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Skin as habitat: Performance through species integration

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Abstract

As the interface between interior and exterior environments, building skins are critical to achieving sustainable architecture. But while sustainability in relation to the building skin is often characterized in terms of energy efficiency and human comfort, we propose an enhanced definition that simultaneously encompasses those concerns while also incorporating the potential benefits of designing with (and for) other species. Examining a series of case studies, we bring to light the ways in which other species can be integrated into the design process and be participants in the performance of building skins. We investigate examples that use living algae that harvest solar energy and retain heat or others that integrate plant species that can provide seasonally appropriate shading in cooling seasons while offering psychological benefits to the building inhabitants. From this perspective, technology can be seen as offering opportunities not just to avoid negative impacts for species, as we see with bird-safe glass, but rather to invite them to cohabit with us through the building skin, identifying space for symbiosis in unconventional ways.

Through the precedents we illustrate how formal, contextual, and spatial configurations can support different species with varying degrees of success, and we illuminate the potential for building skins to be conceived as habitats at multiple scales. We recognize the importance of the integration of interdisciplinary knowledge and data related to species to inform the design and its performance over time. The selection of materials, the height at which the building skin is located, and the activities happening on either side of it are key design considerations when incorporating species in urban contexts. We see the potential positive impact that skins can have on ecosystems through horizontal and vertical urban connectivity. Building skins and their species can contribute to the reduction of heat islands. They can play a role in creating habitat continuity for migratory species and provide nourishment for pollinators that in turn are key to human food production. They can metabolize waste and generate usable heat in the process. In addition to the advantages studied, we expose the tensions that arise between the needs of humans and those of other species, pointing out the types and extent of collaborations that we consider most productive. This reflection questions the space allocated to cohabiting with other species and challenges our behavior in the exchange that occurs at the building skin. This research proposes innovative approaches to conceptualize and materialize building skins that expand the scope of sustainable architecture.

1. Introduction

The presence of plant species in cities is known to enhance well-being for humans [1]. Parks and open spaces serve as places of refuge, repose, regeneration, and connection on a daily basis, and this has been especially so during the recent pandemic. As the mediator between outdoor and indoor environments, building skins are charged with enabling visual and physical connections with those green spaces, just as they also manage daylight, fresh air, temperature, and other factors for the sake of human comfort and health. All too frequently, the connection to the outside environment is reduced to a glazed facade, providing a clear view for humans, but leading to thermal inefficiency as well as lethal consequences for birds and other species [2]. While sustainability in relation to the building skin is often concerned with energy use and human comfort, this paper expands the field of focus to include the potential benefits of designing with other species in mind.

We are witnessing an increase in building designs that envision the integration of vegetation within the facades and roofs of buildings, promising an enticing connection with a new natural environment. As we incorporate vegetation more fully into our building skins, however, we also invite numerous other species to exist within the urban setting. To get beyond pure imagery which may fall short as superficial and trendy, it is key to work towards a more comprehensive understanding of the opportunities, consequences and potential tensions that this integration entails in the realization of living building skins. Our paper acknowledges the specialized contributions of research in the realm of living building skins [3, 4, 5, 6] while presenting a perspective with a wider scope, identifying opportunities for further detailed research.

2. Spatial configuration and habitat

The spatial configuration of the skin has an impact on the promotion of habitat which should inform the building section, the activities happening on either side of the skin, and its deployment at the building, city and regional scale. The skin might support different habitats and interactions between humans and species depending on its position relative to the ground, and the orientation in which it is deployed. For instance, if we consider the vertical section of a skin, some predatory birds might be inclined to occupy the upper elevations characteristic of high-rise construction, which yield perches for spotting prey alongside higher density for humans [7]. However, the skylines full of glass towers also pose a threat to bird species resulting in billions of casualties annually. Favorably, several examples of buildings in dense urban centers like the remodelled facade of Manhattan's Javits Center [8] and the Anchorage Museum expansion are implementing frit-pattern glass to reduce both reflectivity and transparency to help prevent fatal bird strikes [9]. In addition to substantially minimizing collisions, these surface treatments reduce cooling energy requirements and preserve the visual connection for humans.

