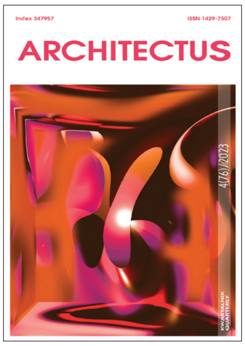

Architectus

2023
4(76)

DOI: 10.37190/arc230408

Cansu Iraz Seyrek Şık*

Vegetated kinetic façade – monographic review

Introduction

Rapid urbanisation results in a shortage of green areas in cities. This creates the need to introduce alternative solutions to cool public spaces in cities, purify the air, control rainwater and influence the health and comfort of city residents. Vertical green façades (VGF) are one of such solutions. These façades are classified in two main groups according to their structural typology: green façades (GF) (Fig. 1a) and living walls (LW) (Fig. 1b). GF are formed by wrapping and climbing plants which grow by clinging to the wall surface or on any surfaces such as rope, steel rope, steel or wooden cage and mesh. Plants can be rooted in soil or in plant pots. LW contain a vertical growth medium for plants to root and grow [1].

Kinetic façades (KF) shown in Figure 1c change their shape according to environmental stimuli or user input for a specific purpose, such as daylighting control and natural ventilation. In this study, responsive kinetic façades, i.e., kinetic façades that respond to environmental stimuli or user input, are defined as kinetic façades.

Vegetated kinetic façades (VKF) represent a relatively new concept (Fig. 2). These façades can be designed in two ways: the plants can be placed on movable modules, or a kinetic and vertical green layer can form a double skin. Combining mobility and vegetation, this concept has many potential benefits to users, designers, and for the urban environment. Due to the opaque growth medium of LW, they cannot be applied on transparent wall surfaces. GF on transparent surfaces allow light to pass through, but they cause visual interruption between the interior and the exterior, even with deciduous species. The idea of planting kinetic modules offers the opportunity to apply GF and LW on transparent façade surfaces without interrupting the visual connection of the user with the outdoor environment. Mobility provides the user with an easy access to products when VGF are used for food production. Due to the sun catching motion of panels, plants can maximise the use of sunlight. Vegetated kinetic modules provide partial shading to the plants and substrate during heat waves periods through self-shading movement performed in the direction opposite to catching the sun. This feature protects the plants from the undesirable effect of excessive solar radiation and prevent water loss on the system. Similarly, a kinetic layer used as a second layer to the vertical greenery in the slab walls enables control over environmental conditions according to plants' requirements while enhancing climate resistance of VGF.

Purpose and scope of research

Façade design requires a holistic approach. Environmental conditions, user requirements, building function and required façade functions directly affect the architect's decisions in the first stage of design. The aim of this study is to present the overview of current technologies and design trends of VGF and KF to provide architects with information advantages and limitations of VGF and KF. The second aim of the paper is to identify new opportunities and the most promising concepts of VKF.

Research methodology

The author carried out the comprehensive literature review on VGF and KF followed by a comparative analysis of the review results. The main source for the review was the Web of Science (WOS) Core Collection Database. "Design trends and technologies", "Kinetic façades" and "Vertical green façades" were identified as the searched key words.

* ORCID: 0000-0002-5190-4195. Doctoral School of Wrocław University of Science and Technology, Poland, e-mail: cansu.seyrek@pwr.edu.pl

Fig. 1 Examples of a vertical green and kinetic façade:
a) view of GF on the National Museum in Wrocław, Poland,
b) view of the LW on the building of the Polish Science Foundation in Warsaw, Poland (photo by C.I. Seyrek Şık),
c) view of KF the on building of MediaTIC in Barcelona, Spain (photo by A. Woźniczka)

Il. 1. Przykłady pionowej fasady zielonej i kinetycznej:
a) widok zielonej fasady na Muzeum Narodowym we Wrocławiu, Polska,
b) widok żywej ściany na budynku Fundacji na rzecz Nauki Polskiej w Warszawie, Polska (fot. C.I. Seyrek Şık),
c) widok fasady kinetycznej na budynku MediaTIC w Barcelonie, Hiszpania (fot. A. Woźniczka)

The search results were filtered for articles, conference proceeding, reports and book chapters from the last 12 years. For the literature review 45 studies were manually selected. The selection was based on the following content criteria: review articles published in the last 12 years on these topics, experimental studies including tests on prototypes that propose a new design or technology, in situ measurements evaluating the function of different system types and reports analysing the characteristics of KF and VGF technologies. Various systems were compared based on performance and environmental sustainability. The research steps are shown in Figure 3.

The state of research

Research on VGF systems has accelerated in the last decades. Firstly, Alexandra Medl et al. [2] stated that while there are many studies on the overall performance of plants in urban environments, studies on the benefits of vertical green systems (vegetated vertical surfaces, whether or not on building façade – VGS) are still fragmented and incomplete. Moreover, there is a research gap in areas such as improving urban biodiversity, stress recovery, reducing glare or the ability of VGS to retain rainwater, the application of VGS in rural areas or the application of VGS to construction buildings. Rosmina A. Bustami et al. [3] summarised research trends in VGS under 13 main headings: thermal, design, vegetation, phytoremediation, economics, acoustics, social studies, biodiversity, irrigation and crop production. It is mentioned that studies about VGS have begun to diversify from building, energy and engineering fields to increasingly multidisciplinary fields such as acoustics and social studies. Fabrizio Ascione et al. [4] emphasised that VGS have a great potential to improve building energy performance, acoustic and indoor micro-

