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Color in eco-architecture as a representation of natural processes

Introduction

The subject of the study covers the research on color manifestations in contemporary architectural solutions, being in line with the trend known as eco-architecture. The research in question was undertaken with the aim of showing a new plastic potential inherent in the experimental green technologies and natural building materials with a zero carbon footprint currently being launched on the market. This study proves a high value and great importance of these applications for achieving diverse and rich color ranges in architecture, while significantly reducing the negative impact of these practices on the natural environment, compared to, e.g., synthetic building materials.

To emphasize these innovative solutions, referred to as *new forms of art*, which include, among others, projects with the use of, for example, panels with algae, hempcrete or vertical gardens that evolve technologically over time, they were shown against the background of eco-solutions, currently considered traditional for some cultural circles. As commonly used in Scandinavia, e.g., green roofs and walls, and in Central Europe, e.g., walls made of ceramic brick, they have been part of the culturally and environmentally conditioned space for centuries. The significance and legitimacy of the presented research into both new eco-technologies and traditional ones, still evolving with the active participation of man, is related to the promotion of bioclimatic policy in architecture, with an indication of new, experimental solutions and the resulting unique, completely new colors.

A significant justification for undertaking research on this topic is the fact that currently about 55% of the world's population lives in cities. According to the United Nations, this number will increase to more than two-thirds by 2050. When combining this data with current climate forecasts, it becomes clear that environmental design is the area of utmost importance for the future of our planet. Hence, the following questions should be asked: What model of urban development and type of architecture would be the most appropriate? What policies and practices for shaping the built environment could help future generations? One of the possible paths of urban development leads directly to nature: its cycles, rhythms and matter, which is characterized by constant interaction and perfect adaptation with the local environment. Eco-architecture as a complementary part of culture, remaining in deep relationship with nature, can guarantee the authenticity and purposefulness of spatial and color solutions. Nature contains all the patterns, forms of spatial organization and colors necessary in the design process, behind which there are subtle vibrations, and which are the basis for creating a sustainable and harmonious living environment. The article shows the use of responsiveness (response to stimuli from the environment) of natural matter used in architectural solutions and the resulting irreversible or cyclically recurring changes in its color as a direct result of the coupling between architecture and biology. As a result of this fusion, natural processes such as, for example, plant vegetation cycles, photosynthesis, biodegradation and absorption of rainwater are behind the variable, colorful image of the object. These processes may additionally affect the favorable energy balance of facilities, electricity and heat production as well as food production and rainwater retention.

The article emphasizes a great value of creating unique solutions for the image of objects, resulting from the construction and finishing materials used, both from the recy-

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cling of traditional (e.g., brick, copper) and new, experimental technologies (e.g., hempcrete). Due to the progressive overpopulation of cities, such spatial recycling is very desirable and valuable. In addition to the time factor, which is an important element in the process of changing the color of materials, the article also puts emphasis on the influence of environmental factors, including the character of natural lighting. The analyses of ecological implementations show that the idea of an organic city and introducing nature to cities in various forms of eco-architecture are part of the long-term deep ecology movement, becoming a means to combat the climate crisis.

Considering the above, the presented research is important not only because of its current character, but above all, due to its future-oriented nature.

The subject of natural building materials in ecological architecture, including their color possibilities, belongs to a dynamically developing area full of innovation, and this article is a unique collection of such examples.

Purpose and scope of research

The purpose of the research is to show how both new, experimental and traditionally used in modern eco-architecture, eco-technologies and natural building materials that are constantly evolving over time, which combine architecture with biology, significantly reduce the effects of the climate crisis. Such practices should be particularly promoted in the context of the advancing climate crisis, and research into materials of organic origin should be given priority.

The purpose of the research is to show how new, experimental used in modern eco-architecture, eco-technologies and natural building materials (e.g., hempcrete, panels with algae) which combine architecture with biology increase aesthetic values of designed buildings, including a deepened, unique color effect. This effect in new and traditionally eco-architecture is a direct consequence of natural processes that organic and often living matter undergoes over time, contributing to the achievement of color-changing and time-evolving images of architectural objects. These images may undergo irreversible changes, when the material used undergoes natural biodegradation over time, as well as cyclical changes – then the applied living matter periodically revives in accordance with the year-round natural rhythms, returning periodically in various colors. This study proves a high value and great importance of these applications for achieving diverse and rich color ranges in architecture.

The present study covered layouts which constitute representative European examples of the use of color solutions based on eco-materials with particular emphasis on new experimental technologies aimed at increasing the energy efficiency of buildings with the use of renewable energy sources. A significant part of the cited projects are Norwegian facilities due to their high artistic rank and the country's leading achievements in promoting the pro-climate policy and the fact that in 2019 Oslo was called the "Green Capital of Europe". Therefore, our research on color is part of the framework considerations on the trans-

formation of the urban landscape into environmentally friendly multi-colored eco-structures.

Research method

Literature studies and case studies (analysis of theory and practice) supported by the *in situ* method – on-site visions became our workshop research method. The criterion for collecting data, systematizing issues and making their synthesis was made dependent on an interdisciplinary approach to the topic and openness of ideas. When selecting publications, efforts were made to present the items representative for a given thematic group. When there was no appropriate monograph, publications in specialized magazines and the Internet were used (the selection of websites was verified, taking into account credibility, inter alia, of people and institutions).

The state of research

The principle of continuation and complementation, which is applied by architects and implemented, among other things, in the form of appropriate colors of eco-facilities, reflects the idea of an organic city, where each new element added to the original structure is perceived as its natural extension. Properly juxtaposed colors of life or the colors of the earth representing this continuation constitute elements which are taken directly from nature or have the character of individual novelties. Among the specialists who deal with this type of eco-architecture, the following authors should be mentioned: Nina Berre, Monika Rydiger, Christem Malmström, Elisabeth Seip, William Stanwix, Alexander Sparrow, Alexandra Martins Teixeira, Ines Daniel de Campos, Juhani Pallasmaa, Pierre Zoelly and Kenneth Frampton. Berre emphasizes that eco-facilities can become catalysts which stimulate the development of a given area. She draws attention to the social priority which constitutes the basis of these layouts and points to the presence of a visually shaped public space which integrates the community. They can also become a brand of cities and investments [1, pp. 8–21]. Rydiger describes architectural activities at the interface with nature as "thinking by means of landscape". She sees in them the implementation of the idea of creating *site-specific* architecture, reflecting *genius loci*, for which the main determinants are parameters of the environment while the elements of the work co-create the landscape which becomes a marked zone – a new quality, where boundaries between architecture and nature blur [2, pp. 26–33]. Malmström points to the artistic nature of these structures, thanks to which they fit into the cultural landscape. He underlines the presence of large and small scales of designed objects and emphasizes complex spatial relations in the sphere of the sacred and the profane [3, pp. 22–25]. Seip, in turn, draws attention to the character of the created eco-architecture based on the awareness of the importance of the tradition of materials, their colors and textures and their influence on the relationships between architectural objects and the landscape [4, pp. 2–4]. The works of such researchers as Stanwix and Sparrow deal with unique, in

