INTERNATIONAL JOURNAL OF CONSERVATION SCIENCE
ISSN: 2067-533X Volume 15, Special Issue 1, 2024: 129-140 www.ijcs.ro
DOI: 10.36868/IJCS.2024.SI.11

TREATMENT OF OUT-OF-CONTEXT BUILDINGS DURING THE RESTORATION OF HISTORICAL TERRITORIES USING GREEN STRUCTURES

Tetiana TKACHENKO[1,*], Viktor MILEIKOVSKYI[2], Adam UJMA[3], Mukhlis HAJIYEV[4]

[1] Environmental Protection Technology and Labour Safety Department, Faculty of Engineering Systems and Ecology, Kyiv National University of Construction and Architecture, 03037, Kyiv, Ukraine
[2] Heat-Gas Supply and Ventilation Department, Faculty of Engineering Systems and Ecology, Kyiv National University of Construction and Architecture, 03037 Kyiv, Ukraine
[3] Faculty of Technical Sciences, University of Applied Sciences in Nysa, Nysa, Poland
[4] Department of construction structures, Faculty of Construction, Azerbaijan University of Architecture and Construction, Baku, Azerbaidjan

Abstract

There are historical places with out-of-context buildings, often of low quality. To restore the places, destruction requires heavy machines and may cause strong vibrations and excess load on the historical pavement intensifying destruction and ageing. Giving the appearance of historical objects requires expensive decoration. Hiding by living plants is the most perspective way with positive side effects: thermal insulation, passive air-conditioning, solar radiation control, urban heat island prevention, air cleaning and sanitation, carbon sequestration, noise absorption, better rainwater management, increasing biodiversity, etc. The approach is shown in an example of a bank at the historical centre of Byczyna, Poland. As the building is too large, using a context collage is proposed to show the results. The fears of damage to the structures by fungi and attraction of biting insects are debunked using three ways – analysis of the facing state under the greening, estimation of the critical air state around the greening, and by field studies of the relative humidity under the greening. CFD simulation shows a significant heat insulation effect of the greening in the heating period. The problem of penetration of moustaches into the facing can be solved by winding the ampeleous plants on a wooden lathing or a grid.

***Keywords**: Out-of-context building; Green structure; Vertical greening; Hiding; Heat insulation; Fungi; Biting insect; Relative humidity*

Introduction

Historical places are very important [1-11] as a national honour, historical information sources, blend of beauty, inspiration for people of art and attractive places for tourism, which give additional income to the municipal budget and different branches of business. Interesting research [12] shows that awareness of the history incl. heritage for modern urbanism may help increase city resilience, biodiversity, etc. Thus, we need to preserve their historical appearance.

The authors encounter historical places, spoiled by out-of-context buildings. The last ones are almost built during the socialist or early post-socialist period of development. The

* Corresponding author: tkachenkoknuba@gmail.com

quality of such buildings is often very low. The structures were made very quickly with violations of norms. But there are some exceptions such as the Tour Montparnasse in Paris, which make dissonance with Basilique du Sacré Cœur or Louvre Palace. Most such buildings violate video ecological principles [13]. The ancient heritage should support mental health, but the out-of-context buildings are too aggressive for the perception.

There are three options for the treatment of such buildings to repair the view. The first and the more obvious is destruction. Nevertheless, this is impossible for skyscrapers due to very expensive procedures and the unprecedented load on the environment. For other buildings, it requires heavy building/transport machines and may cause strong vibrations and excess load on the historical pavement, which intensifies the destruction and ageing of the historical objects.

The second option is to give the appearance like the historical objects. This way is applicable to new buildings around the historical places. The existing out-of-context buildings can have very off-topic shape or a glass envelope, which make the approach inapplicable. Otherwise, this requires very expensive decoration, usually hand made.

And the third option is hiding such objects with minimum intrusion to their structures. It's impossible to use the reflective envelope to inscribe the building. In computer models, it can have a good appearance. It's because we see it not as a passer but from the point of view selected by the architect. Nevertheless, in real life, this architecture is aggressive for mental health.

We propose to use "green" structures to make such objects friendly to the historical environment and mental health. The idea of using "green" structures for hiding has been used for military purposes for at least a half of century. The most known object is Wolfsschanze (Wolf's Lair) – Hitler's headquarters in Gierłoż, Poland (Fig. 1).