Along with the possibilities brought by height, the sectional depth of a living wall or of a green roof influences the types of species it can host, and the degree to which humans are able to interact with, appreciate, or support them. Bosco Verticale (BV), Hotel Klima (HK) and Hotel Viu (HV) in Milan are examples of large-scale buildings with dense vegetation growing on their facades. These structures provide birds with areas for foraging, perching, nesting and breeding through different design configurations of the building skin. Featuring deep balconies that accommodate fruit bearing trees, shrubs and climbing plants, BV and HV have been shown to attract a more diverse range of birds when compared to HK which only features climbing plants in its green wall [10]. The BV and HV examples successfully calibrate the form and capacity of the structure to the scale of the vegetation supported [11], demonstrating how the design of the building skin has a direct impact on promoting the richness and diversity of species. While dense and high-rise buildings like BV, HK and HV, attract more bird diversity than their urban non-vegetated counterparts, they may be acting as merely “stepping stones” in the network of urban vegetation, also constituted by parks and low to mid-rise buildings [10]. In isolation, they do not function as core habitats for bird species [10], pointing towards the importance of ecological connectivity that might transition from buildings to the condition at grade, where pedestrian activity has overlaps with other species that rely on terrestrial mobility, grounding, and continuity.

Whereas green walls and multi-layered green facades can provide a means to support species vertically, green roofs can also support species horizontally, providing a number of benefits to humans and our environment. Shallow, extensive green roofs reduce heat islands and stormwater runoff in urban settings while improving roof longevity and insulation capacity, among others [4]. However, these do not tend to support a wide variety of flora and fauna compared to the designs of biodiverse roofs, which offer a variety of habitats. In other words, the formal decisions of green roofs -- layout, soil depth, soil variety and water inclusion – have an impact on plant diversity, which translates into the provision of food, drinking water, and cover for nesting and breeding of different species [3].

Just as formal choices about building skins impact the quality of habitats, so do the material systems employed to construct them in our urban settings. For instance, the chemical composition and material texture of some stone walls coupled with the environmental conditions found in some cities enable lichens to colonize these vertical surfaces [12]. While cable frameworks in green facades [Figure 1] are sufficient for many climbing plants to thrive, other vegetation like fruit trees, need much more soil depth to grow, which could be accommodated with intensive green roofs or deep balconies. The development of products and techniques for supporting vegetation on walls and roofs is continuously evolving to simultaneously solve for multiple parameters like durability, maintenance of vegetation, compatibility with other building envelope layers, or integration with prefabricated construction [13]. From the perspective of the species being hosted, however, a critical parameter for the skins to achieve is bioreceptibility [14]. As material systems respond to the environmental circumstances in which they exist, such as seasons and diurnal cycles, opportunities for permeability and the exchange enacted at the skin are affected. In certain circumstances and seasons, some species may, in fact, prefer urban systems to forests, pointing toward an intertwined relationship which we can embrace as designers [15]. As we envision the facade as an enabler of habitat, new formal, spatial, and programmatic demands arise and with that new ways in which humans relate to other species and our shared environment.