terms of color, façade solutions with the use of hempcrete [5]. Research on the typology and color possibilities of vertical garden solutions is included in the works by Tavares Martins and Daniel de Campos [6]. The subject of studies by authors such as Pallasmaa [7], [8, pp. 22–25], Zoelly [9] and Frampton [10, pp. 12–15] is the research on shaping tectonics of a building and the colors connected with it, including green roofs which create a new artistic quality along with topographical relief. Research into the color of recycled bricks, which is particularly important in the environmental context, is present in the works by authors such as Kumar et al. [11]. Biotechnology-based construction – as an important development direction for sustainable architecture in the context of depleting natural resources and climate change – is represented by experimental materials with unique colors. The research on them is included in the works of such researchers as Noam Attias et al. [12].

Color in eco-architecture in relation to the energy efficiency of buildings

Colors of living organic tissue that covers and penetrates architectural objects

Green tissues, which cover walls and even entire buildings, constitute an opportunity to introduce vast surfaces of colors coming directly from nature into cities. Moreover, it is a color which transforms over the course of the year-round vegetation cycle of plants. Vertical or horizontal partitions covered with plants affect the observer like large or small-format living and changing images. Such solutions can be classified as a new form of art forming a combination between architecture and biology [6]. The tools which are used to achieve unlimited solutions are plants themselves, their type, colors, size, texture and form, as well as combinations that create unique compositions.

Green roofs and vertical gardens are an example of the deliberate use of colored organic matter as a finishing material of a building to ensure benefits connected with appropriate rainwater absorption, to create friendly biocli-

matic conditions in its interior and to obtain the intended color effect on the façades. The effect of such solutions is the creation of a compensatory green plane or biologically active planes within the space taken away from nature. They can also be applied as a means of revitalizing the existing walls of buildings within development quarters as part of the so-called pocket parks. Green roofs and walls significantly improve the energy efficiency of a building, i.e. they cool the interior space in summer and warm it in winter. These solutions are also effective in reducing the peak rainwater flow. They slow down this flow and thus contribute to the reduction of the risk of flooding. Their effectiveness may vary from 5% to 95% reduction in runoff, depending on the type and depth of the ground and the season, as well as the intensity and amount of rainfall. The division of green roofs into extensive and intensive ultimately affects the color effect obtained after their application. Among the first group, which is disseminated in the Scandinavian countries, including Norway, we can distinguish sedum roofs, eco-roofs and living roofs [13, pp. 150, 151]. The entire surface is covered with light, low, self-sufficient, and low-maintenance vegetation (Fig. 1).

Depending on the type of roof, the effect is a single or multi-colored continuous plane, which cyclically change its appearance subject to the vegetation cycle of the plant species used in its composition. They can be turf-meadow plantings, such as asphodel (*Leucanthemum ircutianum*), Carthusian pink (*Dianthus carthusianorum*), mouse-ear hawkweed (*Hieracium pilosella*), Breckland wild thyme (*Thymus serpyllum* L.), garlic (*Allium nigrum*), sapphires (*Muscari*) and iris (*Iris*), as well as sedum (*Sedum*) and succulents plantings (*Succulentus*). On the other hand, intense green roofs (gardens on roofs) form shaped environments where green surfaces appear in the island system, giving a different color effect – more or less regular colorful patterns as a result of combining a living organic tissue with materials such as stone, wood, or ceramics. The colors of living matter created in this way are the changing colors of the life cycle of plants, which are juxtaposed with natural colors of recreational spaces within the area of the roof plane. The composition also includes



Fig. 1. Extensive green roofs of a residential development in Skaidi, Norway:
a) view of the housing development, b) detail: roof with turf-meadow plantings (photo by E. Cisek)

Il. 1. Ekstensywne dachy zielone zabudowy mieszkaniowej w Skaidi, Norwegia:
a) widok zespołu mieszkaniowego, b) detal: dach z nasadzeniami darniowo-łąkowymi (fot. E. Cisek)



Fig. 2. The geological garden on the roof of the Copernicus Science Center building in Warsaw, Poland:
 a) view of the roof – dense single-species and at the same time single-color carpets, b) detail of the roof: vegetation in aluminum pots
 (photo by R. Czajka)

II. 2. Ogród geologiczny na dachu Centrum Nauki Kopernik w Warszawie, Polska:

a) widok na jednobarwne, zwarte kobierce jednogatunkowe, b) detal: roślinność w aluminiowych donicach
 (fot. R. Czajka)

cobalt-colored photovoltaic materials delineating transportation routes and panels. Solutions which often give surprising color effects are permaculture roof gardens or ornamental plant compositions in pots with a given, usually one-color scheme. A representative example of this is the geological garden on the roof of the Copernicus Science Center building in Warsaw, Poland (arch. RAR-2 Laboratorium Architektury Jan Kubec, implementation in 2011). The garden, which refers to raw rock and erosion forms, was designed in the manner of the topography of the Vistula areas with numerous biotopes – small self-cleaning water reservoirs – waterholes for birds. The layout is kept in subdued colors, where the colors of the earth are dominant, i.e., paths are made of black basalt, patio cladding is sand-like color, and attic walls are in shades of brown (Fig. 2). 8,000 m² of the garden area is arranged in the form of vegetation in aluminum pots which create dense single-species and at the same time single-color carpets such as lavender jak lawenda (*Lavandula* L.), thymes (*Thymus serpyllum*), meadowsweets (*Spiraea*), sedum (*Sedum*), and heather (*Calluna vulgaris*). These compositions are varied with taller plants which are planted pointwise or between lower species such as juniper (*Juniperus communis* L.) and forsythia (*Forsythia Vahl*).

On the other hand, the green roof of the University Library in Warsaw in Poland (landscape architect Irena Bajerska, implementation in 2002) forms a four-color composition, dividing its impressive area of 0.5 hectare into parts, i.e., golden – yellow, silver – blue, carmine and green. In each of them, color-matched plant species grow so that the color assigned in a given location is maintained throughout the year.