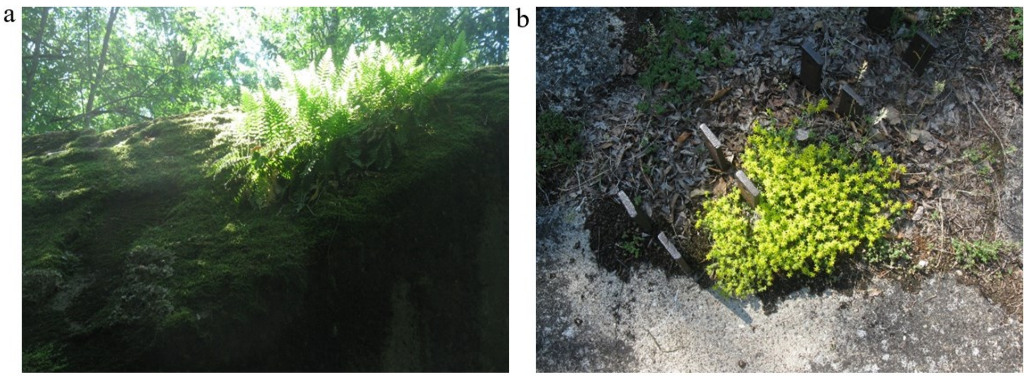

Fig. 1. Wolf's Lair (Wolfsschanze) - Hitler's headquarters in Gierłoż, Poland:
a – the green roof above the bunker; b – a fragment of the green roof with ground support elements

For small buildings, it's possible to use vertical greening – ampeleous plants on walls. For better performance, it's possible to use vertical-horizontal greening. The plants are growing from the walls to the roof. For greater buildings, we can fix trays with plants on the walls.

The latest author's proposal is horizontal and horizontal-vertical greening – placing the trays and/or the pots on the roof. Ampeleous plants can cover the roof and then the walls or descend from trays at the roof perimeter. For this kind of greening, it's possible to use the ground-cover plants or the plants that have branches above the ground at the same height such as *Juniperus sabina L.*

There are a lot of scientific works mentioning or performing case studies and simulations of positive effects on greened buildings and the environment [14-35] such as additional thermal insulation [17, 19, 21, 22, 28, 30, 35], passive air-conditioning (cooling effect) due to transpiration/evapotranspiration [16, 17, 19, 21, 22, 24-28, 30, 35], solar radiation control [17, 19, 24, 26, 27, 30-32, 35], urban heat island prevention [15-17, 20, 23, 26, 29, 35], air cleaning and sanitation [14, 15, 35], carbon sequestration [18, 29, 33, 35], noise absorption [14, 35], better rainwater management [14, 24, 29, 34, 35], increasing biodiversity [14, 35], human-friendly aesthetic environment [14], prolonging of the building life [14], etc. Succulents are fitted to warm and dry climates. They use CAM-metabolism to close the stoma during the day to save water. Thus, they don't provide a good cooling effect [28] during the day.

Nevertheless, there isn't enough understanding of the numerical values of the positive effects because of too little laboratory research. In [36], the thermal performance of a green roof model and the same model without all green roof layers was investigated in open air. The influence of the vegetation layer can't be extracted. The ambient parameters are uncontrolled.

Sensible heat fluxes are investigated in a laboratory [37]. A cold plate method is used. Under the green roof model, a plate with even cooling should be put. The stand is equipped with thermal and heat flux sensors. Another attempt to experimentally evaluate the thermotechnical properties of green roofs was performed in [38]. But the wind tunnel was overfilled by plants, more than 50 % in some sections, which makes the air velocity unknown. The second problem is the detachment phenomena at the front of the model.

The authors' method [39] gives the correct results for the thermal resistance and the cooling effect of the vegetation layer on a green roof and the cooling effect of vertical greening. The results show high unevenness of the heat transfer through *Lolium perenne* because of non-even growth. The wind changes the unevenness due to uneven blowability. But the thermal insulation is significant.

The cooling effect of *Lolium perenne* is more even. It was approximated by the following simple equation (1), in °K:

$$\Delta T_{.} = (0{,}508\ \mathrm{atan}(w) + 0{,}543)\ \mathrm{atan}^2(w) + 0{,}752. \qquad (1)$$

Based on equation (1), the indirect decrease of CO_2 release because of less cold demand can be calculated by the work [40]. This gives additional environmental effects. Nevertheless, the heating period, where the plants lose foliage, wasn't investigated.

