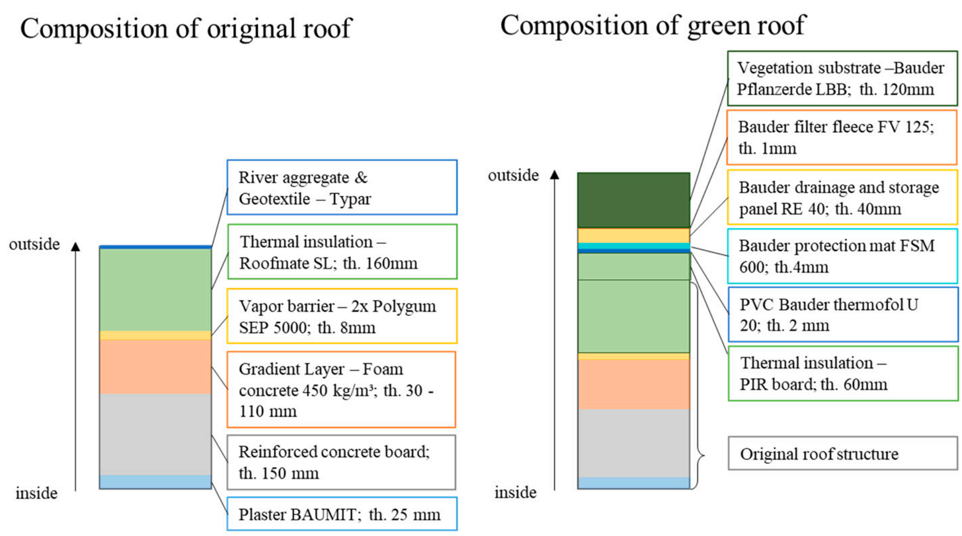
Figure 2. Construction of the greenIZOLA building with the marking of phases. Phases 2 and 3 are not shown as they are not on the building.

Figure 3. Photographs of the construction of the experimental green roof with biodiversity potential. 1—original state of the terrace; 2—removal of unwanted layers; 3—adding an additional thermal layer, a new waterproofing layer, and application of the measuring infrastructure; 4—installation of protection, drainage, and accumulation layers; 5—distribution of the substrate; 6—experimental roof after completion of construction works.

Table 1. Properties of the used green roof materials.

Drainage and storage panel, Bauder RE 40	
Material	HDPE
Height of element	40 mm
Hydroaccumulation	Approx. 13.5 L/m^2
Vegetation substrate, Bauder LBB-E	
Thickness	120 mm
Main mineral element	Lava, slate, pumice
Capacity of hydroaccumulation	40% volume
Vegetation substrate, Bauder LBB-E	
Thickness	240 mm
Main mineral element	Lava, slate, pumice
Capacity of hydroaccumulation	40% volume

Two scenarios are considered for the purpose of the work: the former condition, without a green roof; and the new condition, where a green roof structure is applied to each terrace and roof. The green roof with a substrate thickness of 120 mm on the southern terrace is used. Figure 4 illustrates the composition of the roof structure before and after constructing the green roof (former condition and new condition). After the application of the green roof, the green area will be 459.78 m^2, which represents 82% of the building's roof and terrace area.



(**a**) (**b**)

Figure 4. Roof composition before (**a**) and after (**b**) construction of the green roof of the greenIZOLA building.

2.2. SimStadt

The urban energy simulation platform, SimStadt0.10.0_20230828, is software for creating city quarter energy concepts, which has been used since its development in 2012 [14]. Since then, so-called workflows to assess photovoltaic rooftop potentials [14], building heating/cooling [15], electricity demand [16], or water demand have been developed. Beyond the energy sector, the first theoretical studies on the benefits of green roofs have been performed [17].