Green walls in the form of vertical gardens are increasingly used as a supplement to green roofs and enhance their hydrological, ecological, and utility functions. The vertical planes shaped in this way, depending on the type of solution, give a different artistic effect. As climbing vegetation on a rack with the use of, among other things,

species such as common ivy (*Hedera helix* L.), Japanese creeper (*Parthenocissus tricuspidata*), five-leaf akebia (*Akebia quinata*) and Ipomoea (*Ipomoea batatas*), depending on the type of the covered form (wall, loggia), the color effect is uniform for the entire part of the building covered with vegetation. According to the life cycle of some species of creepers, their leaves may change color cyclically. Thanks to this, the façade acquires a different color effect along with the changing seasons, as in the case of the façade of the National Museum building in Wrocław in Poland. If the green wall obscures the loggia, it also acts as a natural shutter, limiting the sun's flow on summer days and increasing its insolation in winter. Green walls, which are built of coffers filled with organic matter, make it possible to create color compositions of various plant species just like in the case of puzzles. As a result, it is possible to obtain a heterogeneous, multi-aspect, multi-dimensional, and multi-colored biologically active surface which changes color according to the life cycles of plants and the seasons connected with them. This type of green wall is used for large-scale and point-like compositions of gardens on façades. The latter, with a smaller scale, are used in pocket parks, creating a colorful accent on the façade of the building. An example is the vertical garden on the façade of the Municipal Office building in Świdnicka Street in Wrocław in Poland (architect Dobosz Architekci, implementation). The ground floor of the building is designed of specially aged sheet metal, alternating with elements of a vertical illuminated green wall (Fig. 3).

The largest green façade in Europe, consisting of more than 30,000 climbing plants covering the building, is an example of an office building designed by Ingenhoven Architects in Germany (implementation 2020). The color, which is manifested in spatial plant structures, also has an impact in three dimensions, thanks to the use of green tissue on all partitions of the building. The green wall with an impressive area of 240 m², which was put up in the

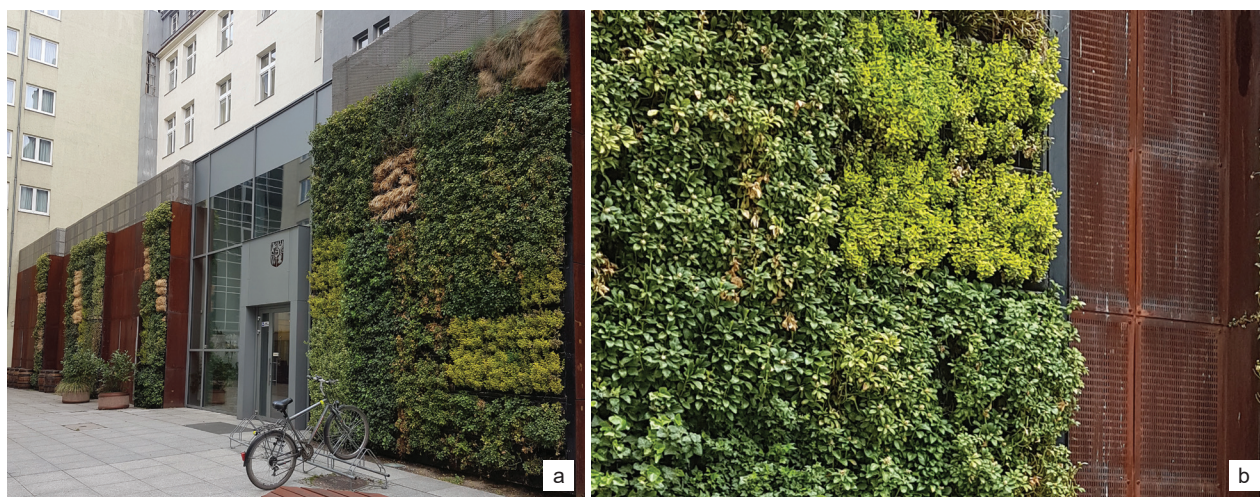


Fig. 3. A multi-aspect green vertical garden as part of a pocket park on the façade of the City Hall building in Świdnicka Street in Wrocław, Poland: a) view of the front elevation, b) detail: specially aged sheet metal with elements of a vertical green wall (photo by E. Cisek)

Il. 3. Wielowątkowy, zielony ogród wertykalny w ramach parku kieszonkowego na elewacji budynku Urzędu Miejskiego przy ul. Świdnickiej we Wrocławiu, Polska:

a) widok elewacji frontowej, b) detal: postarzana blacha z elementami pionowej zielonej ściany (fot. E. Cisek)

building of the Capitol Musical Theater in Wrocław in Poland, is also noteworthy. The green partition has a color effect as a large-format artistic image. A similar intended effect in the form of a single-plane vertical garden on the façade of the building was achieved in the Caixa Forum Madrid – Art Center in Spain (architects Herzog & de Meuron, implementation in 2007).

The color intensity changing components of the façade.

Green panels with algae

– a renewable source of electricity and heat

Green is perceived as the color of reviving life. Its various shades, from luminous and juicy accents to deep bottle tones ones, can reflect the next stages of biochemical processes which the plant world, including also micro algae, is subject to. Among the most progressive and purposeful eco-technologies in recent years is “Bio Solar Leaf” – architecture using bio-reactive glass panels filled with green algae. Algae, which are enclosed in bio-solar façade or roof panels and feed on nutrients supplied by water pumps to them, absorb CO₂ from air and produce oxygen. They produce heat in the process of photosynthesis, which is then captured and converted by bioreactors into energy that supplies the building with heat and electricity. Moreover, biomass is produced in bioreactors during this process – one of the most promising sources of organic energy which is quickly renewable and efficient. Algae that still multiply in the panels can also be a source of protein and thus an example of a futuristic bioclimatic urban agriculture.

The zero-energy BIQ (Bio Intelligence Quotient) building, which was constructed with the use of façade panels with algae, was the first in the world. It was financed by German government subsidy “Zukunft Bau” and implemented in Hamburg in 2013. In BIQ, there are 15 apartments with an area of 50–120 m² each and a penthouse which is locat-

ed on the fifth top floor. The white of the building’s façade is varied with vertical green accents as a result of the deliberate use of movable bio-reactive glass panels – blinds filled with algae. The structure of vertical blinds protects the algae enclosed in them against external conditions, creating a microclimate necessary for their growth. The year-round and all-day solar cycle determines color changes on the building’s façade. The blinds are set at different angles, creating interesting color transitions from light shades of green to their deep bottle-like color. The movable green shutter provides additional insulation from the environment and the necessary shading on hot sunny days.

Bio-solar algae panels were also used as a bio-reactive crowning of the building. The panels are arranged in large horizontal planes, forming the green roof covering, as the fifth, colorful façade of the building visible from the bird’s eye view. This solution, apart from the artistic effect, produces energy more efficiently than advanced photovoltaic panels. Algae multiply quickly, doubling their mass several times a day. They absorb CO₂ from air and produce oxygen 100 times faster than trees which cover the surface area of the panels. A good example of this is represented by Imperial College London (Arborea company). This innovative technology, apart from undeniable aesthetic values, uses biochemical processes, being a self-sufficient renewable source of energy and ecological food.