As a result of the literature analysis, the hiding of out-of-context buildings by plants gives more opportunities than other treatment options for both the buildings and the environment. The most often question is the influence of the plants on the structures, which often are not good quality on the object considered.

The authors' opinion collection shows that many people are afraid of relative humidity under the plants causing fungi development. The other fear is the problem of biting insects passing the rooms. Thus, to implement this very prospective direction of reparation the historical places, we need additional research.

Materials and methods

To show the possibility to hide the out-of-context building, we'll use images from the centre of the Poland town Byczyna. In the middle of the historical square, there are a one-story shop and a one-story bank (Fig. 2a), which are built in socialist and post-socialist times. The quality of the structures is very poor (Fig. 2b-d). We can't apply an additional significant load.

Fig. 2. The bank in Byczyna: a – general view; b-d – the quality of the wall facing

We'll use vertical greening by *Parthenocissus quinquefolia*. and *Hedera* on the example of the bank. The authors' images of the plants will be overlaid according to the perspective. As the building is very large, we couldn't obtain the panorama with adequate sizes of surrounding buildings. In this case, we propose using a context collage (Fig. 3). Pictures from different points should be put together without spaces, if possible.

Fig. 3. Context collage of the historical centre of Byczyna with the bank is in the middle picture

At the middle of the collage, we should put the out-of-context building or structure. The hidden building should be put in the same second collage. If no place to publish two collages, it's possible to combine both non-hidden and hidden objects in the same collage, better if there are images of context buildings between and around them.

To avoid the fears about relative humidity, we'll use three approaches. The first one is the analysis of the state of the facing behind the vertical greening. It's necessary to search for fungi/mould colonies or damages of facing by them.

The second approach is the analysis of the cooling effect by evapotranspiration. The critical relative humidity, at which fungi start rapid development in rooms, is related to the relative humidity $\varphi = 75\%$ [41] at the corresponding temperatures. This corresponds to the admissible relative humidity for ventilation – 70% – with a margin of 5% [42]. Let us assume temperature T (°K) as the second air parameter. The saturated vapour pressure by the modified Buck formula (hPa) [43], after replacement °C by °K is (hPa):

$$P_{sat} = \begin{cases} EF \cdot 6.1115 \cdot \exp\left(\left(23.036 - \frac{T-273.15}{333.7}\right) \cdot \frac{T-273.15}{T+6.67}\right), & T < 273.15; \\ EF \cdot 6.1121 \cdot \exp\left(\left(18.678 - \frac{T-273.15}{234.5}\right) \cdot \frac{T-273.15}{T-16.01}\right), & t \geq 273.15, \end{cases} \quad (2)$$

where *EF* is the enhancement factor [43]:

$$EF = \begin{cases} 1 + 0.0001 \cdot \left(2.2 + P_b \cdot \left(0{,}0383 + 0.0000064 \cdot (T - 273.15)^2\right)\right), & T < 273.15; \\ 1 + 0.0001 \cdot \left(7.2 + P_b \cdot \left(0{,}0320 + 0.0000059 \cdot (T - 273.15)^2\right)\right), & t \geq 273.15. \end{cases} \quad (3)$$

By [44], the absolute humidity at the barometric pressure P_b (hPa) is (g/kg):

$$d = 623 \cdot P_{sat} \cdot \varphi / (100 \cdot P_b - P_{sat} \cdot \varphi). \quad (4)$$

The enthalpy [44] using specific heat of the air 1.006 kJ/(kg·K) instead of 1.005 kJ/(kg·K) and temperature in kelvins (kJ/kg):

$$I = 1.006 \cdot T - 274.7889 + (2.00833 + 0.0018 \cdot T) \cdot d. \quad (5)$$

Let us assume the cooling effect by transpiration ΔT (°K) as adiabatic such as any evaporative cooling. We'll neglect the very important effect of humidity carry-over by the wind. Thus, we'll significantly underestimate the critical relative humidity of ambient air. Real values will be much closer to φ than estimated. The critical initial state of the ambient air can be estimated by the enthalpy $I_0 = I$ (kJ/kg) and the temperature by [39] (°K):

$$T_0 = T + \Delta T. \quad (6)$$

The ambient absolute humidity after transformations of the equation (5) is (g/kg)

$$d_0 = (I - 1.006 \cdot T_0 + 274.7889) / (0.0018 \cdot T_0 + 2.00833). \quad (7)$$