Figure 1: Support for climbing vegetation

Figure 2: SolarLeaf, Hamburg, Germany

3. Designing for human and species needs

The functions that the skin can embody should be studied relative to the benefits that it can bring to different species (including humans), such as habitat, visual interest, sheltering, reproduction, communication, growth, solar shading, wind protection, food production, psychological well-being, or energy harvesting to name a few. For this, it is key to have a deep understanding of the species that the design aims to support and its relationship to humans. Reflecting on the different needs and perspectives of each participant helps to identify the productive overlaps and tensions that can arise when responding to both with one design. For instance, biosolar roofs, which combine solar photovoltaic energy harvesting with biodiverse green roof strategies, have been shown to have mutual benefits. That is, photovoltaic arrays can enhance the spatial heterogeneity of green roofs, increasing biodiversity, while the vegetation has a positive effect on the efficiency of the PV array by providing a cooling effect and reducing particulate matter accumulation [5]. Similarly, the various environments that provide food, cover, and water for birds and insects in the design of the Augustenborg's Botanical Roof Garden respond to the uses that are necessary for species to thrive while also allowing human visitors to learn about habitat promotion, diversity, and green roof construction [3]. However, not all green roofs need to be biodiverse roofs, and careful consideration should be given to the overlaps that might cause tensions between the territory allocated for humans and for other species. At Chicago's O'Hare International Airport, for example, a stonecrop-based green roof is an appropriate choice in that it attracts fewer birds in a location where airplanes place birds in harm's way and vice versa [4]. When considering a horizontal application such as a roof garden, the degree of overlap between humans and species can be designed, at times prioritizing human use and recreation, while at others benefitting species that thrive in territories more isolated from humans.

Just as skins can define the separation between environments, they can also help establish connections and regulate degrees of exchange. In doing so, we can design particular experiences depending on whether or not the species invited to participate are compatible with human programs. For example, building skins could act as agents that negotiate the contact between humans and bee populations when they share urban territories. As a potential response to the decline of pollinator species worldwide due to habitat loss, urban areas may support larger and more diverse pollinator populations than agricultural areas because of their increased floral resources [16]. Furthermore, the fact that urban green roofs are removed from pesticide use, characteristic of agricultural fields, may provide urban bees a healthier environment in which to live. Inviting bee populations in certain circumstances can create conflict for people with bee allergies or phobias, and yet we see the benefits of sharing pesticide-free urban areas with them to promote pollination and food diversity. Education is an important factor in reducing anxiety and appropriately planning for cohabitation. It is not widely known in the general population, for instance, that the most efficient pollinators are not honey bees but rather solitary bees which nest alone and do not swarm, and thus reduce risk of conflict with humans. Research on novel methods of providing nesting habitats for bees, such as bee bricks, is underway and pointing toward a better understanding of the types of support we can provide with the building skin [17].

A project that incorporates living organisms into its skin is SolarLeaf in Hamburg, Germany [Figure 2], which encapsulates micro algae in glass panels that harvest solar energy through photosynthesis. While this project brings algae in close proximity to humans to help meet heating demands in a residential application, its design could go further in considering human program and experience. At the ground level, for instance, what was originally built as a functional array of energy harvesting algae panels is now, years later, covered with a permanent hedge, thick enough to serve as a visual and physical obstruction for the curious public. Unfortunately, the hedge also occludes solar radiation, rendering the panels behind it ineffectual. Beyond this incompatibility at the ground level, the project leaves open the potential for incorporating the phenomenological qualities inherent in the fluid medium, its animation with bubbles of carbon dioxide, its color rendering translucency, and its relationship to the program of dwelling [18].

Whereas SolarLeaf enables habitat in an automated way, independent of the human users, the 9-story high Pasona Office Farm building in Tokyo enables interactions between humans and other species while also supporting their habitat, relying on daily participation to integrate urban farming and green spaces within an office setting. More than 200 species of fruit, vegetables, and rice are grown in its louvered double skin facade and planted interior partitions, allowing inhabitants to enjoy gardening and harvesting in their workspace [19]. This self-sustaining ecosystem in an urban condition prioritizes a healthy work environment over the real estate demands that are otherwise typical of its program and setting. It aims to connect its inhabitants with the growing species, providing benefits of relaxation, food access, and improved air quality while achieving shading and insulation for the interior spaces [19].

The conditions of the Pasona Office Farm depend on humans to provide the infrastructure for relationships with plant species to succeed. Similarly, the Mediated Matter Group's Silk Pavilion at MIT exemplifies how a skin can be the result of a collaboration between humans and silkworms at an architectural scale. A human-designed, digitally fabricated fiber structure serves as a scaffold onto which silkworms complete a second skin of varying density [20]. The design of the initial structure is based on predictions of the behavior of the silkworms, in turn determining organizational outcomes of deposition. The behavioral patterns, range of motion, and the ability of silkworms to deposit fibers under specific conditions of light and temperature [20] are at play in shaping their fabrication process and result in the formal characteristics of the pavilion such as density, translucency and structural performance. Unlike other silk-spinning processes, this project promises more sustainable manufacturing by using material resources efficiently without harming the metamorphosis of silkworms [20]. Although this inspiring project shows a reciprocal relationship between humans and species, parameters of scalability and durability of the skin must be considered in future research on the path to usability in architecture. Nonetheless, it represents the promise of innovation through species collaboration and a lighter environmental footprint.