Colors of earth. Recycled bricks as an example of environmentally friendly construction waste management

Recycled bricks constitute a valuable building material with unique colors, which, recovered from the architectural structures of their original use, can be reused. It should be emphasized that in the contemporary design context, the reuse of building materials is one of the priority assumptions. These practices contribute to the real minimi-

zation of significant amounts of waste generated by the construction sector. In the EU alone it is nearly 36% of the total annual waste [14], and thus reducing the negative impact of this sector on the natural environment. The most appropriate solution, which at the same time creates an ethical potential for shaping color in eco-architecture in the context of the future, is to dispose of waste so that it remains in a closed circuit becoming (as a result of the recycling process) a secondary construction material [15]. It is worth adding that contemporarily used recycled bricks are also bricks made of various construction waste. For this purpose, wastes such as fly ash or slags are processed [16]. Bricks based on recycling of plastic waste are also being developed. Bricks for the production of which a mixture of plastic and sand is used, are characterized, among other things, by much lower water consumption, which is particularly important in the environmental context [11]. Traditional brick is an organic material, usually formed from mineral resources, the composition of which determines the color of the final clay brick. Moreover, specific conditions and processes of brick fabrication define both its color (e.g., firing temperature), as well as the degree of its resistance to weather conditions and resistance to the passage of time.

Recycled bricks offer a wide range of colors and aesthetics, which creates a potential for architects to use them to shape architectural forms with a variety of visual effects, from traditional forms to modern aesthetics. The individual recycled bricks represent exceptionally diverse colors of different saturation, namely from light shades of beige, yellow, through orange, rust tones, browns, to gray and ash-like. Most bricks have a warm color temperature. These are mainly shades of red with various dominant tones and degrees of intensity depending on the firing temperature. Due to the above, it is possible to obtain

bricks with shades of white and yellow, which is thanks to the high content of calcium, or specimens with pink tones due to the high content of iron in the raw material. Moreover, in the case of recycled bricks, it is possible to modify them in color using the painting or staining process, including the entire existing brick walls [17]. An important feature of this material, influencing both its color and the possibility of repeated use, is high resistance to the influence of the time factor on its structure. Over the years, under the influence of weather conditions, brick façades are constantly transformed, gaining various forms and details, depending on the individual specimen. Bricks reused in construction bear the sign of the times in the form of characteristic lime blooms of light tones and dark tones caused by dirt remaining in the porous structure of the material. The above-mentioned characteristic form of this material is worth emphasizing as an important component of the aesthetics of brick, which (as a material commonly hand-formed in the past) is characterized by the unique texture of each piece. These heterogeneous surfaces affected by variable natural lighting generate interesting light and shade transforming the basic colors of recycled bricks over the course of the day and year.

The GjG House (Fig. 4), which was designed by the BLAF architecten studio (2015, Gentbrugge), is an apt illustration of the unique color of the object that was obtained thanks to the use of recycled brick. The building was erected with the use of bricks recovered directly from the ruins of former farm buildings on the plot. This is a representative example of the rich tonal colors of brick partitions, the building material of which is construction waste.

The unique transitions of various colors seem to follow the heterogeneous curving (to avoid the existing tree stand) planes of the walls. The object blends in with the surrounding nature by means of its organic form and



Fig. 4. Unique light and shade transitions of various colors of recycled bricks on the curving surfaces of the walls in GjG House, Belgium: a) view of the GjG House, b) detail of the brick wall (photo by S. Bollaert, BLAF)

Il. 4. Unikatowe przejścia światłocieniowe różnorodnych barwowo cegieł z recyklingu na zakrzywiających się płaszczyznach ścian w domu GjG House, Belgia: a) widok domu, b) detal ściany ceglanej (fot. S. Bollaert, BLAF)

colors, the so-called colors of earth. The texture of their surfaces also influences the final perception of the color of brick partitions. Due to the use of recycled bricks, it is heterogeneous and variable. Thus, an interesting visual effect depending on the light intensity and the viewing angle was achieved. The surfaces with a clear texture reflect the light, creating chiaroscuro tonal nuances on the face of the material. It is worth mentioning that in order to achieve this effect, nowadays, the faces of brick walls are also often exposed in interiors, which is a procedure for the effective and economical introduction of both color and texture in a given room. A similar solution for introducing an authentic brick color in interiors are tiles made of original cut old bricks. Moreover, currently available on the market of building materials are also new bricks, deliberately visually aged already at the production stage to imitate the original old copies. The universality of this type of solutions confirms that brick is a timeless and attractive material in its colors.

Another interesting artistic effect is achieved by *mélange* – a combination of bricks of different shades of the same color. Examples of such solutions, being part of the so-called Rural neo-Gothic style of housing, can be found in Belgium [18, pp. 52, 53], e.g., in Braaschaat and Houvenen (Fig. 5).

Another important example of architectural actions within brick structures is the recovery of not only the brick itself, but also the entire existing brick structures (remains of old buildings), while integrating them into new architectural forms. An example of such actions is an old country cottage in the Czech Republic (Jevíčko), which was transformed by architects from the ORA studio into a modern single-family house aptly named House inside a ruin (implementation in 2020). As the name suggests, it is essentially a building within a building where a brick framework fills a newly designed home. The result of combining the old and new structure is unconventional elevations (Fig. 6). It is a good example of real recycling of both materials and space.

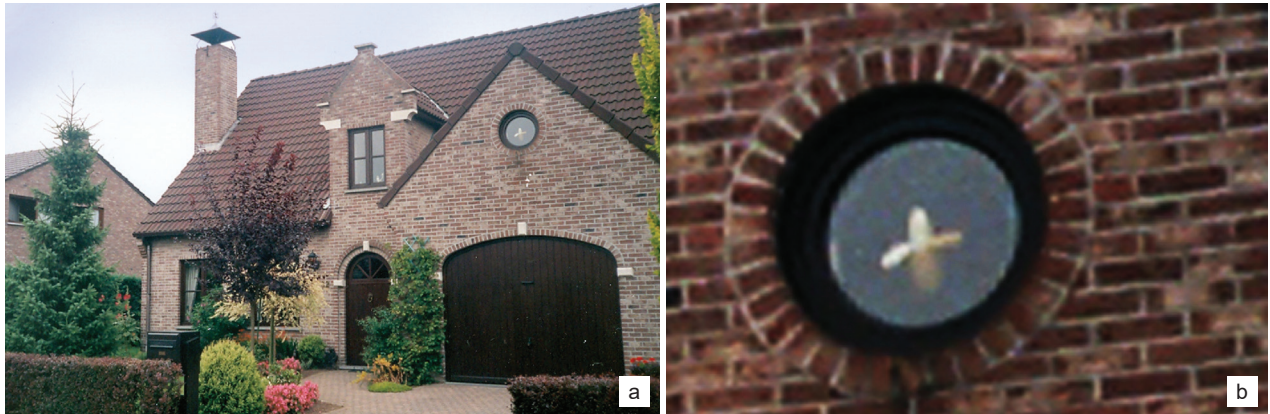


Fig. 5. *Mélange* of the brick color used is visible in the façade of the residential house in Houvenen, in Belgium: a) view of the front façade, b) detail of the brick wall (photo by E. Cisek)