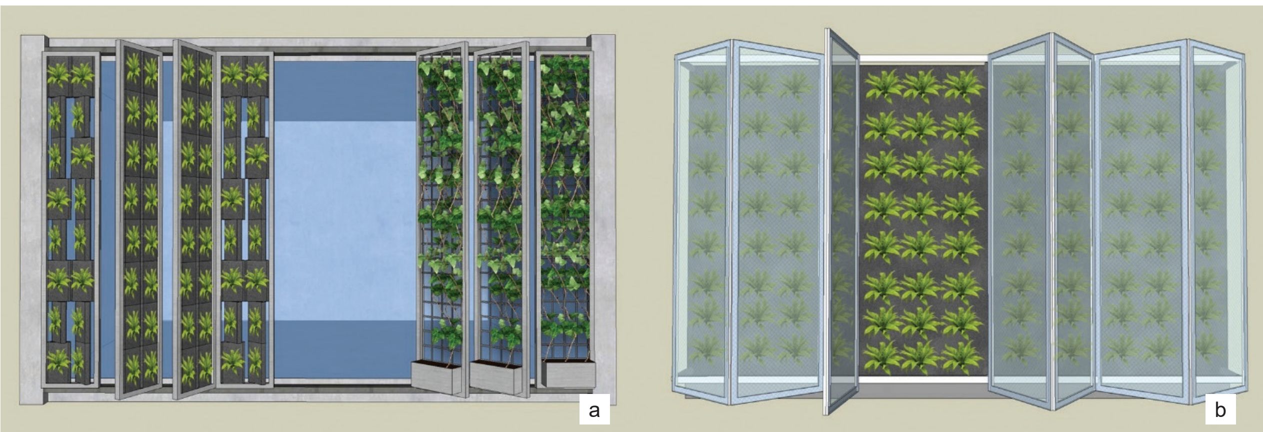

Fig. 2. Examples of vegetated kinetic façades:
a) view of two types of VKF with vegetated modules,
b) view of the double skin VKF (elaborated by C.I. Seyrek Şık)

Il. 2. Przykłady fasad kinetycznych z roślinnością (FKR):
a) widok dwóch typów FKR z modułami wegetacyjnymi,
b) widok podwójnej powłoki FKR (oprac. C.I. Seyrek Şık)

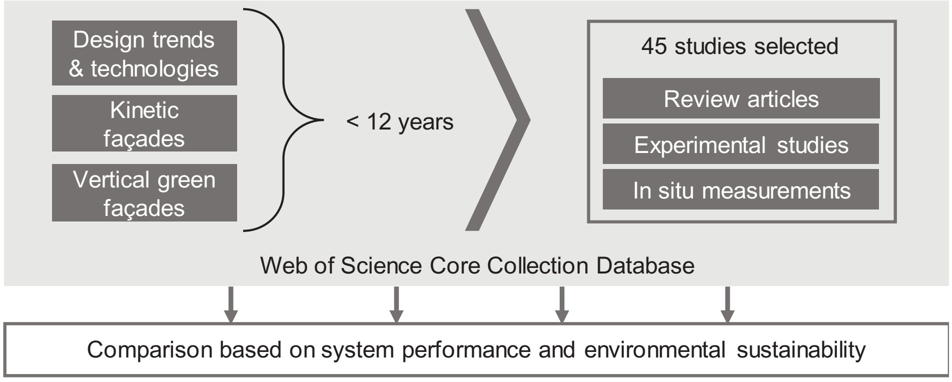

Fig. 3. Visualisation of the research steps towards the literature review described in the chapter "Research methodology" (elaborated by C.I. Seyrek Şık)

Il. 3. Wizualizacja kroków badawczych w kierunku przeglądu literatury opisanego w rozdziale „Metodologia badań" (oprac. C.I. Seyrek Şık)

climatic comfort according to the results of conducted comprehensive literature review. On the other hand, the lack of consistency in data collection methods due to the lack of an international standard for VGS and the incomparability of experimental and numerical results in terms of energy savings and thermal adaptability are pointed out. Puyi Wang et al. [5] ranked the keywords frequently used in research on VGS as "Urban heat island", "Thermal performance", "Energy performance" and "Climate change". This order is followed by "Indoor air quality" and "Life cycle assessment". In addition, the study draws attention to different design trends in different countries. In China, the main focus is on energy saving benefits, whereas in Australia and Italy the potential of using LW for waste treatment and indoor application is being investigated. In this study, the concept of KF is defined as a responsive façade that moves and changes its shape in an externally observable way. Many different terms are used to describe these façades. Some of these terms are "dynamic, active, kinetic, intelligent, smart, movable, responsive, interactive", or the more comprehensive term "adaptive" [6]. Since many examples of KF show different characteristics from each other, various approaches have been proposed for their classification, and even classifications have been made under the definition of adaptive façade, which covers a wider group than KF [6], [7]. On the other hand, Negar Heidari Matin and Ali Eydgahi [8] categorised the technologies used in responsive façades. As mentioned earlier, the wide variety of systems causes the complexity of the research field and does not make precise distinctions possible.

The COST TU 1403 Adaptive Façades network initiative published three booklets documenting the interdisciplinary, horizontal and vertical networking and communication between the different stakeholders of the COST-Action, including the introduction and classification of different adaptive façades technologies, the discussion of numerical and experimental research methods and finally the organisation of support sessions, industry workshops and related surveys as specific dissemination tools to link research and education[1]. In addition, there are studies carried out on the performance evaluation of KF. These are generally simulative studies on daylight control, visual comfort and solar thermal heating [9]. The lack of research on KF about acoustic performance and natural ventilation control is striking.

