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Performance^2: Responsive and Adaptive Building Skins

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Abstract

Dynamic skins are functional systems that change based on a specific input. They are performative insofar as they fulfil an intended function, yet their ability to transform holds great potential for communicating narrative-based content since these systems reveal the exchange that occurs at the façade/face of buildings. We consider Performance^2 as both the numerically quantifiable functional characteristics – such as heat transfer, energy use, daylighting, air quality, humidity transfer, or solar energy harvesting – as well as the social and communicative characteristics of building skins. Case studies are presented to illustrate underlying performance benefits for dynamic skins spanning from examples which rely upon human action, to others which use sensors, motors, and other automated technology. Key differences in responses associated with the type of exchange and types of materials used in the designs are identified. Limits and opportunities pertaining to scale, occurrence cycles, and reaction time, are considered in conjunction with the cause of transformation, be it environmental, human. Following the analysis of case studies, our work explores future research and development of responsive and adaptive building skins when both types of performance are considered in tandem, promising more meaningful and impactful design of building façades.

Keywords: Dynamic Skin, Responsive, Adaptive, Kinetic, Performance^2

1. Introduction

Building skins can reveal the program of a building, follow formal compositional orders of a specific style, exemplify the building technologies of the time, or stand as registrations of a building's age and existence within its context. In addition to serving as the communicative face of buildings, they are functional membranes that mediate the exchange between interior and exterior. Subject to environmental and human forces, their transformation over time is inevitable. Even the simple act of opening and closing a window shutter to admit light and air brings life to the façade literally and symbolically, signaling to the outside world that the eyes of the building are open or closed.

However, change is often resisted in the production of buildings for pragmatic reasons, in opposition to the inherent properties of materials, like their potential for movement, their tendency to weather, to expand and contract, or to retain and release moisture. Whereas building skins are predominantly designed as static and often hermetic entities, the goal of this investigation is to explore the emergent potential of *dynamic skins*, which are designed for transformation in response to exterior environmental conditions and in response to the needs and desires of humans or other species. In this way, we posit that the Performance^2 of a dynamic building skin is the combination of two types of transformations. There are quantifiable parameters that are typically associated with the word *performance* when we think of building technology which include characteristics like heat transmission, energy consumption, energy harvesting, natural light, indoor air quality, or humidity control. And then there are the qualitative and experiential layers of social, cultural, narrative, aesthetic, and communicative capacity enabled by the building skin. When design considers both types of performance in tandem, synergies emerge that have the potential to deliver skins that are simultaneously more efficient and meaningful.

This research investigates the notion of Performance^2 in building skins through the analysis of several case studies. The selected skins are dynamic in a variety of ways. They include examples employing kinetic transformation, growth of living organisms, phase changes, and biochemical processes. They display different levels of control, be it through the use of automated systems or human operation, and they respond to human or environmental stimuli. Located in a broad range of environmental and cultural contexts, the skins use different technologies and achieve spatial definition and comfort in unique ways. We note how these skins are perceptible and engaged through experience at various scales, and how they act as elements for communication. In presenting these case studies, we found it productive to consider their future performance potentials and the possible benefits of cross pollinating them.

2. Background

As the awareness, utility, accessibility, and variety of non-static skins grows, so does the terminology used to describe them. What has been referred to by others using many different names with specific characteristics, we are here grouping together under the umbrella of *Dynamic Skins*. Numerous analyses in recent years provide a panorama of the state-of-the-art technologies used in the design of dynamic skins, with a range of evolving nomenclature such as adaptable, responsive, intelligent, kinetic, or interactive, among others [1]. Reviews exist that catalogue and classify precedents according to their characteristic properties in relation to physics, time intervals, scales, and control types [2]. Some focus on morphological characteristics, types of stimuli, user responses, materials, and types of movement [3]. Others place primary importance on operational energy efficiency and on optimizing fabrication, assembly, and installation, including parametric design [4]. In many instances, the relationship between biological systems and building skins offers insights into the design of architectural systems that seek to be sustainable and adaptable [5].