II. 5. Melanz zastosowanego koloru cegieł widoczny w elewacji domu mieszkalnego w Houvenen, w Belgii: a) widok frontowej elewacji, b) detal ściany ceglanej (fot. E. Cisek)



Fig. 6. House inside a ruin in Jevíčko, Czech Republic. The old cottage has become a brick colorful skin for a new home: a) view of the building, b) detail of the brick wall (photo by BoysPlayNice)

II. 6. House inside a ruin w Jevíčko, w Czechach. Dawna chata stała się ceglana, „barwną skórą” dla nowego domu: a) widok domu, b) detal ściany ceglanej (fot. BoysPlayNice)

The perception of brick partitions is also significantly influenced by tectonics and the drawing of the planes themselves, i.e. the brickwork bond. The way the bricks are arranged in the wall creates a specific composition of the brick surface. Formally, the brick usually takes the shape of a cuboid with similar side proportions 1:2:4, and the possibility of obtaining various geometries is extremely wide. In the building designed by Biuro Toprojekt (implementation in 2017), the possibility of a non-standard arrangement of brick in the wall was applied in order to provide additional chiaroscuro and spaciousness with the plane of vertical partitions (Fig. 7). Moreover, the reverse procedure was used by subtracting individual bricks in some places, creating openwork. The sculpted façade obtained a dynamic brick color scheme, changing with the movement of the sun and the shade appearing on it. The walls were made of hand-sorted waste bricks from the nearby brickyard. Again, this is an example of obtaining waste material which is available locally, thereby reducing the carbon footprint of its transport to the construction site.

The design assumption was for the building to give the impression of rising out of the ground. As architects M. Wawrzyniak and K. Wawrzyniak say: *In the process of patinating the ceramic material, the line of contact with the ground should become more and more blurred, and the colors of the roof and wall surface should be joined together. The green roof, over time, will have a plant cover and colors will start to harmonize making the house and the natural surrounding as one* [19, p. 1].

*Heterogeneous and unique façade colors.
Hempcrete, an eco-building material
with a building carbon footprint close to zero*

Hempcrete is a material with significant potential for applications in the 21st-century architecture, both in terms of possible color solutions as well as the energy efficiency of buildings. The Climate Special Report of the Intergovernmental Panel on Climate Change (IPCC, 2019) em-

phasizes the urgent need to reduce CO₂ emissions by all sectors of the economy in order to delay human-induced climate change [20]. The construction sector alone is responsible for 36% of final energy consumption. Additionally, its activity is the cause of 39% of carbon dioxide emissions to the atmosphere, which is a consequence of energy and technological processes, of which as much as 11% is the result of the production of building materials such as steel, cement, and glass [21, pp. 9–12]. The natural material hempcrete is a material with a particularly low environmental impact. Its widespread use is a way to minimize the extremely negative impact of the architecture and construction sector on the environment, and hence on climate change. Hempcrete also represents an important and exceptionally beneficial feature of the so-called enclosing CO₂ in the building structure. This is due to the fact that plants are the raw material for it. This means that during the stage of cultivation and growth of the plant, it absorbs carbon dioxide from the atmosphere. When processing plant raw materials into construction materials, it is in the building structure that CO₂, which is so harmful to the climate, is ultimately blocked. An unquestionable advantage is also the possibility of storing such a total amount of CO₂ by plant raw materials, which value exceeds the sum of carbon dioxide generated during the construction phase of the facility. To sum up – the energy necessary to construct a building in the hempcrete technology is much lower than in the case of commercial technologies at every stage of the building's life [22].

Hempcrete, as a kind of conglomerate of hemp shives, a binder (mainly lime) and water, is a heterogeneous material, also in terms of color and uniqueness in each case. Depending on the purpose and composition of hemp concrete (including proportions of individual components of the mixture), structures with a different degree of mixing density, and thus a different texture, are obtained [23]. The porosity of the final plane of horizontal or vertical partitions made in this technology also significantly influences the perception of their colors. Due to the organic

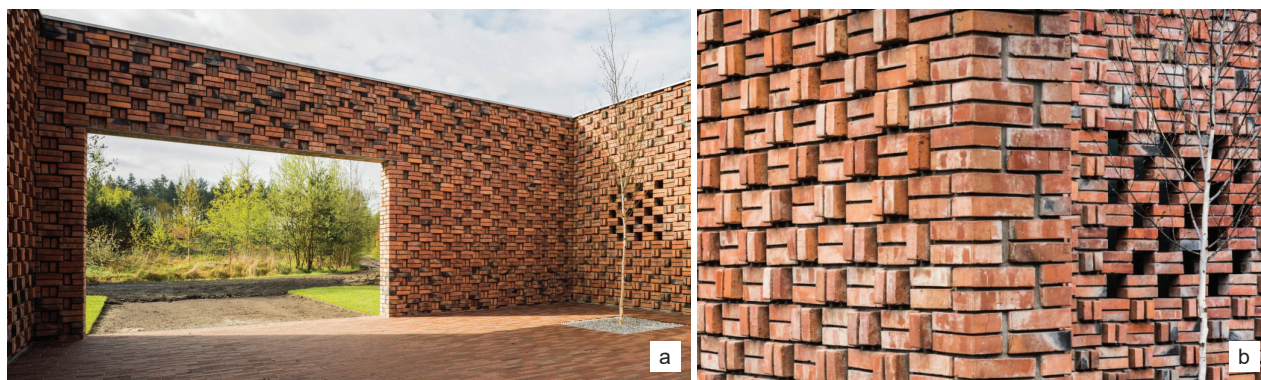


Fig. 7. The building of Red House in Rudy Wielkie, Poland (from the color of brick walls) is characterized by dynamic variable colors due to the tectonics of the planes and rich light and chiaroscuro: a) view of residential development, b) detail: the sculpted façade obtained a dynamic brick color scheme, changing with the movement of the sun and the shade appearing on it (photo by J. Sokołowski)