Research on VKF is limited. The idea of designing LW on movable panels was discussed by Leann Andrews and Nancy Rottle in 2012 [10]. Design possibilities were mentioned as a hinged green window wall, a sliding balcony door green wall and folding brise soleil. The prototype was then applied to a building at the University of Washington in Seattle. The prototype was evaluated under the headings of access and movement systems, water, plant growth and habitat. "American Food 2.0: United to Feed the Planet" designed by Biber architects as the American pavilion for the Expo 2015 in Milan, Italy featured the "Vertical Farm". The façade consisted of moving panels of plants containing a variety of harvestable crops [11]. In 2017, Monica Mercedes Sanchez [12] presented kinetic green façade and kinetic living wall designs in her master thesis. Built by Associative Data (BAD) initiative and Green Studios collaboration designed Kinetic Green Canvas, a dynamic green art installation for building façades[2]. Anastasia Globa et al. [13] mentioned that the kinetic façade module they designed can also be used for planting vertically. Xing Zheng et al. [14] proposed the movable greenery window shading systems by using climbing plants and tested it. The results showed that heat flux transferred through the window glass were reduced by 11.5% and 64.8%. The scarcity of studies which examine VKF concept in a broader context than proposing single typology was noted. Therefore, in this study, technologies and promising design ideas for VKF concept are comparatively analysed in terms of compatibility, environmental sustainability and user comfort. The outcomes are presented to assist designers in the early design phase.

Assessment of advantages and limitations of VKF

In this section the author presents results of the comparative analysis of design trends and technologies of KF and VGF developed in the last decade. The system detail parameters of VGF and KF are defined, and the results

[1] Access to the reports via http://tu1403.eu/?page_id=1562 [accessed: 25.11.2023].

[2] https://www.archdaily.com/803168/video-this-kinetic-green-wall-displays-pixel-plant-art [accessed: 25.11.2023].

are collected under a separate heading for each parameter. The key parameters of VGF are substrate, structure, irrigation, and plant type [15]. Those for KF can be defined as geometry and movement, technology (sensing technology, control and actuating), structure and material [7], [8]. Sustainability-related parameters of VKF were defined by Cansu Iraz Seyrek et al. [16] as morphological design, plant type, control of the mechanism and material type. But to predict advantages and limitations of the VKF concept, it is necessary to define the system detail parameters at length. Considering the similarity of the two main features of VKF, enabling plant growth and providing movement, with the main functions of VGF and KF, these parameters can be defined as the sum of the ones of these two systems. Although the comparative analysis was carried out for VGF and KF, the results are informative also for the design alternatives of VKF.

Comparison of structure types of VGF benefits and extra function opportunities

The first main system detail parameter of VGF systems is the structure. GF are classified as direct and indirect according to attaching surface of plants. GF are cheap, easy to install and lightweight. They require less maintenance than LW. However, direct green façades (DGF) may cause integrity damages on the wall surface due to roots of plants attached to the wall. The extra carrier of indirect green façades (IGF) avoids this damage while providing weather resistance and rigidity to the system by preventing falling of vegetation [17]. The air gap between the wall and the plant layer for IGF affects the thermal performance of the system positively [15].

LW are heavier and more complex systems in comparison to GF. According to the structure of growth medium, LW are classified as continuous living walls (CLW) and modular living walls (MLW) [17]. Depending on the technology used, the amount of material and the complexity of the design, maintenance needs (usually due to problems with irrigation and nutrition system) and installation costs can be high. Furthermore, the durability of the system is also an important factor, e.g. the lifetime of a system based on planting pots is 5 times longer than that of a felt system [18]. However, wide range of design alternatives that LW provide to the designer in terms of aesthetical composition is one of advantages compared to GF [17]. The growth medium forming a separate layer on the façade surface provides noise insulation to the building [19]. They provide better thermal performance by evaporation from the substrate surface [4], [15]. Recently, the design of both GF and LW has been enriched with extra functions added to these systems. For example, the VertiKKA ("Vertical Air Conditioning and Wastewater Treatment System") project developed in Germany aims to provide energy production by integrating photovoltaic panels to VGF [20]. This project shows that, with the PV technologies addition to the VGF structure, they can be used not only to improve energy efficiency but also to generate energy.

Xi Meng et al. [21] stated that if the air conditioning system is connected to the indoor LW, it will effectively improve indoor air quality. Michael J.M. Davis et al. [22] tested the performance of LW as an active air conditioning unit. These two studies show that LW can be used to improve indoor air quality if they are designed in the form of a conditioning unit that will provide air circulation with the help of a motor. Xiangyu Li et al. [23] developed a hydroponic VGS for disposal and utilisation of pre-treated blackwater. Peter J. Irga et al. [24] designed the Tessellated Double Green Perforated Façade System to create a hybrid of GF and LW. The perforated structure of this system is expected to allow the creation of habitat corridors that facilitate the movement of birds, flying insects and land-climbing animals between and across the openings of the façade elements. The aforementioned studies show that the structural design of VGF directly affects the façades functions, such as energy generation and water treatment.