Another opportunity for species integration resides in urban composting, which exists in many metropolitan areas. There are, however, inaccessibility issues and inefficiencies associated with the collection, transportation, processing, and distribution of compost material, because the buildings in which we normally produce food waste are not equipped to carry out these functions. With the existence of small-scale prototypes that integrate composting into domestic interior spaces [21], it is conceivable that this logic could be applied to the building skin in such a way that the benefits of heat generation, solid waste reduction, and soil production can be made more local and commonplace. A skin with the capacity to metabolize human food waste in close proximity to the generation of that waste, while solving issues related to odors and unappealing appearance, could add a critical convenience that stimulates human participation and that can contribute to the reduction of food waste in landfills.

As we bring plants and animals closer to us in cities we foresee the implementation of material, construction, and biological technologies that might help us adapt them further to mutually align our needs and programs. Many of our ornamental and edible plants and animals are already genetically engineered, and new advances are allowing modifications at the cellular level where characteristics of one species can be introduced to another to enhance performance [22]. Bioglow, working with synthetic biology, is developing a plant that emits light on its own by introducing a bioluminescent marine bacterium into its genome [23]. This type of research, along with artistic projects such as Bioglyphs [24], and speculative initiatives by companies such as Glowee [25] make room for the use of bioluminescent organisms in applications servicing human needs. And although much research is needed to ensure appropriate light levels, durability, and feasibility of these types of technologies, it is not unreasonable to imagine incorporating them into the skin of buildings to help illuminate our urban environments in sustainable ways. Similarly, living organisms can be incorporated to be used as environmental indicators. For instance, the blood of horseshoe crabs has been used as a testing agent to aid humans in detecting the presence of bacteria in medical applications [26]. At the building scale, lichens are one type of organism whose presence on certain kinds of walls has been understood as an indicator of atmospheric nitrogen deposition [12] demonstrating that the living skins can perform the role of Bio-Indicator, signaling environmental conditions.

The ethical debates embedded in the incorporation of species in living skins, along with the development of genetically engineered plants and animals – while not the central topic of this paper – is a profoundly important issue related to the potential of living skins. With the power to influence living organisms at the level of DNA comes unknown and known biological risks. We can anticipate that the potential positive outcomes will continue to motivate innovation in this area to generate ever more opportunities for humans but we must strive to also achieve mutual benefit.

Planning for the future of the living skin early in the design is key in assuring symbiosis between the humans and other species that are invited to cohabitate. The amount and location of the space dedicated to each species and whether these should be shared or not must be considered relative to the program enacted by the participants. Identifying the problems that emerge from the intersection of habitat and human needs, such as disease transmission, unhygienic conditions, or extensive maintenance can guide strategies to achieve an appropriate balance. For example, in Bosco Verticale, the program of housing is compatible with the vegetation and the avian species that it attracts. The vegetation contained within the balconies is maintained by repelling gardeners to ensure that it does not overgrow. In contrast to cases of unkempt ivy occluding windows and deteriorating building materials, the well-groomed vegetation in the design of the high rise adds visual appeal and marketability to these high-end apartments while enhancing the experience of dense urban housing through routine connection with living species. These examples illustrate the potential productive overlaps between human and other species and the tensions to be avoided at the building scale and underline the importance of living building skins in relation to experience.

Figure 3: Novartis Campus - Virchow 16.