II. 7. Budynek Red House w Rudach Wielkich, w Polsce (od barwy ceglanych ścian) za sprawą tektoniki płaszczyzn i bogatego światłocienia cechuje się dynamiczną, zmienną kolorystyką: a) widok założenia mieszkaniowego, b) detal: rozrzeżbiona elewacja, zmieniająca się wraz z ruchem słońca i kładącym się na niej cieniem (fot. J. Sokołowski)

origin of the main raw material of hemp concrete, namely hemp stems (*Cannabis sativa* L.), individual batches of material may differ in size and color. The final color of the material is influenced by the degree of its humidity; the form in which hemp concrete occurs; possible addition of natural coloring pigments. Due to the controlled conditions of prefabrication, hemp concrete in the form of blocks (bricks) or ready-made wall panels is characterized by a more homogeneous structure and color (the material dries under controlled conditions). On the other hand, the material produced on-site as a mixture distributed directly around the supporting structure of the building is characterized by a greater variety. Generally, individual layers of the wall are applied to the formwork and compacted (manually or with the use of devices), which translates into the structural and color multilayer of the final face of the vertical partition (Fig. 8). This specific manufacture of the building creates an extremely authentic, each time unique, artistic visual effect of the finished walls. The individual layers of walls create a monolithic structure with interesting and irregular patterns, resembling the cross-sections of rocks, e.g., sandstone. Undyed hemp concrete assumes colors from neutral to warm tones of gray and beige with low saturation. Moreover, with the help of hempcrete, it is possible to freely shape forms, which makes it possible to obtain interesting chiaroscuro bodies and planes. Walls can take on soft lines, on the surfaces of which light refracts gently and subtle tonal transitions are observed.

It is possible to achieve many color shades depending on the composition of the mixture and the additives applied. Hempcrete can be colored by adding mineral pigments [24]. It is worth mentioning that this material is often covered with internal and external finishing layers in the form of natural plaster: lime, hemp, clay, with aggregates and natural paints [5, s. 230].

In the context of the reception of architectural works as spatial objects, we should take into account the haptic nature of the recipient's experiences, which constitutes the overall aesthetic perception of the object. As Pallasmaa pointed out in the *Thinking Hand: An architectural work is not experienced as a series of isolated retinal pictures; it is touched and lived in its full integrated material, embodied and spiritual essence* [25, p. 130]. Thus, parallel to visual properties of an object, i.e., color, the aesthetics and perception of the experience of architecture are influenced by haptic properties such as structure and texture. Undoubtedly, hemp concrete is an example of such a material which engages the aforementioned multi-sensory perception in a recipient. In the case of buildings which are constructed by means of this technology, the user experiences architecture through sight – a variety of colors with a unique drawing as well as by touch – non-uniform structure with a characteristic texture.

A good model for the use of hempcrete in deeply pro-ecological architecture is the project of a single-family house called Flat House (Cambridgeshire, Great Britain,



Fig. 8. Various colors, structures and textures of the surfaces of vertical partitions made of hempcrete: a), b) the examples of walls (photo by M. Gacek)

Il. 8. Różnorodne kolorystycznie, strukturalnie i fakturowo powierzchnie przegród pionowych z betonu konopnego: a), b) przykładowe detale ścian (fot. M. Gacek)



Fig. 9. Zero-emission hemp house Flat House at Margent Farm in Cambridgeshire, England, covered with innovative hemp fiber tiles: a) view of the front elevation, b) detail of the wall (arch.: Practice Architecture, photo by O. Proctor)

Il. 9. Zeroemisyjny dom z konopi Flat House na farmie Margent w Cambridgeshire, w Anglii, pokryty innowacyjnymi płytkami z włókna konopnego: a) widok frontowej elewacji, b) detal: płytki z włókna konopnego (proj. Practice Architecture, fot. O. Proctor)

2019) by the Practice Architecture studio (Fig. 9). This is another example of noticing the locally available material, here – hemp grown directly on the construction site, and then using it for construction, thus minimizing the carbon footprint generated on the production line of building material – construction site. The house was built of hemp-filled prefabricated panels. From the inside of the building, the wall panels were left in a raw state, exposing the aesthetic properties of hempcrete. The surfaces have an interesting diverse texture and ambiguous colors which change under the influence of light intensity. The flat house is an example of the so-called a zero-emission house. In the case of hemp concrete buildings, it is the plant material that is responsible for negative carbon dioxide emissions [5, p. 63] – the material stores the amount of CO₂ that exceeds the total amount of CO₂ emitted during production and transport of the material. The external surfaces of the building are covered with specially developed façade tiles, also made of hemp. The individual hemp fiber plates are joined with sugar-based resin obtained from agricultural waste. This action is an illustration of a truly ethical color in eco-architecture. As a result, the building adopted warm tonal colors in shades of brown and from a distance the covering resembles wood. Moreover, the grooved structure of the tiles contributes to an interesting play of light and chiaroscuro on the façades, which react to changes in lighting and undergo a color transformation on a daily and yearly scale.

Color in eco-architecture in relation to the time factor and environmental conditions. Façades with the use of materials of organic origin which change color permanently over time

Time is a direct factor which has an influence on the color of façades made of organic materials. Their surfaces undergo a constant color transformation over the years. Combined with the parallel influence of changing weather conditions, these façades take on various tones and textures.

The most common example of such façades is represented by wooden façades. Wood is a material which, when left unfinished on the façade and exposed to weather conditions, loses its original color very quickly. This property is often used on purpose, especially since some types of wood give the intended color effect after many years, e.g., the wood of Siberian larch (*Larix sibirica*) changes to a silver color with time. An example is the paneling of this type of wood used in the building of the Norwegian Parliament of the Saami People in Karasjok (architect Stein Halvorsen, Christian Sundby, implementation in 2000), in Norway (Fig. 10).

Due to an inevitable change in the color of wood, impregnation agents have been used for hundreds of years to prevent premature aging. The traditional Japanese technique of impregnating wood with fire called shou-sugi-ban (as well as yakisugi) involves the controlled burning of the wood to give it the desired color and specific properties. As a result of this treatment, the burned wood acquires fire-resistant properties, is more durable and resistant to weather conditions and pests [26].

When it comes to colors, due to the charring process, the wooden surface heated in this way takes on dark tones, i.e. close to black. It can also be cleaned and oiled. The visual effect of the wooden surface treated in this way is unique, as in the completed project (2020) by the 89° studio. This single-family house near Warsaw (Poland) is characterized by a minimalist form emphasized by a large black surface of the façade. With the surrounding vegetation, it creates an interesting black and green assemblage (a spatial collage) in which the verticalism of harmoniously contrasting façade boards with tones close to black with the white of the surrounding birches is visible (Fig. 11).

Impregnations based on iron oxides, commonly used in Norway, especially in farm buildings, significantly influenced the colors of Norwegian farm buildings. Deep red barns are an integral part of Norwegian landscapes [27] (Fig. 12).