Influence of the substrate choice on the VGF functioning

The substrate of VGF, where plants are rooted getting access to water and nutrients, influences functions of the façades. The substrate for GF is either ground soil or plant pots. In CLW, plants are rooted between two layers of felt attached to waterproof panels [17]. MLW systems differ in substrate content for different designs and technologies such as felt pockets, framed planted boxes, felt + panel technology, ceramic planting cells, rockwool panels that can be commonly found in the market [1]. Substrate types differ in weight, durability and price according to their structure and content. A number of research on bio-based substrate material contents and substrate technologies is increasing. Scientists and designers are looking for natural and sustainable substrates as an alternative to heavy substrate assemblies with high environmental burden made of plastic or metal. For example, Andreia Cortes et al. [25] presented MLW panels made of expanded cork agglomerate. Benjamin Riley et al. [26] mentioned that LW are excessively expensive and introduced the Living Concrete concept, enabling plants growth on it at a lower cost. Ji Yoon Bae and Daekwon Park [27] presented the concept of 3D printed Weeping Brick. The bricks are made of soil that becomes porous after baking or drying. Water from the reservoirs slowly seeps through the porous brick, forming a water layer on the brick surface. This creates more effective cooling, and the water-seeded plants absorb the surface water. All these studies show that by using bio-based materials in substrate assemblies, the environmental burden of VGF can be reduced while reducing the cost and increasing the cooling performance. The substrate content affects features of VGF. The substrate of CLW is lighter than that of many MLW, so they do not represent significant structural load for the building. However, MLW, which form a thicker and porous insulation layer on the building surface, may have better acoustic and thermal performance. MLW are also easier to maintain depending on the technology. MLW containing plastic pots have a longer lifespan than CLW. Moreover, modularity is one of the most effective factors in the mobility of LW.

Effect of the irrigation amount and technologies on VGF

Irrigation is one of the key factors affecting the lifetime and performance of VGF. It is usually provided manually or by rainwater for GF. If plants are rooted in plant pots, automatic irrigation and nutrition systems are also used [4]. Although automatic irrigation and nutrition systems provide convenience and continuity in irrigation compared to manual methods, the amount and frequency of irrigation should be calculated correctly. LW are hydroponic systems. Irrigation and fertilization system is automatic. The amount of water is pre-calculated according to the plant species used in some systems and the system is adjusted. The irrigation requirements of LW are highly variable and depend on various factors such as location (outdoor or indoor), light exposure (direct sunlight and shading), temperature and humidity conditions, functional type (passive or active) as well as the vegetation and substrate used [28]. The life span of the plants, the maintenance needs of the system, the thermal and acoustic performance of the system are related to how often and how much watering is done [15]. Excessive watering causes damage to LW. Algae growing on the substrate surface, yellowish plants with a "washed-out" appearance are indicators of this destruction [29]. Automatic irrigation systems with sensors that monitor and analyse environmental and systematic factors perform better [4]. Irrigation causing excessive consumption of potable water is considered unsustainable [29]. As an alternative solution, rainwater can be used for the irrigation of LW. Moreover, LW can improve storm-water retention in cities [30]. Grey-water treatment and utilisation in VGF irrigation is another option for preventing excessive consumption of potable water [31].

Influence of plant types on features of VGF

Choosing the correct plant type to the environmental context is of great importance in terms of energy and water efficiency as well as the longevity of GF. One of the main factors affecting plant selection is climate [17]. In sustainable VGF design, it is very important to choose plants that can adapt to the local climate. For GF, hardy species such as *Clematis montana*, *Fallopia baldschuanica* or semi-hardy species such as *Akebia quinata*, *Bouganvillea glabra*, *Plumbago auriculata*, *Trachelospermum jasminoides* and *Doxantha unguiscati* are examples of plants that can adapt to cold climates. *Hedera helix* is a plant that can adapt to almost any climate. Therefore, it is frequently encountered along with *Parthenocissus tricuspidata* and *Wisteria*. Plant species such as *Smilax aspera*, *Clematis flammula*, *Eriocereus bonplandii*, *Tecomaria capensis* and *Delairea odorata* adapt to hot climates. For IGF, climbers such as *Camellia*, *Ceanothus*, *Chaenomeles*, *Coronilla valentine*, *Garrya*, *Fuchsia*, *Magnolia grandiflora* and *Pyracantha* as tendril-bearers, hook-climbers or twining plants are necessary [4]. Plant species compatible to LW are very diverse. Woody, herbaceous, succulent plant species can be used for these façades. It has been observed that woody species grow more than succulent species in hot and humid climatic conditions [32]. However, succulent plant species are frequently used in other climate zones such as temperate climate [5]. Other factors influencing plant growth are light quality, quantity, and duration [29]. In addition, the quality, type and quantity of irrigation are directly related to plant growth and VGF' performance [33].

Pros and cons of technologies for KF

Sensing, control and actuating technologies for KF enable façade systems to continuously change their properties or behaviour over time in response to environmental stimuli, occupant preferences and needs, such as improving thermal and visual performance and providing natural ventilation. Negar Heidari Matin and Ali Eydgahi [8] classified the technologies used in KF in five main groups as mechanical, electro-mechanical, passive, information, material-based technologies. Mechanical technology is defined as a manually operated system with a mechanism consisting of gears, pulleys and cables. This technology does not need extra energy sources, but it is not suitable for every user. Moreover, parts of the system require maintenance. Actuators such as pneumatic actuators, hydraulic actuators, and servomotors are used in electromechanical technologies (Fig. 4a). These systems can be controlled automatically by sensors or manually by the user via a central computer. Electro-mechanical technology has advantages such as standardisation of parts, modular design components, low initial cost and central monitoring and control [34]. Disadvantages of this technology include the complexity of the system, maintenance and replacement cost of parts [35]. In addition, façades consume high amounts of energy during shape change. The passive technology in KF is that the façade contains modules that can move with external factors such as wind without any mechanism or energy (Fig. 4b). These modules protect the façade from strong storm effects and create a dynamic image [36]. However, these systems do not allow the façade to be controlled according to user needs [8].