Figure 4: MFO Park, Zurich, Switzerland

4. Experience and temporality when cohabiting with species

We are interested in asking how the exchange enacted through building skins can influence our habits and those of other species. There is growing evidence to support the idea that contact with nature promotes human learning and creativity by increasing our curiosity and recharging our directed attention [27]. We know that a connection to nature can improve physical health – having a positive impact on blood pressure, obesity, and diabetes – and it can improve mental health, reducing stress and depression while improving happiness, cognitive development, social behavior, and cooperation with other species [1, 28, 29]. Our human capacity and inclination to nurture other organisms is apparent in innumerable examples, like child rearing, loving our pets, or outdoor and indoor gardening [30]. Caring for these other beings can provide daily, weekly, or seasonal rhythms through associated beneficial activities like exercise. Allowing building skins to act as hosts to plants and animals that the inhabitants can be in contact with and care for has the potential to redefine daily routines in a direction that is psychologically, emotionally, and physically rewarding while having mutual benefits for the other species. In contrast, our health suffers when our work schedule is in opposition to our own circadian rhythm [31] and environmental cycles [32], whereas being in tune with nature and its patterns allows us to be better stewards of the environment [33].

This is the spirit behind the Biosphere for Treehotel in Sweden, which places visitors, albeit a very privileged few, in a position to view the comings and goings of winged species who may inhabit the hundreds of birdhouses surrounding the dwelling unit suspended in the tree canopy. While both the imageability of the project and the intent to incorporate species are successful in their own right, we see greater potential for overlapping experiences between humans and other species. We can imagine, for example, a condition that would allow humans a better visual connection with the birdhouses, offering an enhanced auditory experience, or enabling conditions for nurturing. Dealing with living organisms gives building skins a latent dimension to explore their quantitative and qualitative capabilities over time. For example, Virchow 16 (Figure 3), by RMA Architects, demonstrates a skin that changes throughout the year, helping us mark time seasonally. In this facade, a cable system supports deciduous climbing plants that transform the building façade from dense green foliage that provides the needed shade in summer to a bare condition that allows solar gain in winter, while presenting a visually rich composition in Autumn and Spring. Similarly, the MFO Park (Figure 4), which also incorporates climbing plant species that transform over time, invites humans to inhabit the thickness of its vertical and horizontal skin. As a result, the conditions of the spaces defined in this vertical park change over time according to growing patterns. As these dynamic skins adjust seasonally, their ability to host species varies accordingly. These examples help us imagine how living building skins could set up the conditions for humans to be in productive contact and interaction with nature, considering the temporal cycles that species experience – from birth, growth, reproduction, and death – revealing nocturnal habits, seasonal migrations, annual gatherings, and how these align with and complement the human experience.

5. Urban ecological strategy

The task of orchestrating the distribution and character of green spaces in between the buildings in a city normally resides within the disciplines of urban design, planning, and landscape design. Especially promising currents of thinking and practice pair these disciplines with an understanding of urban ecology, ecosystem services, and a multi-scalar approach [34]. Recently we are also beginning to understand that access to green infrastructure is an issue of urban equity [28]. There remains, however, a latent and meaningful role for building skins to play in that network of living assets. The design proposal for the Writers Theater in Chicago points toward the way in which a building can be conceived as part of a larger ecological region. The project takes into account its geographical position, a stop on the densely populated Mississippi Flyway migratory route, by including a number of design strategies that account for bird species such as wood lattice screens for canopy walkways in addition to frit-patterned glass that helps birds identify built surfaces as barriers while allowing inhabitants to enjoy the views and a connection with the outside [35]. While successful on its own as a building skin intervention aware of a larger context, a deeper impact is possible when it becomes part of a larger regional or city masterplan.