Although these in-depth reviews illuminate unique and emerging characteristics of dynamic skins, they leave room to simultaneously identify the social, communicative, and performative exchange that happens at the face of buildings. Looking outside of engineering and design circles, we find discussion of work that explores the transformation of building skins as canvases for conveying cultural meaning. Whether through juxtaposed digital projection [6], messaging through coloration and anamorphosis [7], physical masking [8], or other means, skins are shown to be participants in delivering political messages, promoting urban revitalization, or inspiring awe and delight. Taking stock of these disciplinarily divergent perspectives, our study aims to shed light on the benefits of considering the fundamental concerns of efficiency in tandem with the expansive and impactful role that building skins can play as cultural mechanisms.

3. Case Studies and Discussion

The following analysis of case studies attempts to illustrate a perspective that merges the two modes of understanding performance as they relate to dynamic skins. Parameters were identified for each of the chosen case studies including scope, context, stimuli, materials and technology, form, and type of transformation. For each case, we identify moments where Performance[2] is evident or a latent potential that could be further expanded upon. In concluding we speculate on possibilities for cross-pollination of performance between the case studies.

3.1 Vernacular evaporative cooling and shading windows in hot arid climates

Numerous examples of vernacular windows in the hot arid climates of the Middle East and India, are exquisitely informed by their cultural and environmental contexts. Particularly when considered collectively, these embody the notion of Performance[2] in a rich way. For instance, Mashrabiyas respond to the cultural norms of the Middle East. These veiled screens are typically located in a raised space and generally occupied by women, allowing for conversation and street viewing while ensuring privacy [9]. The porous screens act as shading and glare control devices that respond to the climatic conditions in which they exist. They are calibrated to human perception, with intricate and culturally resonant geometric ornamentation that results in the animation of interior spaces as light patterns are modulated throughout the day. In the case of Jalis in India, screens are scaled to allow for numerous viewing modes, since parts of them open like framed windows allowing uninterrupted views if necessary. As inhabitants act upon the operable shutters – introducing light, air, and view – they modify the homogenous reading of the façades from an urban perspective and establish a different kind of exchange with the exterior. Through these examples we see that unique spatial characteristics and programs are intrinsically related to the spaces beyond these screens.

A modest version of this porous screen is used in another way in the vernacular window observed in Muscat, Oman, which introduces the evaporative cooling process, using the properties of materials to achieve a passive and sustainable design solution [10]. An unglazed earthenware jar is filled with water and placed in the window opening on the interior side of the screen. Being a porous medium, the jar becomes saturated with water and provides a large surface area for evaporative cooling when the hot dry air passes from the outside to the inside and over the moistened clay surface [11]. The passage of air can be regulated by occupants through interior shutters. A protruding wood canopy and wood screen enclosure, being of low thermal mass, protect the jar and window from solar heat gain, while simultaneously reducing glare and providing privacy. While the Muscatese window integrates evaporative cooling into the screened window opening, it does not provide the ample space for social activities as seen in the Mashrabiya. Meanwhile, in Egypt, a similar screened window made of earthen construction is used in conjunction with unglazed ceramic jars known as Maziara, which induce evaporative cooling, and provide water filtration for domestic use [12]. The tending of Maziara clay pots involves women carrying non-potable water from the wells for daily filtration and consumption [13]. The associated evaporative cooling provides a passively conditioned interior environment that allows inhabitants to access cool drinking water. We see adaptations of this vernacular construction expanding to the interior spaces and having programmatic resonance when this passive technology is placed in the lower spaces in between courtyards and considered in relation to draft direction [14].

Each of these instances of porous window openings has its own strengths with regard to space making, programmatic organization, interior cooling and comfort, façade design, play of light, or social and human engagement. When considered together we see the potential of integrating them to address a multiplicity of realms. Synthesizing the learnings from these precedents, we could imagine an enhanced building skin for contemporary contexts, which could retain the principles embodied by these vernacular examples, such as the cultural resonance and space making capacity of the Mashrabiya, the evaporative cooling of the Muscatese, and the daily social rituals of the Maziara.