The saturated vapour pressure $P_{sat,0}$ (hPa) should be found by equations (2-3) replacing T by T_0 (°K). And critical ambient relative humidity will be (%):

$$\varphi = (100 \cdot d_0 \cdot P_b) / ((623 + d_0) \cdot P_{sat,0}). \quad (8)$$

The cooling effect dependent on wind speed w (m/s) can be found in (°K) [45]:

$$\Delta T = (0{,}508 \operatorname{atan}(w) + 0{,}543) \operatorname{atan}^2(w) + 1{,}23. \quad (9)$$

To perform estimations, it's necessary to accept the wind speed. High wind speed isn't prolonged in the cooling period in Europe. Medium wind speeds (up to 5m/s) are usually changed by calm. Thus, the wind can be accepted approx. 2.5m/s. The cooling effect by equation (9) is ΔT = 2.86°K. The temperature range in this work is accepted as T = 290...340°K (16.85...66.85 °C) – from cold to desert regions.

The third is the field studies using a D91 gas analyser, which measures relative humidity from 0 to 100% with an uncertainty ± 5% at the temperature from 9 to 55°C with an uncertainty ±1°C. The device was covered by reflective aluminium film to avoid the influence of thermal radiation. It was put on an aluminium reflective tripod near to greening and was hung under the greening. All plastic parts of the tripod were covered by aluminium reflective foil to avoid heating. If no significant increase in relative humidity below the plants, there is also no attraction for mosquitoes.

Most buildings inherited from socialist times are insufficiently thermally insulated. Ampeleous plants can throttle the air movement evenly if loose the foliage. To estimate the effect, we performed computational fluid dynamic simulation using the standard k-ε model.

At first, pictures of different vertical wall greening were obtained (Fig. 4a-c) and the distance between stems was measured. As it's not easy to build real models, the equivalent periodical structure was built using average measuring results (Fig. 4d).

Fig. 4. Simulation of heat transfer through vertical greening of walls (authors' pictures):
a-c – living vertical greening; d – model:
1 – house fragment; 2 – vertical greening; 3 – ground (the appearance is snow); 4 – computational domain

The model is built to comply with limitations by the random access (operative) memory – 64GB – 1m of width and 4m of height. The height allows the simulation of the thermogravitational flow effects. The thickness of the greening is 260mm, which corresponds to the average-developed greening in Kyiv. The diameter of the stems is 10mm. The external temperature is 251.15°K (– 22°C). The temperature of the wall is $\Delta\tau = 5$°K higher. The heat flux q (W/m^2) will be obtained from the centre of the wall. The thermal resistance (m^2·°K/W)

$$R_q = \Delta\tau/q. \tag{10}$$

The reference value at the design value of outer heat transfer coefficient 23 W/(m^2·°K) is 1/23 = 0,0435m^2·°K/W.

And finally, we'll propose to use measures to avoid penetration of moustaches based on the analysis of the experience using authors' pictures from travels.

Results and discussion

Let us analyse the bank building at the historical square of Byczyna. To simplify the process, we should look for possible elements, which are inscribed to the context. It's the brick wall, which can be left intact.

The most out-of-context structures are grey walls and canopy. To hide them, we can use trays with ampeleous plants (Fig. 5) at the top of them, which will be hidden by them. For the wall under the canopy, we should use a tray at the ground or, if it's possible, disassemble the pavement at a distance of 0.5...1m from the foundation and make a lawn for the plants.

In addition, we can use the option to grow the plants on the blank wall from the bottom tray or lawn. In this case, it's better to grow the plants above the canopy from the tray on it, but this will require more mechanical load on it. The glass has a green tint, which allows for hiding the great glass wall by trees (for example, Thuja occidentalis) in pots.

The concrete advertising pole is too highlighted on the green background. It should be hidden by ampeleous plants, possibly of other species than walls. This makes it enough highlighted for passers with good environmental consonance.