Living building skins cannot wholly replace the biodiversity and complexity of intact ecosystems, but they can provide a means to achieve living connective tissue for insects and birds to use as they live and move about in urban conditions, and most certainly represent a dramatic improvement over the biodiversity found on walls and roofs without living material [36, 37]. Green roofs and green facades are often dealt with independently of one another from one project to the next. Focusing on the importance of continuity for urban species, however, we identify the importance of making connections between these two planes where green walls can act as vertical corridors to provide species a means to move from the ground to a green roof [14]. The connection at the ground level between street vegetation including small to mature trees and shrubs, and adjacent green walls is another critical area for design and study. While the importance of habitat continuity is well understood in ecological terms, its study and documentation in relation to green roofs and walls is still evolving. It stands to reason, however, that with time we will understand more and more how to attract and host species with building skins, and that their connectivity within cities can positively impact habitats, and potentially humans. We can imagine, for instance, that supporting habitats for pollinators could increase their population, which in turn could support urban agriculture, an emergent means of improving food quality while reducing resource depletion. Visions of the urban environment like this one need a large-scale approach, rather than singular and fragmented attempts at the building level.

In this way, we have an opportunity to work toward a vision of a more thoughtfully shared habitat, designing holistically at the scale of the building, the block, the neighborhood, the city, and the region to include other species in the experience of the city. Knowing that continuity is key to achieving richer urban biodiversity, we imagine a network of habitats that may at times prioritize undisturbed green roofs and walls, while at other times becomes a shared zone that can be occupied and enjoyed by humans with recreational or other similar uses. While architects have the capacity to design green walls and roofs at the building level, they need a fundamental awareness of the larger dynamics at play to extend an invitation beyond the local instance, and in this way must be able to rely on and synthesize the knowledge of other disciplines.

Collaborations between architects and specialists of all disciplines are commonplace in contemporary practice. Building skin design frequently receives input from structural and mechanical engineers, and a variety of building envelope consultants. It is not hard to imagine the benefits of adding the voice of an ecologist, botanist, or an ornithologist to the team, providing insight into the needs of other species and the benefits of designing with and for them when conceiving building skins. We are starting to see projects where the presence of other species is being accounted for by specialists like ornithologist Ulf Öhman collaborating with Bjarke Ingels Group on the Biosphere for Treehotel in Sweden [6]. In that project, which features 340 small bird houses with varied apertures and sizes, the needs of the avian species of the area -- including bats and bees in addition to many birds -- were the driver for the formal variation in species accommodations in response to decreasing populations in the region as a result of logging operations [6]. In this way we see how data pertaining to the species in question can be a motivator for architectural form and building skin. Another recent example, the Pollinators Pavilion designed by Harrison Atelier, places primary importance on the collection of data itself, gathering information on solitary bee species through the use of non-invasive digital video capture, artificial intelligence, and machine learning [38].

6. Conclusions

The spatial configuration of the building skin impacts the promotion of habitat and the activities on either side of it. By designing with and for species other than humans, we can harness their properties for the sake of building performance, which can yield innovative living skins that can filter air, control rainwater, manage daylight, harvest energy, provide a safe space for reproduction, support nutrition and growth, allow pollination, and potentially facilitate waste metabolism. These performance benefits are enhanced when studying micro to macro relationships, considering the connectivity between vertical and horizontal living skins at the architectural, urban, regional, and ecological scales. The incorporation of species in our material and building technologies is an evolving locus of design innovation, pointing toward emergent and unconventional roles for species, like bioluminescence or composting, while helping to balance pragmatic requirements, like durability and maintenance, with the tendencies and needs of plant and animal species. Designing habitat and the incorporation of species into the skins of our urban contexts needs to be informed by a fundamental awareness of the larger dynamics at play to balance the benefits and tensions that arise when we deliberately and carefully cohabit with other species. Central to achieving a positively impactful design is the ability to synthesize the knowledge of other disciplines, and simultaneously to see the city as an ongoing experiment that informs our understanding of the ecology of urban environments. Rather than seeking further isolation through the design of our building skins, we should aspire to gain the many physical and mental benefits that emerge when humans engage with nature, however curated that nature may be in urban conditions. We can lean into the capacity of living skins to change awareness and enhance human experience by bringing us in contact with other species more regularly, over our daily and seasonal cycles, and in ways that help us see mutual benefits.

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8. References

[1] A. Nowak-Olejnik, U. Schirpke, U. Tappeiner. "A systematic review on subjective well-being benefits associated with cultural ecosystem services", *Ecosystem Services*, Vol. 57, 2022, pp. 1-13.