The tool requires 3D building models in CityGML (City Geography Mark-up Language) format, which contain the geometric properties and the type of use of a building [18]. This input is coupled with a building physics library [19] and the dynamic energy simulation engine INSEL [20]. SimStadt is structured as a modular system with workflows that allow its users to analyze energy conditions, e.g., the above-mentioned aspects of a building or a city quarter based on a consistent set of input data, which greatly facilitates the comparison of different technologies and the creation of integrated scenarios. A comprehensive overview of the simulation platform's methods and its limitations can be found in prior publications [17–21].

The building physics library in SimStadt required adjustments to examine the impact of green roofs on heat demand. It consists of four parts (see Figure 5). Part one hierarchically structures the German residential building typology in building types and year of construction classes. In part two, each class of year of construction per building type is depicted with default values for the outer walls, ground, and roofs. Parts three and four show more background information on typical materials used for construction and include detailed parameters for each material.

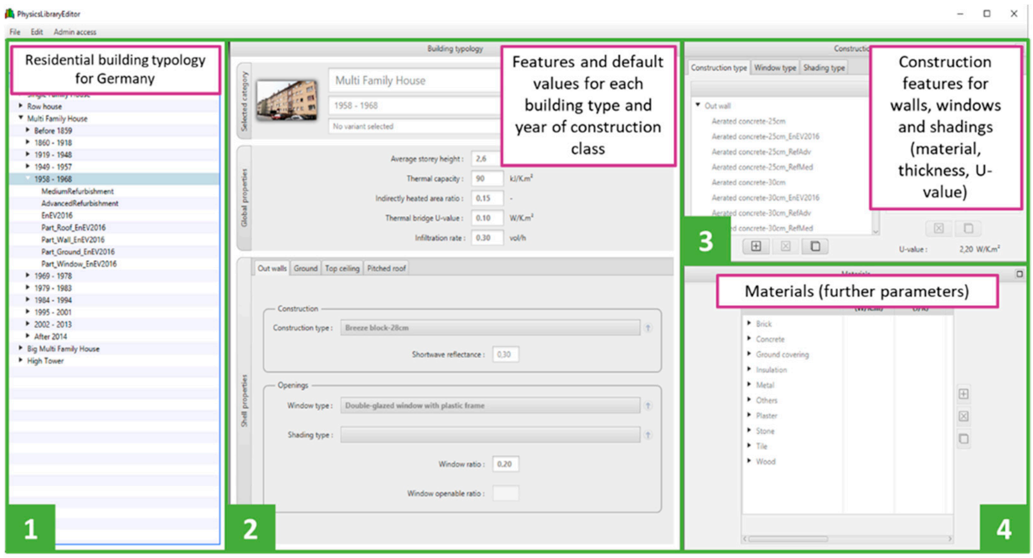


Figure 5. Overview of building physics library in SimStadt.

This building physics library was adapted to reflect the features of the greenIZOLA experimental building before and after the construction of the green roof. Hereby, the most prominent parameter change was the U-value of the roof. The determination of the roof's U-values is explained in the following section.

2.3. U-Value

By applying a green roof, it is possible to improve the insulating properties of the roof and thereby reduce the annual energy consumption. However, a green roof is a dynamic element, and its thermal and technical properties are influenced by several factors. Therefore, the vegetation part of the roof (above the waterproofing layer) is not included in the classic calculation when determining the U-value. Regulations in Slovakia require that the U-value be 0.15 $W/m^2{*}K$ for roofs of new buildings and roofs that were reconstructed in 2020 when the changes were made.

The substrate of a green roof can consist of various components such as clay, porous rock, crushed aggregate, crushed expanded shale, sand, and organic matter. The type of mixture and the compaction itself have an effect on the thermal conductivity of the roof substrate. At the same time, the water content (humidity) can affect the ability of the growth medium to conduct heat. Sailor and Hagos [22] studied the thermal conductivity of the substrate (in the compacted state) at different values of substrate humidity. The thermal conductivity of a dry substrate doubles when the humidity increases to about 35% of saturation and triples when the substrate is completely saturated with water.