Fig. 5. Context collage of the historical centre of Byczyna (authors' pictures) with the 4hidden bank is in the middle picture: the photomontage was performed using authors' pictures

As the structures of the bank are poor-quality, we should ground that the plants will not damage them due to the high relative humidity. One of the possibilities is to check the state of the wall facing that is located under such plants for many years. For this, we took pictures from different buildings in Kyiv behind the plants (Fig. 6). As we see, the state of facing is now ideal without traces of fungi or mould.

Fig. 6. The wall facings behind greening for at least 20 years in Kyiv:
a – an apartment building, Ivana Mazepy str., 14; b – Sichovykh Striltsiv str., 51, the greening was broken by a russian missile and trimmed; c – former Pecherskyi Trade Centre, Omelianovycha-Pavlenka str., 4, now the building was declared emergency

The second proof is the estimation of the ambient relative humidity, at which the fungi can quickly grow, by equations (2-9). The program has been written for SciLab open-source computer algebra system, which takes temperature and barometric pressure as the required inputs, and also critical relative humidity and cooling effect as optional ones to overwrite the defaults above. The results (Fig. 7) show that in most regions there is no risk of fungi. Only in regions with continuous cold and moist weather in summer, there is a possibility of fungi, but we should remember the underestimation of the results. Thus, in Europe, there is no real risk of fungi or biting insects.

The final proof is field studies, which were performed on 17 August 2023 in the morning. There were periodical wind gusts up to 4...5m/s. The first object is a blown fence at Osvity Street in Kyiv (Fig. 8a and b). The second object is a solid fence of the Kyiv National University of Construction and Architecture.

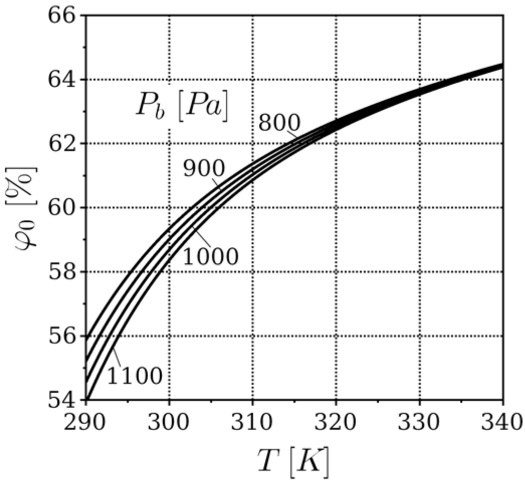

Fig. 7. The estimation (underestimated) of the critical ambient relative humidity φ [%], at which fungi can quickly grow under the ampeleous plants (authors' plot)

Fig. 8. The field studies of relative humidity around and under the wall greening (authors' picture): a – a blown fence, measuring near to the greening; b – the same, measuring under the greening; c – a solid fence, measuring near to the greening; b – the same, measuring under the greening

The results (Table 1) show no significant difference in relative humidity outside and inside the greening. Thus, no danger of fungi, breaking the structures, and no attraction to mosquitoes. Possible failures may be caused by roots if the plants will grow to belong to the founding. They can break hydro-insulation, which converts walls to a wick, which will absorb water from the ground. The distance from the plants to the founding should be at least 0.5m.

As we prove the absence of negative effects due to the greening of walls, let us focus on the positive influence on the thermal performance of the building during the heating period. The results (Table 2) of the CFD simulation of thermal resistance, added by the vegetation layer of vertical greening of the walls, are significant except wind speed of 5m/s at the angle of attack of π/4. At calm, the thermal resistance is $0{,}71 m^2 \cdot °K/W$, which is comparable with the thermal resistance of walls in the middle of the XX^{th} century.

Table 1. The results of measurements.

Object	Average relative humidity outside [%]	Average relative humidity inside [%]
The blown fence	44	45
The solid fence	39	40

Table 2. CFD simulation results

Wind direction	Thermal resistance R_q [m²·K/W] at wind speed [m/s]		
	0 (calm)	2	5
Normal to the facade	0,71	0,12	0,09
At π/4 angle	0,71	0,077	0,035

The results should be treated as an estimation. To confirm them and give the final recommendations, we should perform experimental research. Field studies should be performed during the heating period only, when the plants are without the foliage.

During the experiments, we'll measure heat flux from walls and the temperature difference around and under the plants. The heat flux meter ITP-11, made by the Institute of Technical Thermal Physics, has been certified. The experiments will be performed this winter when the weather will be appropriate.