In responsive façades based on information technology, there are interconnected panels consisting of units working as sensing and activating elements (Fig. 4c) [37]. Data is shared between these panels. Therefore, changes in the façade are scalable. The advantages of this façade are its ability to fully respond to environmental stimuli due to its scalable adaptability, low cost, diversity in aesthetic composition and decentralized control. Centralized controlled systems mean that it is controlled through a central computer. In decentralized controlled systems, kinetic adaptation is performed like flock behaviour. Therefore, the main computer is only necessary to serve as user interface for maintenance and occupants control device. However, any computer failure poses a risk for the systems [8], [34], [37].

Material-based technologies do not need any mechanical or electro-mechanical actuator. The material has kinetic potential that allows it to respond to solar, thermal environmental stimuli [36], [38]. These systems have limited response capacity and cannot be controlled by occupant [7].

Fig. 4. Examples of three of the five main category groups of kinetic façade technology:
a) view of an electromechanical system used on the kinetic façade of the HTBLVA Spengergasse building in Vienna, Austria (photo by C.I. Seyrek Şık),
b) view of a passive technology in the form of metal modules used on the kinetic façade known as "Dragon skin" at the Warsaw Unit building, Poland (photo by C.I. Seyrek Şık),
c) view on information technology based kinetic façade on the MediaTIC building in Barcelona, Spain (photo by A. Woźniczka)

Il. 4. Przykłady trzech z pięciu głównych grup kategorii technologii elewacji kinetycznych:
a) widok systemu elektromechanicznego zastosowanego na fasadzie kinetycznej budynku HTBLVA Spengergasse w Wiedniu, Austria (fot. C.I. Seyrek Şık),
b) widok technologii pasywnej w postaci metalowych modułów zastosowanych na fasadzie kinetycznej znanej jako „Dragon skin" w budynku Warsaw Unit, Polska (fot. C.I. Seyrek Şık),
c) widok fasady kinetycznej opartej na technologii informacyjnej na budynku MediaTIC w Barcelonie, Hiszpania (fot. A. Woźniczka)

Different technologies determine the energy efficiency and cost of KF. The development of long-lasting and inexpensive materials and technologies that use less or no energy will enable the spread of KF.

The geometry and movement type for solar thermal performance and applicability of KF

Dynamic shading devices create shaded areas in various ways according to their shape and direction of their movement. Solar thermal heating control of building is strongly related with the size of these areas [9]. The movement and geometry of KF depend on the façades' function, orientation and the designer's choices. KF modules perform movements such as flapping, folding, translating, rotating, sliding, scaling, expanding and extracting. In addition, some façade surfaces undergo deformation in the form of bending or twisting, contraction or expansion, extension or compression, deploying and retraction [39]. Recently, also principles of biomimetics (the use of models imitated from nature to solve various complex problems) inspire the design of KF. For example, Flectofin a hinge-less flapping mechanism is inspired by elastic deformation in the *Strelitzia reginae* flower. This mechanism aims to replace many hinges with an all-in-one pliable component [40]. Currently, Flectoline, a façade system with pneumatic actuators inspired by the same moving principles, is being investigated at the University of Stuttgart [41]. Adaptive Solar Facade modules developed within ETH Zurich perform solar tracking. This movement provides effective shading in interiors and ensures that the photovoltaic panels integrated into the modules produce the maximum amount of energy [42]. Origami art offers flexibility of a form change and represents another inspiration for KF such as Al-Bahar Towers [38]. Geometry and movement are the most important factors determining the cost, lifetime, and applicability of KF since they define the design of movement mechanism and material usage. Systems that require many motor drives using smaller and complex parts can be built but are expensive. Considering that one of the main reasons for using kinetic façades is to improve energy performance and reduce cost, the application of multiple expensive mechanical and electrical devices contradicts this goal [39].

Features and requirements of structures and materials of KF

The structure and materials of KF are determined according to the designer's geometry and movement decisions, the function, its location and environmental conditions. Different types of wood resistant to outdoor conditions (e.g. Aalen university extension by MGF architekten), bamboo (e.g. Carabanchel social housing by FOA), aluminium, stainless steel, high strength and elastic materials made of fibre-reinforced polymers (e.g. Thematic Pavilion for the EXPO 2012 by SOMA Lima or Flectofin) and shape memory materials are examples of materials used in KF [38], [40]. To assess the pros and cons of the materials used for KF, the main function of the façade, determined by the architect, should be considered. In the HygroSkin – Meteora Sensitive Pavilion project, the dimensional instability of wood due to its moisture content is utilised to open and close autonomously in response to weather changes. This autonomous movement cannot be planned and controlled by the occupants. Although this may seem like a disadvantage, the main aim of this project is to build a metereosensitive architectural shell that requires neither operating energy nor any mechanical or electronic control. Here, the material fulfils the project requirement [43].

Every material used in the structure and façade should be able to resist both the static load and dynamic load of the façade, as well as any wear and deformation that may occur due to environmental factors such as wind, rain and sudden temperature changes [7]. The structure must also fulfil other stringent structural performances such as fire resistance, the capacity to sustain severe seismic events or other natural hazards. Therefore, the structural design of KF can involve uncertainties and challenges. It is advantageous to test it by experiments to prove that it meets all expected performances [44]. Natural materials such as timber or bamboo can be good options to reduce the carbon footprint of the system. Shape memory materials are the ones that respond to environmental stimuli and change their shape, returning to their original shape in the event that this stimulus disappears [45]. The advantage of these materials is that they are cheaper than other systems and allow lightweight building skin design. However, these materials are relatively new, and more research is needed for better understanding of their advantages and limitations. High strength and elastic materials made of fibre-reinforced polymers allow designers to design durable, cheap and lightweight KF inspired by biomimetics [40].