Studies monitoring the thermal interaction of the green roof in a steady state and an unsteady state (dynamic conditions) are ongoing in the world. The benefits of applying such a roof to a building and saving energy are evaluated with the help of in situ experiments and simulation programs. It turns out that a well- to moderately-insulated roof, to which a vegetation layer is added, can improve the coefficient of thermal conductivity by 8–26% and on non-insulated roofs by up to 80% [23,24].

On the southern experimental roof, the interaction of the green and reference compositions of the roof was observed in our climatic conditions (Figure 6). For two years, the temperature courses inside the experimental roof structure, internal surface temperatures, and heat flow density through the internal surface of the ceiling structure were aligned. The test segments were exposed to the extremes of the current seasons during the year. Phase shifts of the temperature maxima and the reduction of temperature extremes were visible in the case of the vegetated roofs during the summer. Hence, the vegetation segments protected the structure from overheating. During the winter months, a more intense heat flow was recorded through the inner surface under the reference segments compared to the vegetation segment [12]. As a result, the building loses more heat in the case of the reference roof structure.

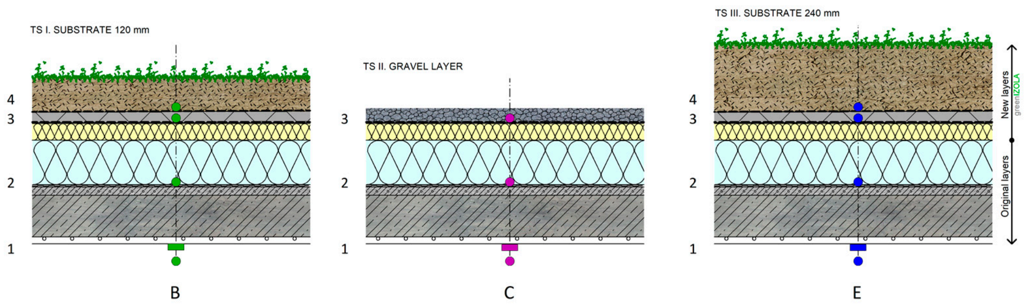


Figure 6. Compositions of test segments and placement of sensors in individual layers.

By monitoring the test segments and analyzing the collected data, it appears that the vegetation layer with a substrate thickness of 120 mm can improve the U-value by 10% compared to the reference roof. The new value was subsequently used in the simulation system in the case of the application of a green roof with a substrate thickness of 120 mm.

3. Results

3.1. Stormwater Management

The proposed green roofs on the terraces and roof of the building will contribute to an 83% increase in the area of vegetation. This area will have the capacity to accumulate rainwater, thereby delaying its peak flow. Rainwater is first captured by the vegetation and substrate. Excess water is drained through the filter layer into the drainage layer. Once the drainage layer is completely filled, the water will run off. A portion of the captured rainwater serves as a water source for the plants, while another portion evaporates, thus remaining part of the natural water cycle. The reduction of runoff depends on many factors, such as the type of vegetation, the thickness and type of substrate, the type of drainage material and its storage capacity, the intensity of precipitation, the duration of the previous dry season, and the slope of the roof. A calculation was carried out to determine the rainwater flow per year, Qr (m^3/year), of the building without vegetation and with the construction of all the green roofs. The following equation was used:

$$Q_r = A * H_z * C, \tag{1}$$

where A (m^2) is the drainage area, H_z (mm) is the long-term rainfall total for the given location, and C (-) is the runoff coefficient.

The long-term total on the territory of Košice according to SHMU was 624 mm per year in 2022. The runoff coefficient is a dimensionless parameter. It is determined using a test structure with a slope of 2%, on which irrigation was applied to saturate the material and then left to drip for 24 h. The structure is exposed to 15 min of block rain of 24 L/m^2. The output water flow is monitored as a function of time. The measurement must be repeated three times at 24 h intervals. Certain standards and directives determine the runoff coefficient depending on the thickness of the substrate and the slope of the roof. For comparison, the runoff coefficients for green roofs were considered from the Slovak standard (STN 73 6760 2009) [25], the German standard (DIN 1986-100:2016-12 2016) [26], and the FLL directive (FLL 2008) [27], which were used for the calculations in Table 2.