In the context of pro-ecological architecture, it is necessary to mention a new material with great development

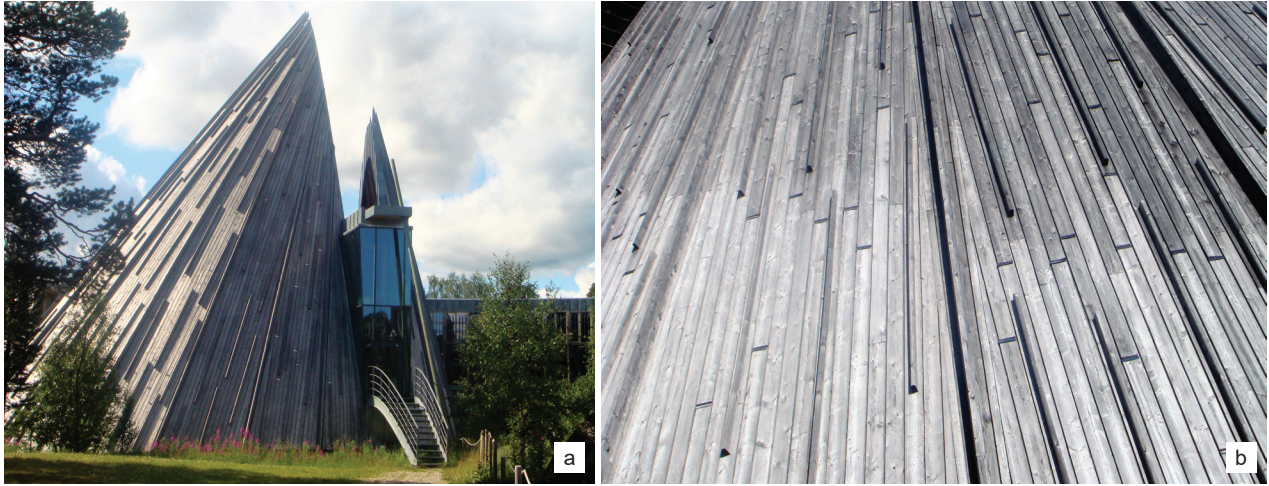


Fig. 10. Siberian larch wood, discoloring with time from gray to silver, used as a cladding for the façade of the Norwegian Parliament of the Saami People in Karasjok, Norway: a) view of the front façade, b) detail of the roof (photo by E. Cisek)

Il. 10. Drewno modrzewia syberyjskiego przebarwiający się z czasem z koloru szarego na srebrzysty zastosowane jako okładzina elewacji Budynku Norweskiego Parlamentu Ludu Saami w Karasjok, Norwegia: a) widok frontowej elewacji obiektu, b) detal dachu (fot. E. Cisek)

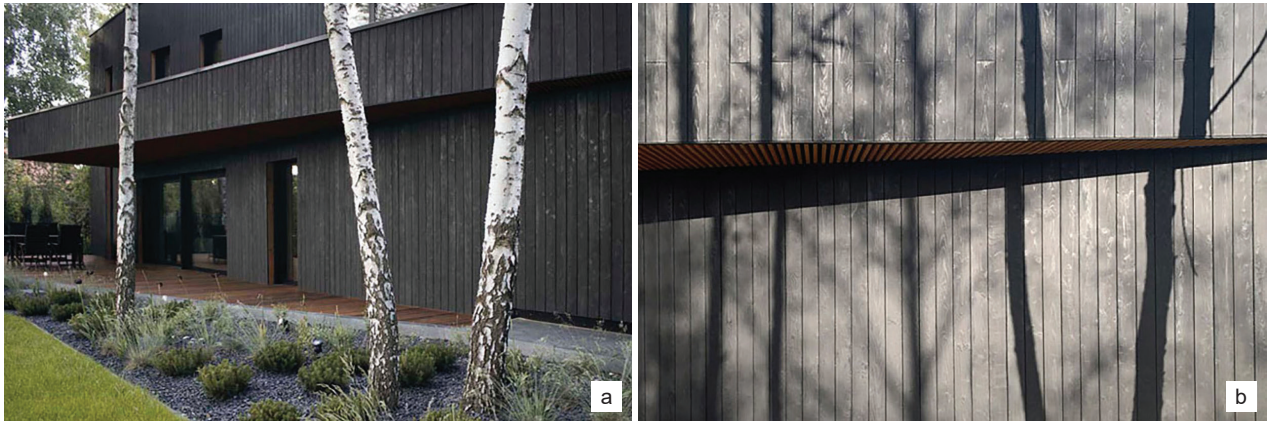


Fig. 11. Wooden house façades with dark colors, treated with the shou-sugi-ban method:

a) view of the building with tones close to black with the white of the surrounding birches, b) detail of the façade (photo by A. Olczak, studio 89°)

Il. 11. Ciemne tonalnie elewacje drewniane domu mieszkalnego pod Warszawą potraktowane metodą shou-sugi-ban:

a) widok budynku zestawiony z bielą otaczających go brzoź, b) detal elewacji (fot. A. Olczak, studio 89°)

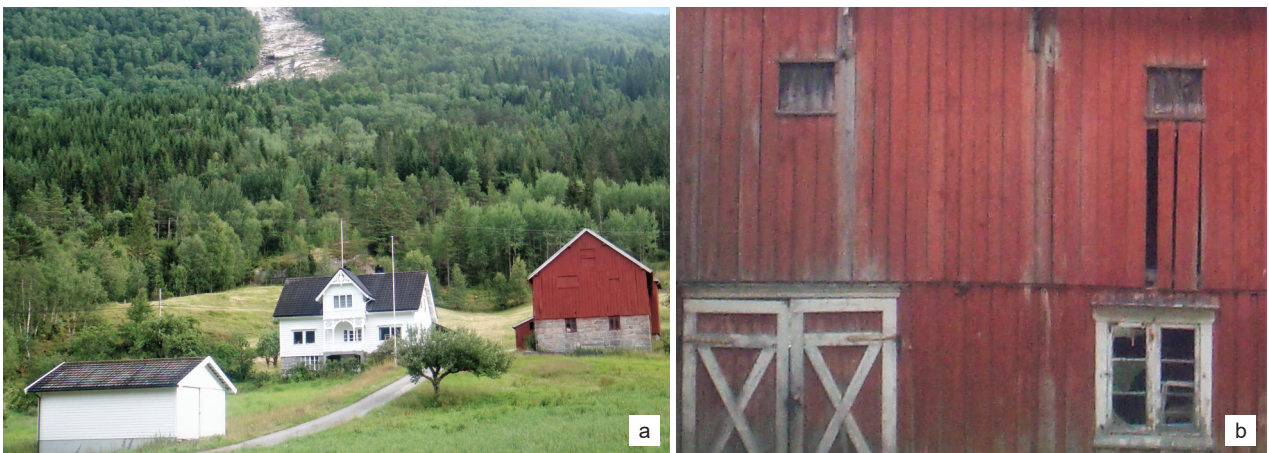


Fig. 12. Deep red barn – a permanent element of the Norwegian landscape, Stryn, Norway:

a) view of the farm development with barn, b) detail: the elevation of the red Barn (photo by E. Cisek)

Il. 12. Stodoła w kolorze głębokiej czerwieni – stały element norweskiego krajobrazu, Stryn, Norwegia:

a) widok zabudowy farmerskiej ze stodołą, b) detal elewacji stodoły (fot. E. Cisek)

potential in the context of the future. It is the so-called hempwood, which has a chance to become a substitute for wood. This ecological material, which is modeled on the physical characteristics of oak commonly used in construction, surpasses its properties – it is 20% more durable than oak and its production is 100 times faster. Hempwood has very interesting visual characteristics, i.e., a variety of colors, from shades of gray to browns with varying degrees of saturation; unique surface drawings depending on the material, from linear to irregular, resembling a pattern of natural stones [28]. This innovative material offers wide aesthetic possibilities and at the same time constitutes a valuable potential in the perspective of the deepening climate crisis, environmental protection, and thus minimizing the excessive reduction of trees.