Conclusions

The advances in the design and technologies of KF and VGF in the last decade were examined and presented in this study. The system detail parameters of VGF and KF were analysed. Considering the similarity of two main features of VKF which are movement capability and enabling plant growth to KF and VGF, the system detail parameters of VKF are determined as the sum of the ones of KF' and VGF'. These parameters are listed as structure and material, substrate, irrigation, plant type, geometry, movement and technology. The results of the analyses were compared for each of these parameters separately in order to present effect of every different system detail alternative for each of these parameters. The results of the study show that depending on the structural design, material selection and substrate content, VKF can generate energy, actively improve indoor air quality as an air conditioning unit, purify grey and black water and create habitat corridors for species. Since the durability of the system depends on the structural design and material selection, the preference should be given to durable materials that will not corrode due to dynamic loads, irrigation problems and negative effect of environmental conditions.

For VKF, it is advantageous to use sensor irrigation and feeding systems that automatically adjust the amount and frequency of irrigation according to environmental conditions. In the choice of substrate, for the types in which the plants are located on moving modules, lighter ingredients are preferred. The use of thick and porous substrates favourably affects the acoustic and thermal performance of the system, while the use of bio-based material for the substrate reduces the environmental impact.

Technologies used in VKF should be compatible to the concept and size of system. Considering the limitations of mechanical and electro-mechanical technologies, the use of information-based technology in VKF is more advantageous in terms of both decentralised control and ease of maintenance. For smaller size projects mechanical systems also can be used. During material selection, the effect of the evapotranspiration and evaporation from substrate surface to the moisture balance between layers should be considered for double skin VKF. In the geometrical design, attention should be paid to the cost and constructability of the system, as well as the availability of sufficient space for the plants to be able to root and grow. In the double skin VKF, there should be a gap between 2 layers to provide sufficient place to the plants to grow. Finally, by analysing the system detail parameters of VGF and KF and comparing the alternatives, inferences can be made to guide the early design stage decisions of VKF. In order to reach precise and detailed assessment, a design framework should be created and validated on case studies. Thermal, acoustic, carbon dioxide sequestration, daylight control performance of vegetated kinetic façades should be tested on pilot sites. Climate resilience of VKF should be also investigated comprehensively.

Translated by
Barbara Widera

References

[1] Radić M., Brković Dodig M., Auer T., *Green façades and living walls – a review establishing the classification of construction types and mapping the benefits*, "Sustainability" 2019, 11(17), 4579, doi: 10.3390/su11174579.

[2] Medl A., Stangl R., Florineth F., *Vertical greening systems – a review on recent technologies and research advancement*, "Building and Environment" 2017, Vol. 125, 227–239, doi: 10.1016/j.buildenv.2017.08.054.

[3] Bustami R.A., Belusko M., Ward J., Beecham S., *Vertical greenery systems: A systematic review of research trends*, "Building and Environment" 2018, Vol. 146, 226–237, doi: 10.1016/j.buildenv.2018.09.045.

[4] Ascione F., De Masi R.F., Mastellone M., Ruggiero S., Vanoli G.P., *Green walls, a critical review: knowledge gaps, design parameters, thermal performances and multi-criteria design approaches*, "Energies" 2020, 13(9), 2296, doi: 10.3390/en13092296.

[5] Wang P., Wong Y.H., Tan C.Y., Li S., Chong W.T., *Vertical greening systems: technological benefits, progresses and prospects*, "Sustainability" 2022, 14(20), 12997, doi: 10.3390/su142012997.

[6] Tabadkani A., Roetzel A., Li H.X., Tsangrassoulis A., *Design approaches and typologies of adaptive façades. A review*, "Automation in Construction" 2021, Vol. 121, 103450, doi: 10.1016/j.autcon.2020.103450.

[7] Bedon C., Honfi D., Machalická K.V. et al., *Structural characterisation of adaptive façades in Europe. Part I: Insight on classification rules, performance metrics and design methods*, "Journal of Building Engineering" 2019, Vol. 25, 100721, doi: 10.1016/j.jobe.2019.02.013.

[8] Matin N., Eydgahi A., *Technologies used in responsive façade systems: a comparative study*, "Intelligent Buildings International" 2019, Vol. 14, Iss. 1, doi: 10.1080/17508975.2019.1577213.

[9] Hosseini S.M., Mohammadi M., Rosemann A., Schröder T., Lichtenberg J., *A morphological approach for kinetic façade design process to improve visual and thermal comfort. Review*, "Building and Environment" 2019, Vol. 153, 186–204, doi: 10.1016/j.buildenv.2019.02.040.

[10] Andrews L., Rottle N., *Deploying living walls as kinetic façades*, "Journal of Living Architecture" 2017, Vol. 4, No. 2, 17–31, doi: 10.46534/jliv.2017.04.02.017.

[11] Nowysz A., *Urban vertical farm – introduction to the subject and discussion of selected examples*, "Acta Scientiarum Polonorum Architectura" 2021, Vol. 20, Iss. 4, 93–100, doi: 10.22630/aspa.2021.20.4.38.

[12] Sanchez M.M., *Kinetic Green Wall System Applications on Reducing Carbon Emissions in Hot-Arid Climates*, MA thesis, University of Arizona, 2017, http://hdl.handle.net/10150/626722 [accessed: 25.11.2023].

[13] Globa A., Costin G. Tokede O., Wang R., Khoo C.K., Moloney J., *Hybrid kinetic façade: fabrication and feasibility evaluation of full-scale prototypes*, "Architectural Engineering and Design Management" 2021, Vol. 18, Iss. 6, 1–21, doi: 10.1080/17452007.2021.1941739.

[14] Zheng X., Dai T., Tang M., *An experimental study of vertical greenery systems for window shading for energy saving in summer*, "Journal of Cleaner Production" 2020, Vol. 259, 120708, doi: 10.1016/j.jclepro.2020.120708.