Table 2. Rainwater flow per year according to the German standards, Slovak standards, and the FLL directive, using the rainwater runoff coefficient, C, for green roofs according to the thickness of the substrate.

	Green Area (m^2)	Substrate Thickness (mm)	STN 75 6760	DIN 1986-100	FLL	Bauder Test
Western	34.46	100	0.7	0.5	0.5	0.11
Northern	131.75	250	0.3	0.4	0.2	0.1
Southern	17.6	120	0.4	0.4	0.4	0.1
	17.6	240	0.3	0.4	0.2	0.1
Northern	45.35	200	0.4	0.4	0.3	0.1
Roof	213.02	120	0.4	0.4	0.4	0.1
Non-green area	101.01	-	0.9			
Rainwater flow (m^3/year)			168.62	173.64	152.17	85.63

In the case without the green roof, the runoff of rainwater is 314.94 m^3/year. After completion of all the phases (realization of the green roofs), the runoff will be reduced due to the vegetation layer, which covers 83% of the roof area of the building. According to the Slovak standard, the runoff should drop to 168.62 m^3/year and, according to the FLL directive, up to 152.17 m^3/year. The difference between the standards is only 5%. Therefore, it can be assumed that 45–52% of the rainwater that falls on the building per year will be captured in the proposed green roofs.

Moreover, the calculations can be compared with the laboratory values of the system solution from Bauder. Laboratory tests showed that in the case of a system solution with a substrate thickness of 100 mm, the runoff coefficient is 0.11, and with a thickness of 120 mm, it is 0.1. If this system were used for every roof and a coefficient of 0.1 was applied in the calculation in the case of substrate thicknesses of 120 mm and more, the rainwater runoff would decrease by 73%.

3.2. Energy Consumption

In order to determine the energy-saving potential that can be achieved through a green roof, the building of the case study was digitally reconstructed. In the first step, the building was drawn in the CAD tool, SketchUp, and subsequently translated into a 3D building model in CityGML format. This step was necessary due to the lack of 3D building data models in the CityGML format in Slovakia.

In the CityGML file's metadata, the building's location was set to Košice, Slovakia, thus allowing the use of the correct local weather data in SimStadt. Furthermore, the original building's U-values of windows, walls, roof, and floor slab were transferred to the building physics library. With this, the monthly heat demand of the building was determined according to DIN 18599. SimStadt divides the greenIZOLA building into five building parts, as seen in Figure 7. To determine the impact of a green roof on the building's heat demand, the U-value of the respective roof part was adjusted according to the calculation described in Section 2.3.

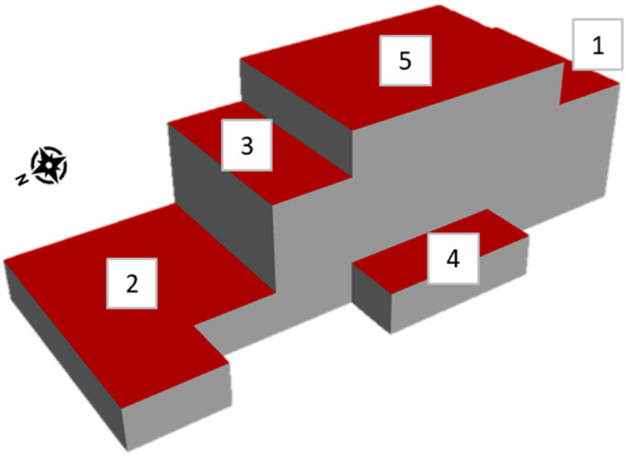


Figure 7. Five parts of the greenIZOLA building.