[2] Y. Gelb, N. Delacretaz. "Windows and Vegetation: Primary Factors in Manhattan Bird Collisions." *Northeastern Naturalist*, vol. 16, no. 3, 2009, pp. 455–70.

[3] R. Fernandez, P Gonzalez-R, "Green Roofs as a Habitat for Birds: A Review" *Journal of Animal and Veterinary Advances*, Vol 9. 2010, pp. 2041-2052.

[4] B. Washburn, R. Swearingin, C. Pullins, M. Rice, "Composition and Diversity of Avian Communities Using a New Urban Habitat: Green Roofs", *Environmental Management*, Vol 57, no.6, 2016, pp. 1230-39.

[5] C. Catalano, N. Baumann, "Biosolar Roofs: A Symbiosis between Biodiverse Green Roofs and Renewable Energy", *City Green*, Vol. 15, 2017, pp. 42-49.

[6] https://www.dezeen.com/2022/06/23/big-treehouse-hotel-bird-houses-biosphere/ [Accessed March 7, 2022]

[7] M. Brandon, R. Francis, M. Chadwick. "Living in the concrete jungle: a review and socio-ecological perspective of urban raptor habitat quality in Europe", *Urban Ecosystems*, 2021, pp 1179-1199.

[8] https://www.nytimes.com/2015/09/05/nyregion/making-the-javits-center-less-deadly-for-birds.html [Accessed August 24, 2022]

[9] https://www.bloomberg.com/news/features/2022-01-04/how-to-design-buildings-to-prevent-bird-crashes [Accessed August 5, 2022]

[10] R. N. Belcher, L. Fornasari, S. Menz, T. Schroepfer, "Birds use of vegetated and non-vegetated high-density buildings—a case study of Milan", *Journal of Urban Ecology*, Vol. 4(1), 2018, pp. 1–6.

[11] https://www.arup.com/projects/bosco-verticale [Accessed January 19, 2022].

[12] L. Bergamaschi, E. Rizzio, G. Giaveri, S. Loppi, M. Gallorini. "Comparison between the accumulation capacity of four lichen species transplanted to an urban site". *Environmental Pollution* (Barking, Essex : 1987). Vol. 148. 2007, pp. 468-76.

[13] F. Penkert, M. Schultz-Cornelius, M. Pahn, "Precast concrete façade with integrated trellis for permanent façade greening" *Proceedings of the 16th Advanced Building Skins Conference & Expo*, Bern, Switzerland, 2021, pp. 336-344.

[14] F. Mayrand, P. Clergeau, "Green Roofs and Green Walls for Biodiversity Conservation: A Contribution to Urban Connectivity?" *Sustainability*. Vol. 10 (4), 2018, pp. 1-13.

[15] I. MacGregor-Fors, “Winter thriving: on the role of a boreal city on bird communities”, *Journal of Urban Ecology*, Volume 8, Issue 1, 2022, pp. 1-7.

[16] R. Shaw, K. Christman, R. Crookes, C. Gilbert, J. Osborne “Effect of height and colour of bee bricks on nesting occupancy of bees and wasps in SW England”, *Conservation Evidence Journal*. Vol. 18, 2021, pp. 10-17.

[17] K. Baldock, M. Goddard, D. Hicks, W. Kunin, N. Mitschunas, L. Osgathorpe, S. Potts, K. Robertson, A. Scott, G. Stone, I. Vaughan, J. Memmott, “Where is the UK’s pollinator biodiversity? The importance of urban areas for flower-visiting insects”, *Proceedings of the Royal Society of London B: Biological Sciences*, 2015, p. 282.

[18] O. Mesa, N. Fash, “Performance2: Dynamic Skins”, *Proceedings of the 16th Advanced Building Skins Conference & Expo*, Bern, Switzerland, 2021, pp. 435-436.