[15] Seyrek Şık C.I., Woźniczka A., Widera B., *A conceptual framework for the design of energy-efficient vertical green façades*, "Energies" 2022, 15(21), 8069, doi: 10.3390/en15218069.

[16] Seyrek C.I., Widera B., Woźniczka A., *Sustainability-related parameters and decision support tools for kinetic green façades*, "Sustainability" 2021, 13(18), 10313, doi: 10.3390/su131810313.

[17] Manso M., Castro-Gomes J., *Green wall systems: a review of their characteristics*, "Renewable and Sustainable Energy Reviews" 2015, Vol. 41, 863–871, doi: 10.1016/j.rser.2014.07.203.

[18] Perini K., Ottelé M., Haas E., Raiteri R., *Vertical greening systems, a process tree for green façades and living walls*, "Urban Ecosystems" 2013, Vol. 16, 265–277, doi: 10.1007/s11252-012-0262-3.

[19] Yan F., Shen J., Zhang W., Ye L., Lin X., *A review of the application of green walls in the acoustic field*, "Building Acoustics" 2022, Vol. 29, Iss. 2, 295–313, doi: 10.1177/1351010X221096789.

[20] Schinkel U., Becker N., Trapp M., Speck M., *Assessing the Contribution of Innovative Technologies to Sustainable Development for Planning and Decision-Making Processes: A Set of Indicators to Describe the Performance of Sustainable Urban Infrastructures (ISI)*, "Sustainability" 2022, 14(4), 1966, doi: 10.3390/su14041966.

[21] Meng X., Yan L., Liu F., *A new method to improve indoor environment: Combining the living wall with air-conditioning*, "Building and Environment" 2022, Vol. 216, 108981, doi: 10.1016/j.buildenv.2022.108981.

[22] Davis M.J.M., Ramirez F., Pérez M.E., *More than just a Green Façade: Vertical Gardens as Active Air Conditioning Units*, "Procedia Engineering" 2016, Vol. 145, 1250–1257, doi: 10.1016/j.proeng.2016.04.161.

[23] Li X., Zhou J., Tang Y. et al., *A hydroponic vertical greening system for disposal and utilization of pre-treated Blackwater: Optimization of the operating conditions*, "Ecological Engineering" 2022, Vol. 183, 106739, doi: 10.1016/j.ecoleng.2022.106739.

[24] Irga P.J., Torpy F.R., Griffin D., Wilkinson S.J., *Vertical Greening Systems: A Perspective on Existing Technologies and New Design Recommendation*, "Sustainability" 2023, 15(7), 6014, doi: 10.3390/su15076014.

[25] Cortês A., Tadeu A., Santos M.I., de Brito J., Almeida J., *Innovative module of expanded cork agglomerate for green vertical systems*, "Building and Environment" 2021, Vol. 188, 107461, doi: 10.1016/j.buildenv.2020.107461.

[26] Riley B., de Larrard F., Malécot V., Dubois-Brugger I., Lequay H., Lecomte G., *Living concrete: Democratizing living walls*, "Science of The Total Environment" 2019, Vol. 673, 281–295, doi: 10.1016/j.scitotenv.2019.04.065.

[27] Bae J.Y., Park D., *Weeping Brick: The Modular Living Wall System Using 3D Printed Porous Ceramic Materials*, [in:] J.H. Lee (ed.), *Computer-Aided Architectural Design*, *"Hello, Culture"*, *Daejeon 2019*, *Republic of Korea*, *June 26–28*, *2019*, *Selected Papers*, Springer, Singapore 2019, 399–409, doi: 10.1007/978-981-13-8410-3_28.

[28] Perez Urrestarazu L., Egea G., Franco-Salas A., Fernandez-Canero R., *Irrigation Systems Evaluation for Living Walls*, "Journal of Irrigation and Drainage Engineering" 2014, 140(4), 04013024-1/11, doi: 10.1061/(ASCE)IR.1943-4774.0000702.

[29] Riley B., *The state of the art of living walls: Lessons learned*, "Building and Environment" 2017, Vol. 114, 219–232, doi: 10.1016/j.buildenv.2016.12.016.

[30] Xie L., Shu X., Kotze D.J., Kuoppamäki K., Timonen S., Lehvävirta S., *Plant growth-promoting microbes improve stormwater retention of a newly-built vertical greenery system*, "Journal of Environmental Management" 2022, Vol. 323, 116274, doi: 10.1016/j.jenvman.2022.116274.

[31] Alsaad H., Hartmann M., Voelker C., *The effect of a living wall system designated for greywater treatment on the hygrothermal performance of the façade*, "Energy and Buildings" 2022, Vol. 255, 111711, doi: 10.1016/j.enbuild.2021.111711.

[32] Charoenkit S., Yiemwattana S., *The performance of outdoor plants in living walls under hot and humid conditions*, "Landscape and Ecological Engineering" 2021, Vol. 17, 55–73, doi: 10.1007/s11355-020-00433-8.

[33] Bustami R.A., Beecham S., Hopeward J., *The influence of plant type, substrate and irrigation regime on living wall performance in a semi-arid climate*, "Environments" 2023, 10(2), 26, doi: 10.3390/environments10020026.

[34] Decker M., Zarzycki A., *Designing resilient buildings with emergent materials*, [in:] E.M. Thompson (ed.), *Fusion – Proceedings of the 32nd International Conference on Education and research in Computer aided Architectural Design in Europe, Newcastle upon Tyne, England, UK, 10-12 September 2014*, Vol. 2, Northumbria University, Newcastle 2014, 179–184, doi: 10.13140/2.1.1060.8967.