The original U-value of the roof was calculated as 0.184 W/(m^2∗a). After the installment of the green roof, the new U-value of the roof decreased to 0.108 W/(m^2∗a). This new U-value was imported into SimStadt, and the heat demand for the building with the green roof was calculated. According to the simulation, the building's annual heating demand can be reduced by 4%. For the individual parts of the building, however, the results can be viewed in a more nuanced way.

Building part 2 shows (Table 3) the greatest savings of 11% due to its high ratio of roof to wall/ground area. It is followed by building part 4 with 8%. Building parts 1, 3, and 5 each achieve a heat demand decrease of 3%.

Table 3. Comparison of different parameters for all five building parts of greenIZOLA with and without green roofs.

Building Part	Total Wall Area	Total Roof Area	Mean U-Value (without Green Roof)	Mean U-Value (with Green Roof)	Heating Dem. without GR)	Heating Dem. with GR
	(m^2)	(m^2)	(W/(m^2∗a))	(W/(m^2∗a))	(kWh)	(kWh)
1	370.9	79.6	0.5	0.48	17,458	16,889
2	190.0	189.8	0.37	0.32	13,771	12,456
3	364.8	75.5	0.5	0.49	17,104	16,563
4	100.5	48.3	0.42	0.39	4591	4253
5	794.4	230.8	0.48	0.46	55,706	53,985

4. Discussion

The presented results highlight the contribution of green roofs to circularity and cities' resilience. Green roofs are gaining interest as nature-based solutions to counteract several environmental and socio-economic problems associated with urban sprawl and climate change. Taking advantage of the existing space on top of buildings, the integration of green roofs will support the greenIZOLA project vision of a gradual green conversion transition towards circularity and resilience in Slovakia. In order to boost these services, green roofs need to be effectively incorporated and replicated in the urban landscape [28–31].

Our article is a part of the mentioned project and aims to transform the building into a green structure that is economically and environmentally justified. The transformation process uses a multidisciplinary approach, including data analysis, life cycle analysis, water retention, modeling in the environment, analysis of vegetation units, energy and Multiphysics simulations, building information modeling, etc.

This knowledge has been proven by several research studies [7–11,29]. However, the quantification is different depending on the location, the type of green roof material used, the type of building (material point of view), the operation of the building, the type of vegetation, and the size of the vegetation cover. Therefore, the implementation of local in situ experiments is key for the possible validation of simulation programs. The information obtained from the work is specific to this situation—location, type of building, type of operation, and the type of green roof. It can serve as a basis for further research, which is necessary for the optimization of green roof designs in our location.

The SimStadt simulation confirmed that the amount of deviation between simulated demand and real consumption with green roofs (the key parameter in the simulation is the adjusted U-value of the roof) is necessary. If the deviation is large, it may be due to the quality of the 3D model, other interactions not yet considered, or the consumer consuming much less or more.

Regarding the economic benefits, we need to consider the investment costs of the green roofs in greenIZOLA, how much energy is saved, what are the energy costs, and what is the payback period. In our SimStadt GreenRoof simulation, we found that the payback period is long, and therefore does not provide a good economic justification for the investment and energy-saving costs alone.

It is argued that green roofs will play an important role in the future as they have a cooling effect on buildings, especially in urban areas [6,31–42]. Our contribution is the first to simulate green roofs with SimStadt on a self-developed 3D building model with an adapted building physics library in Slovakia.

The implementation of green roofs offers numerous benefits, including the retention of rainwater, which is gradually evaporated, thus remaining in the water cycle. The primary difference between extensive and intensive green roofs is the depth of the growing medium and the amount of maintenance required. Extensive green roofs are lightweight and have a shallow growing medium, typically less than 200 mm, which makes them ideal for flat roofs. They are primarily designed to promote biodiversity and require minimal maintenance. On the other hand, intensive green roofs are the most expensive and thickest type of living roof. They can replicate a natural landscape and can even be used for agricultural purposes. They provide the best insulation, drainage management, and temperature regulation. They require more maintenance than extensive green roofs and are better suited for highly visible, accessible roofs.