[19] http://konodesigns.com/urban-farm/ [Accessed August 8, 2022]

[20] N. Oxman, J. Laucks, M. Kayser, J. Duro-Royo, C. Gonzales-Uribe, “SILK PAVILION: A CASE STUDY IN FIBRE-BASED DIGITAL FABRICATION”, *FABRICATE Conference Proceedings*, 2014, pp. 48-255.

[21] https://www.dezeen.com/2011/10/29/microbial-home-by-philips-design/ [Accessed August 8, 2022]

[22] Q. Shan, Y. Wang, J. Li, et al. “Targeted genome modification of crop plants using a CRISPR-Cas system”. *Natural Biotechnology*, Vol. 31, 2013, pp. 686–688.

[23] A. Krichevsky, B. Meyers, A. Vainstein, P. Maliga, V. Citovsky, “Autoluminescent Plants”, *PloS one*, Vol 5. Issue 11, 2010, pp. 1-6.

[24] https://biofilm.montana.edu/bioglyphs/project-2/gallery.html [Accessed August 8, 2022]

[25] https://unreasonablegroup.com/ventures/glowee [Accessed August 8, 2022]

[26] T. Maloney, R. Phelan, N. Simmons, “Saving the horseshoe crab: A synthetic alternative to horseshoe crab blood for endotoxin detection”, *PLOS Biology*, Vol. 16, 2018, pp. 1-10.

[27] T. Plambech, C. Konijnendijk van den Bosch, “The impact of nature on creativity – A study among Danish creative professionals”, *Urban Forestry & Urban Greening*, Vol 14, 2015, pp. 255-263.

[28] G. Bratman, C. Anderson, M. Berman, B. Cochran, S. de Vries, J. Flanders, C. Folke, H. Frumkin, J. Gross, T. Hartig, P. Kahn, M. Kuo, J. Lawler, P. Levin, T. Lindahl, A. Meyer-Lindenberg, R. Mitchell, Z. Ouyang, J. Roe, G. Daily, “Nature and mental health: An ecosystem service perspective”, Science Advances, Vol 5, 2019, pp. 1-14.

[29] J. Zelenski, R. Dopko, C. Capaldi, “Cooperation is in our nature: Nature exposure may promote cooperative and environmentally sustainable behavior” *Journal of Environmental Psychology*, Vol. 42, No. 1, 2015, pp. 24-31.

[30] C. Hall, M. Knuth, “An Update of the Literature Supporting the Well-Being Benefits of Plants: A Review of the Emotional and Mental Health Benefits of Plants” *Journal of Environmental Horticulture*, Vol. 37, pp. 30-38.

[31] A. Copertaro Alfredo, M. Bracci, “Working against the biological clock: a review for the Occupational Physician” *Industrial Health*, Vol. 57, 2019, pp. 557–569.

[32] P. Devlin, “Signs of the time: environmental input to the circadian clock”, *Journal of Experimental Botany*, Volume 53, Issue 374, 2002, pp. 1535–1550.

[33] M. Mucioki, J. Sowerwine, D. Sarna-Wojcicki, F. Lake, S. Bourque, “Conceptualizing Indigenous Cultural Ecosystem Services (ICES) and Benefits under Changing Climate Conditions in the Klamath River Basin and Their Implications for Land Management and Governance” *Journal of Ethnobiology*, Vol. 41, 2021, pp. 313-330.

[34] S. Connop, P. Vandergert, B. Eisenberg, M.J. Collier, C. Nash, J. Clough, D. Newport.,“Renaturing cities using a regionally-focused biodiversity-led multifunctional benefits approach to urban green infrastructure”, *Environmental Science & Policy*, Vol. 62, 2016, pp. 99–111.

[35] https://www.writerstheatre.org/blog/construction-update-birds-eye-view/ [Accessed August 12, 2022]

[36] R. Sutton, *Green Roof Ecosystems*. Springer International Publishing, 2015.

[37] J.W. Dover, "GreenWalls", In *Green Infrastructure. Incorporating Plants and Enhancing Biodiversity in Buildings and Urban Environments*, J.W. Dover, Ed., Routledge: London, UK, 2015.

[38] https://www.pollinatorspavilion.com/ [Accessed June 18, 2022].