Ice is a similarly unstable, biodegradable, and environmentally dependent eco-material which gives the façade a white effect changing into various shades of gray over time. Representative examples include ice hotels which are usually built in winter and operate until January/April. With spring warming, these facilities melt and the next year they are erected again. Such facilities are constructed all over the Scandinavian Peninsula (e.g., Sweden – Jukkasjärvi, Finland – Kemi, Arctic Resort Kakslauttanen, Snow Village, Norway – Kirkenes Snøhotel, Sorrisniva Igloo Hotel in Alta, Bjorli Snøhotel, Hunderfossen Snøhotel) and also in other places (e.g., Canada – Ice Hotel de Glace in Quebec, Spain – Igloo Hotel in Granvalira). The cyclical existence of these architectural forms means that every year a slightly different structure is created, which varies from its predecessor and has a different artistic expression [5, pp. 121–125].

Summary and conclusions

Our research on color is part of the framework considerations on the transformation of the urban landscape into environmentally friendly eco-structures of various scales and colours [29], [30]. Analyses of ecological implementations show that the idea of an organic city and introducing nature to cities in various forms of eco-architecture are part of a long-term deep ecology movement initiated in Norway, which is becoming a means of fighting the climate crisis [29], [31]. This study proves a high value and great

importance of these applications for achieving diverse and rich color ranges in architecture, while significantly reducing the negative impact of these practices on the natural environment, compared to, e.g., synthetic building materials. Such practices should be particularly promoted in the context of the advancing climate crisis, and research into materials of organic origin should be given priority.

Summarizing these considerations, it should be emphasized that:

1. The color appearing on the façades of eco-facilities constitutes a changing element which evolves over time, making up the image of an architectural object.

2. This image may be a complementary component of an artistically shaped, often revitalized public space, integrating the community (e.g., green vertical gardens as part of pocket parks) or become a brand of investments and cities (e.g., roofs and vertical gardens on external and internal barriers significant for culture). objects, panels with algae, Vertical Forest).

3. Changes in the color of an object's image, resulting from the organic materials used and the natural cycles connected with them, are referred to as new forms of art, reflecting the link between architecture and biology. As a result of this fusion, processes such as plant vegetation cycles, photosynthesis, biodegradation and absorption of rainwater are behind the variable, colorful image of the object. These processes can additionally affect the favorable energy balance of facilities, electricity and heat production, as well as food production.

4. The creation of unique and unrepeatable in terms of color solutions of images of objects may result from the construction and finishing materials used, which come from recycling (e.g., brick, copper) or are new experimental technologies (e.g., hempcrete). Due to the progressive overpopulation of cities, such spatial recycling is very desirable and valuable [32], [33].

5. The use of non-durable, biodegradable finishing materials that change color under the influence of light and environmental conditions introduces the narrative of the place, making the image of the object closer to life and nature, a part of a larger and higher order [34].

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Abstract

Color in eco-architecture as a representation of natural processes

The article aims to analyze the relationships between natural processes of organic materials which are used in eco-architecture and the resulting color effects. It was indicated that images of objects may undergo irreversible changes, when the material used undergoes natural biodegradation over time, as well as cyclical changes – then the applied living matter is periodically reborn in colors consistent with year-round natural rhythms. These solutions, which are implemented on various scales, are defined as new forms of art forming a combination of architecture and biology. Our research on color is part of the framework considerations on the transformation of the urban landscape into environmentally friendly eco-structures of various scales. Analyses of ecological implementations show that the idea of an organic city and introducing nature to cities in various forms of eco-architecture are part of a long-term deep ecology movement initiated in Norway, which is becoming a means of fighting the climate crisis. This study proves a high value and great importance of these applications for achieving diverse and rich color ranges in architecture, while significantly reducing the negative impact of these practices on the natural environment, compared to, e.g., synthetic building materials. Such practices should be particularly promoted in the context of the advancing climate crisis, and research into materials of organic origin should be given priority.

Key words: eco-color, eco-architecture, renewable energies, ecology, colors of earth

Streszczenie

Kolor w ekoarchitekturze jako odwzorowanie procesów zachodzących w naturze

Artykuł poświęcony jest badaniom nad relacjami, jakie zachodzą pomiędzy naturalnymi procesami, którym podlegają materiały pochodzenia organicznego stosowane w ekoarchitekturze, a uzyskiwanymi, będącymi ich następstwem efektami kolorystycznymi. Wskazano, że wizerunki obiektów mogą ulegać zmianom zarówno nieodwracalnym, gdy użyty materiał ulega z czasem naturalnej biodegradacji, jak i cyklicznym – wówczas zastosowana żywa materia odradza się okresowo w kolorach zgodnych z całorocznymi rytmemi przyrodniczymi. Takie rozwiązania realizowane w różnych skalach definiowane są jako nowe formy sztuki, będące sprzężeniem architektury z biologią. Przedmiotowe badania nad kolorem wpisują się w ramowe rozważania nad transformacją pejzażu miejskiego w przyjazne środowisku ekostruktury o różnych skalach i kolorach. Analizy ekologicznych realizacji pokazują, że idea miasta organicznego oraz wprowadzanie do miast natury w różnorodnych formach barwnej ekoarchitektury wpisują się w długofalowy ruch ekologii głębokiej, zapoczątkowanej w Norwegii, stając się środkiem do walki z kryzysem klimatycznym. Niniejsza praca pozwala podkreślić wysoką wartość i ważność tych zastosowań dla osiągnięcia różnorodnych i bogatych zakresów kolorystycznych w architekturze, przy istotnej redukcji jej negatywnego oddziaływania na środowisko naturalne, w porównaniu np. z architekturą wykorzystującą syntetyczne materiały budowlane. Takie praktyki powinny być szczególnie promowane w kontekście postępującego kryzysu klimatycznego, a badania nad materiałami pochodzenia organicznego traktowane priorytetowo.

Słowa kluczowe: ekokolor, ekoarchitektura, energia odnawialna, ekologia, kolory ziemi