[35] Capeluto G., Ochoa C., *Intelligent envelopes for high performance buildings: Design and strategy*, Springer, Cham 2017, doi: 10.1007/978-3-319-39255-4.

[36] Fox M., *Interactive Architecture: Adaptive World*, Princeton Architectural Press, New York 2016.

[37] Grobman J., Yekutiel T., *Autonomous movement of kinetic cladding components in building façades*, [in:] A. Chakrabarti, R. Prakash (eds.), *ICoRD'13. Lecture Notes in Mechanical Engineering*, Springer, Chennai 2013, doi: 10.1007/978-81-322-1050-4_84.

[38] Aelenei L., Aelenei D., Romano R., Mazzucchelli E.S., Brzezicki M., Rico-Martinez J.M., *Case Studies: Adaptive Façade Network*, TU Delft Open 2018.

[39] Tabasi S.F., Banihashemi S., *Design and mechanism of building responsive skins: State-of-the-art and systematic analysis*, "Frontiers of Architectural Research" 2022, Vol. 11, Iss. 6, 1151–1176, doi: 10.1016/j.foar.2022.05.006.

[40] Lienhard J., Schleicher S., Poppinga S. et al., *Flectofin: a hinge less flapping mechanism inspired by nature*, "Bioinspiration and Biomimetics" 2011, Vol. 6, No. 4, 045001, doi: 10.1088/1748-3182/6/4/045001.

[41] Gonzalez E.A., Moser S., Körner A. et al., *Advancing solar control and energy harvesting through the use of pneumatically actuated elastic adaptive façades*, [in:] D.A. Saravanos, A. Benjeddou, N. Chrysochoidis, T. Theodosiou (eds.), *X ECCOMAS Thematic Conference on Smart Structures and Materials SMART 2023, 3–5 July 2023, Patras, Greece*, Eccomas Proceedia, 744–756, doi: 10.7712/150123.9828.444680.

[42] Nagy Z., Svetozarevic B., Jayathissa P. et al., *The adaptive solar façade: From concept to prototypes*, "Frontiers of Architectural Research" 2016, Vol. 5, Iss. 2, 143–156, doi: 10.1016/j.foar.2016.03.002

[43] Correa D., Krieg O.D., Menges A., Reichert S., Rinderspacher K., *HygroSkin: A climate-responsive prototype project based on the elastic and hygroscopic properties of wood*, [in:] *ACADIA 2013 Adaptive Architecture: Proceedings of the 33rd Annual Conference of the Association for Computer Aided Design in Architecture, October 21–27, 2013*, Cambridge, Ontario, 33–42, doi: 10.52842/conf.acadia.2013.02.

[44] Bedon C., Honfi D., Machalická K.V. et al., *Structural characterisation of adaptive façades in Europe – Part II: Validity of conventional experimental testing methods and key issues*, "Journal of Building Engineering" 2019, Vol. 25, 100797, doi: 10.1016/j.jobe.2019.100797.

[45] Holstov A., Farmer G., Bridgens B., *Sustainable materialisation of responsive architecture*, "Sustainability" 2017, 9(3), 435, doi: 10.3390/su9030435.

Abstract

Vegetated kinetic façade – monographic review

Vertical green façades and kinetic façades are environmentally friendly and energy efficient construction technologies that have gained popularity in recent years. Vegetated kinetic façades are a relatively new façade concept that can combine the positive features of these two systems, while the research on them is limited. The aim of this study is to identify the new opportunities and the most promising concepts of vegetated kinetic façades in terms of environmental sustainability and user comfort. In this article, technologies and design trends developed in the last decade are examined for vertical green façade systems and kinetic façades through literature review followed by the comparative analysis. Based on the results of the comparative analysis of vertical green façades and kinetic façades, the author will discuss potential risks and disadvantages of vegetated kinetic façade concepts. The conclusions go beyond the main benefits of vegetated kinetic façades such as energy efficiency, daylight control and outdoor air quality improvement, to present additional potential advantages such as energy generation, rainwater collection and carbon sequestration.

Key words: vertical green façades, kinetic façades, vegetated kinetic façades

Streszczenie

Roślinna fasada kinetyczna – przegląd problematyki

Pionowe zielone fasady i fasady kinetyczne to przyjazne dla środowiska i energooszczędne technologie budowlane, które zyskały popularność w ostatnich latach. Roślinne fasady kinetyczne są stosunkowo nową koncepcją elewacji, która może łączyć pozytywne cechy tych dwóch systemów, podczas gdy badania nad nimi są ograniczone.

Celem niniejszego badania była identyfikacja nowych możliwości i najbardziej obiecujących koncepcji wegetacyjnych fasad kinetycznych pod względem zrównoważenia środowiskowego i komfortu użytkownika. W niniejszym artykule przeanalizowano technologie i trendy projektowe opracowane w ostatniej dekadzie dla pionowych systemów zielonych fasad i fasad kinetycznych poprzez przegląd literatury, a następnie analizę porównawczą. Na podstawie wyników analizy porównawczej pionowych zielonych fasad i fasad kinetycznych autorka omówiła ich potencjalne wady w celu wyboru optymalnych rozwiązań. We wnioskach przedstawiono nie tylko główne walory roślinnych fasad kinetycznych, takie jak efektywność energetyczna, kontrola światła dziennego i poprawa jakości powietrza na zewnątrz, ale także dodatkowe potencjalne korzyści płynące z ich zastosowania, takie jak wytwarzanie energii, zbieranie wody deszczowej i sekwestracja dwutlenku węgla.

Słowa kluczowe: pionowe zielone fasady, fasady kinetyczne, fasady kinetyczne z roślinnością