The last problem can be caused by moustaches, which can penetrate the facing. We analyse the experience in different countries by travelling and photographic fixation of the successful objects (figure 9). We propose using a wooden lathing or a metal/plastic grid as it's shown in figure 9.

Fig. 9. Examples of moustache-safe vertical greening:
a – using wooden lathing, Praha, Check Republic; b – using a grid, Warszawa, Poland.

Conclusions

Out-of-context buildings on historical places, usually inherited from socialist and early post-socialist times, create problems for the conservation of historical memory, national honour, beauty, and also the inspiration of people of art and tourism. Often, they have a low quality of structures. To restore the value of places, it's necessary to properly treat the buildings. Destruction causes intensive vibrations, which may negatively influence the historical objects and pavement. Giving the appearance like the historical objects is an expensive solution, which often requires hand-made facing. The perspective solution is hiding such buildings by plants.

As out-of-context buildings can be disproportioned relative to historical objects, it's difficult to obtain pictures adequate for the presentation of the solutions. It's proposed to use a context collage, which is made of different pictures of historical parts putting the building at the middle of the collage. The new appearance of the building can be put on the copy of the collage or embedded into the same collage.

It's shown that plants are an effective solution to hide buildings. It will not cause problems with relative humidity, fungi and biting insects, which is shown by observations of facing after many years of coverage by ampeleous plants, by estimation of the state of the air around greening, which causes critical relative humidity, and by field studies of relative humidity under the plants. The last ones show no reliable difference in the relative humidity outside and inside the vertical greening of walls.

The problem of penetration of moustaches into the facing can be solved by winding the ampeleous plants on a wooden lathing or a grid. There is a successful experience of the solution in different world countries, which is confirmed by the authors' photography fixation.

Acknowledgements

The work is performed in the framework of state grant 0223U000498 "Creating perspective technologies of forming the safe building environment combining "green structures", phytodesign, and engineering systems".

References

[1] L. Lombardo, M. Saeli, T. Campisi, *Smart technological tools for rising damp on monumental buildings for cultural heritage conservation. A proposal for smart villages implementation in the Madonie montains (Sicily)*, **Sustainable Futures**, **6**, 2023, p. 100116.

[2] R. Sospedra-Roca, F. X. Hernàndez-Cardona, I. Boj-Cullell, D. Íñiguez, *Virtual approach to a battlefield: Fatarella Ridge 1938. Spanish Civil War*, **Cogent Arts & Humanities**, **10**, 2023, p. 2172807.

[3] Z. Chunhui, W. Yi, Q. Lili, *The Process of Constructing the Geographical Imagination of the Sacredness of Memorial Landscape of Fear under the Media Discourse: A Case Study of the Memorial Hall of the Victims of the Nanjing Massacre by Japanese Invaders*, **Redai Dili**, **43**, 2023, pp. 1563-1574.

[4] M. Pentz, N. Albert, *Cultural Landscapes as Potential Tools for the Conservation of Rural Landscape Heritage Values: Using the Example of the Passau Abbey Cultural Site*, **Modern Geográfia**, **18**, 2023, pp. 1-16. https://doi.org/10.15170/MG.2023.18.02.01.

[5] A. Bosi, G. Peruzzi, A. Ciccola, I. Serafini, F. Vincenti, C. Montesano, P. Postorino, M. Sergi, G. Favero, R. Curini, *New Advances in Dye Analyses: In Situ Gel-Supported Liquid Extraction from Paint Layers and Textiles for SERS and HPLC-MS/MS Identification*, **Molecules**, **28**, 2023, p. 5290.

[6] F. Zhang, *Virtual space created by a digital platform in the post epidemic context: The case of Greek museums*, **Heliyon**, **9**, 2023, p. e18257.

[7] Y. Zhang, *Victoria Park in Tianjin: British urbanism shaped by interaction with an evolving Chinese society*, **Journal of Asian Architecture and Building Engineering**, **22**, 2023, pp. 2020-2032.

[8] S. Kowalski, S. La Placa, A. Pettineo, *From Archives Sources to Virtual 3d Reconstruction of Military Heritage – The Case Study of Port Battery, Gdańsk*, **The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences**, **XLVIII-M-2-2023**, 2023, pp. 885-893.