The amount of water captured by a green roof can vary based on several factors, such as the type of substrate used, the drainage and accumulation layer, the slope of the roof, the intensity of precipitation, and the duration of the previous dry season. As Maschler (2022) [30] states for practical applications, the theoretical approach needs to be adapted to the usable soil water storage capacity and relationships describing evapotranspiration for given substrate–turfgrass combinations.

Simultaneously, the vegetation layer serves as a protective barrier for the waterproofing layer against direct UV radiation and mechanical damage. It also stabilizes the temperature of this layer, preventing material expansion and contraction. The green roof shields the building from overheating in summer and heat loss in winter. It reduces the annual need for heating; however, this depends not only on the type of roof but also on the ratio of the roof area to the wall/ground area. In the case of well-insulated roofs, this effect can be minimal or even negligible. Moreover, the created vegetation areas enhance city biodiversity. By combining different types of roofs (including vegetation), alternative habitats for fauna and flora are created. Overall, green roofs can be an effective way to improve building energy efficiency and reduce the environmental impact of buildings.

The maintenance of green roofs depends on the type of green roof, as already mentioned in the introduction. Minimal maintenance means that the roof needs to be checked once or twice a year to remove unwanted (invasive) plants and possibly fertilize. The intensive green roof has a greater substrate thickness due to more demanding vegetation. Its maintenance is necessary on a regular basis, controlling and removing invasive plants, fertilizing, cutting vegetation or lawns, and watering the roof.

In our case, two of the experimental green roofs are extensive, although TS III. has a substrate thickness of 240 mm, which could appear to be a semi-intensive roof. However, its maintenance is the same as that of a roof with a substrate thickness of 120 mm. Maintenance only consists of removing unwanted invasive plants.

Even though the test segments had the same maintenance (minimum), the vegetation on the 240 mm substrate did better. The same plants were used for planting, and their location was identical for both TS I. and TS III. Some vegetation species completely disappeared after three years on TS I. with a substrate thickness of 120 mm, such as Dianthus deltoides 'Zing Rose' or Sedum Kamtschaticum. Although no irrigation or fertilization was added for TS III., the green roof was able to create suitable conditions for vegetation growth by retaining sufficient moisture and nutrients. Therefore, the given system solution is suitable in the case of choosing an extensive (low-maintenance) green roof but with more lush vegetation for our climatic conditions.

As a limitation of our research, we assume that further research must continue with the comparison of simulated data to measured data and analyzing the real benefits of green transformation impact. Due to the lack of built experimental green roofs in Slovakia, we see the vision of the greenIZOLA Experimental Center as important and inevitable. The current study is significant in the green transformation process and has a profound impact on sustainability solutions. The insight represents an opportunity for scientific development and multidisciplinary connections in Slovakia within the field of construction with a vegetation layer and supports our hypothesis.

5. Conclusions

Green roofs embody a transformative approach to sustainable urban development, offering economic, ecological, and societal benefits. These benefits position green roofs as invaluable assets in contemporary architecture. As cities worldwide grapple with climate change and urbanization, green roofs emerge as beacons of innovative and sustainable design. Our study compares measured and simulated data for temperature, water runoff, energy consumption, and biodiversity across three types of roofs: extensive, intensive, and reference. The findings reveal that green roofs can reduce the U-value of roofs by 15–40%, enhance stormwater management and local water balances, improve biodiversity, and extend the lifespan of roofs. This study provides valuable information for validating building energy demand simulation models using the SimStadt platform. It concludes that green roofs offer multiple benefits for urban environments and advocates for their more widespread implementation in Slovakia and Eastern Europe, and as such, confirms our proposed hypothesis.

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