[9] S. S., Sujood, N. Bano, Sh. Hamid, *An Evaluation of Tourists' Intention towards the Sustainable Conservation of Cultural Heritage Destinations: The Role of Place Identity, Destination Image & Sustainable Intelligence*, **Journal of Tourism, Sustainability and Well-Being**, **11**, 2023, pp. 81-99.

[10] I. Tavantzis, Z. E. Tsifodimou, I. Skalidi, E. Karachaliou, I. Giannaris, A. Bakousi, A. Skondras, K. Katakalos, E. Stylianidis, *Restoration Workflows by Means of*

Photogrammetry: The Case Study of Pashas Bridge, **The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLVIII-M-2-2023**, 2023, pp. 1543-1548.

[11] A. Zienkiewicz, T. Podciborski, R. Kaźmierczak, *Increased Interest in Military Tourism on Selected Examples from the Area of Northern and Northeastern Poland*, **Travel and Tourism Studies in Transport Development, 23**, 2023, pp. 38-50.

[12] I. Tavantzis, Z. E. Tsifodimou, I. Skalidi, E. Karachaliou, I. Giannaris, A. Bakousi, A. Skondras, K. Katakalos, E. Stylianidis, *Restoration Workflows by Means of Photogrammetry: The Case Study of Pashas Bridge*, **The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLVIII-M-2-2023**, 2023, pp. 1543-1548.

[13] N. Kozlova, *Architectural organization of facades according to principle of variability: videoecological aspect*, **Journal of Architecture and Urbanism, 42**, 2023, pp. 52-62.

[14] R. Gioannini, M. Al-Ajlouni, R. Kile, D. VanLeeuwen, R. St. Hilaire, *Plant Communities Suitable for Green Roofs in Arid Regions*, **Sustainability, 10**, 2018, p. 1755.

[15] H. Chen, J. Ma, X. Wang, P. Xu, S. Zheng, Y. Zhao, *Effects of Biochar and Sludge on Carbon Storage of Urban Green Roofs*, **Forests, 9**, 2018, p. 413.

[16] A. Afshari, *A new model of urban cooling demand and heat island–Application to vertical greenery systems (VGS)*, **Energy and Buildings, 157**, 2017, pp. 204–210.

[17] J. Coma J, G. Pérez, A. de Gracia, S. Burés, M. Urrestarazu, L. F. Cabeza, *Vertical greenery systems for energy savings in buildings: A comparative study between green walls and green facades*, **Building and Environment, 111**, 2017, pp. 228–237.

[18] N. Seddon, A. Smith, P. Smith, I. Key, A. Chausson., C. Girardin, J. House, S. Srivastava, B. Turner, *Getting the message right on nature-based solutions to climate change*, **Global Change Biology, 27**, 2021, pp. 1518–1546.

[19] B. Scharf, I. Zluwa, *Case study investigation of the building physical properties of seven different green roof systems*, **Energy and Buildings, 151**, 2017, pp. 564–573.

[20] J. Fu, K. Dupre, S. Tavares, D. King, Z. Banhalmi-Zakar, *Optimized greenery configuration to mitigate urban heat: A decade systematic review*, **Frontiers of Architectural Research, 11**, 2022, pp. 466–491.

[21] D. Maier, *Perspective of using green walls to achieve better energy efficiency levels. A bibliometric review of the literature*, **Energy and Buildings, 264**, 2022, p. 112070.

[22] Y. He, H. Yu, A. Ozaki, N. Dong, S. Zheng, *Long-term thermal performance evaluation of green roof system based on two new indexes: A case study in Shanghai area*, **Building and Environment, 120**, 2017, pp. 13-28.

[23] E. Jameia, H. W. Chaua, M. Seyedmahmoudianb, A. Stojcevskib, *Review on the cooling potential of green roofs in different climates*, **Science of the Total Environment, 791**, 2021, Article Number: 148407.

[24] H. Takebayashi, M. Moriyama, *Surface heat budget on green roof and high reflection roof for mitigation of urban heat island*, **Building and Environment, 42**, 2007, pp. 2971-2979.

[25] L. Jiang, M. Tang, *Thermal analysis of extensive green roofs combined with night ventilation for space cooling*, **Energy and Buildings, 156**, 2017, pp. 238-249.

[26] N. H. Wong, Y. Chen, C. L. Ong, A. Sia, *Investigation of thermal benefits of rooftop garden in the tropical environment*, **Building and Environment, 38**, 2003, pp. 261-270.

[27] P. Bevilacqua, J. Coma, G. Perez, C. Chocarro, A. Juarez, C. Sole, M. De Simone, L. F. Cabeza, *Plant cover and floristic composition effect on thermal behaviour of extensive green roofs*, **Building and Environment, 92**, 2015, pp. 305-316.

[28] M. Squier, C. I. Davidson, *Heat flux and seasonal thermal performance of an extensive green roof*, **Building and Environment, 107**, 2016, pp. 235-244.

[29] V. W. Y. Tam, J. Wang, K. N. Le, *Thermal insulation and cost effectiveness of green-roof systems: An empirical study in Hong Kong*, **Building and Environment, 110**, 2016, pp. 46-54.

[30] P.-Y. Chen, Y.-H. Li, W.-H. Lo, C. Tung, *Toward the practicability of a heat transfer model for green roofs*, **Ecological Engineering, 74**, 2015, pp. 266-273.

[31] T. Tkachenko, V. Mileikovskyi, *Geometric basis of the use of "green constructions" for sun protection of glazing*, **Advances in Intelligent Systems and Computing, 809**, 2019, pp. 1096-1107.
[32] T. Tkachenko, V. Mileikovskyi, *Assessment of Light Transmission for Comfort and Energy Efficient Insolation by "Green Structures"*, **Advances in Intelligent Systems and Computing, 1296**, 2021, pp. 139-151.
[33] T. Tkachenko, V. Mileikovskyi, *Capturing Carbon Dioxide from Human-Driven Vehicles by Green Structures for Carbon Neutrality*, **IOP Conference Series: Earth and Environmental Science, 1111**, 2022, p. 012056.
[34] R. Hlushchenko, T. Tkachenko, V. Mileikovskyi, V. Kravets, O. Tkachenko, *Green structures for effective rainwater management on roads*, **Production Engineering Archives, 28**, 2022, pp. 295-299.
[35] T. Tkachenko, O. Voloshkina, V. Mileikovskyi, R. Sipakov, R. Hlushchenko, O. Tkachenko, *Using Rain-Garden Bands for Rainwater Drainage from Roads*, **Selected Papers from World Environmental and Water Resources Congress 2023**, 21-25 May 2023, Henderson, Nevada, The United States of America, pp. 295-299.
[36] S. Collins, K. Kuoppamaki, D. J. Kotze, X. Lu, *Thermal behavior of green roofs under Nordic winter conditions*, **Building and Environment, 122**, 2017, pp. 206-214.
[37] T. Ayata, P. C. Tabares-Velasco, J. Srebric, *An investigation of sensible heat fluxes at a green roof in a laboratory setup*, **Building and Environment**, **46**, 2011, pp. 1851-1861.
[38] S.-E. Ouldboukhitine, R. Belarbi, *Experimental characterization of green roof components*, **Energy Procedia**, **78**, 2015, pp. 1183-1188.
[39] T. Tkachenko, V. Mileikovskyi, *Methodology of thermal resistance and cooling effect testing of green roofs*, **Songklanakarin Journal of Science and Technology**, **42**, 2020, pp. 50-56.
[40] T. Tkachenko, *Energy efficiency of "green structures" in cooling period*, **International Journal of Engineering and Technology(UAE)**, **7**, 2018, pp. 453-457.
[41] A.-L. Pasanen, P. Kalliokoski, P. Pasanen, M. J. Jantunen, A. Nevalainen, *Laboratory studies on the relationship between fungal growth and atmospheric temperature and humidity*, **Environment International**, **17**, 1991, pp. 225-228.
[42] EN 16798-1:2019, **Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics - Module M1-6**, CEN, 2019, p. 79.
[43] http://www.hygrometers.com/wp-content/uploads/CR-1A-users-manual-2009-12.pdf .
[44] V. N. Bohoslovskyi, V. I. Novozhylov, B. D. Symakov, V. P. Tytov, **Heating and Ventilation. Part 2. Ventilation**, Stroiizdat, 1976, p. 439.
[45] T. Tkachenko, V. Mileikovskyi, O. Hunchenko, *Assessment of energy savings and indirect reduction of CO2 emissions by vertical gardening*, **Ventilatsiia, Osvitlennia ta Teplohazopostachannia**, **31**, 2019, pp. 16-23.

Received: November 20, 2023
Accepted: February 21, 2024