3.2 Al Bahr Towers by Aedas

The Al Bahr Towers, located in Abu Dhabi, utilize an adaptive kinetic shading skin attached two meters in front of a glazed envelope [15]. Inspired by the formal language of the Mashrabiya, the outer skin is discretized into a series of hexagons and nested triangles that fold to open and close through automated means in response to solar exposure [16]. The environmental context, with its intense sunlight and extreme temperatures surpassing 100 degrees Fahrenheit, is a primary driver for the design and perception of the folding façade. The surface of the folding panels is made of stretched micro-perforated polytetrafluoroethylene (PTFE), which allows the passage of diffused daylight while reducing solar heat gain [17]. The team of designers and engineers developed computer-controlled linear actuators to open and close the modules in groups, once per day on a programmed schedule, to block direct solar exposure based on the known solar path [18]. In addition to the programmed sequence, the modules are capable of closing in response to sensor input when high winds or overcast conditions are detected [19]. Through its kinetic transformation, the façade traces the solar path, modulating light, mitigating glare, and rejecting solar heat gain to reduce cooling demand [20]. Visually, the dynamic composition stands as a registration of the diurnal cycle perceptible at an urban scale, while having cultural resonance with the geometries of the Mashrabiya.

The towers are an impressive example of adaptive kinetic skins at a large scale, which point toward many more opportunities for Performance[2]. Though inspired by the Mashrabiya, the geometric design could further incorporate more of the qualities of those vernacular lattice screens, such as their capacity to form and transform interior spaces as they filter light. Working with additional nested scales could allow various degrees of porosity that could potentially respond to human input. We also see a possibility to calibrate motion to respond to human perception and desires on a smaller scale. Although the skin is effectively responding to environmental fluctuations, the infrastructure could display playful compositions, especially at night where the light emanating from within could produce an array of visual communications. In addition to these opportunities for space, light, and experience, the surface of the panels could be conceived as a means to harvest energy by using photovoltaics, since the skin is already designed to deploy in response to solar exposure.

3.3 KMC Corporate Offices by Rahul Mehrotra Architects

This office building, located in the hot dry climate of Hyderabad, India exemplifies the skin as habitat. It has been widely recognized that views of natural environments bring enjoyment and support the productivity of people inside a building [21]. What makes this project of special interest as an example of Performance^2, however, is not simply the inclusion of visually appealing plant material, but its concomitant performance benefits over time. Namely, that the skin provides shading along with moisture infrastructure that has cooling benefits and that the space between the living green wall and the building opens up opportunities for human engagement and exchange.

An aluminum lattice, designed to encourage plant growth, stands approximately one meter away from a fully glazed enclosure. Hydroponic trays are supplied with moisture from an automated integrated drip irrigation system, as well as a misting system which also serves the purpose of cleansing and cooling the glass façade in the hot and windy summer. This technique of humidified surfaces has long been employed in this climate [22]. By incorporating living organisms in the form of plants, the timeline for change has been expanded from the diurnal, to the seasonal, and beyond. Flowering plants put on a display during discrete portions of the year, enlivening the appearance of the skin as if to celebrate a natural cycle. The design of the façade is compositional in that specific plant species with varied appearance have been selected and distributed in patterns which are appreciable at an urban scale. On a social level, the living façade is actively maintained by hand by a group of gardening staff who access the plants by way of internal catwalks. The socioeconomic realities of Indian society are part of the daily life of the building, in that the gardeners can see and be seen by the office workers within the glass enclosure [23].

The many successes of the project point us to additional opportunities for enhancing Performance^2. In climates with both heating and cooling seasons, plant species could be chosen that drop foliage in the winter, thereby enhancing solar heat gain, while retaining the capacity for shading when in bloom. One can imagine social contexts in which the gardening activity could be performed by the intended occupants of the office space, extending an invitation to exercise, and encouraging well-being through the work environment. At the same time, if this zone between skins were conceived and valued for promoting productivity and happiness through engagement with the natural world, we can imagine it as a rich spatial experience that extends the functions of the building outside of a conditioned interior environment. The skin could thus be a protagonist in reducing expectations for the interior volume to be hermetically sealed from the exterior, opening the door, so to speak, to natural ventilation strategies and an enriched spatial and sensory experience.

3.4 SolarLeaf by Strategic Consult of Germany (SSC), Colt International, and Arup

By incorporating living organisms into the design of architectural components, SolarLeaf exemplifies the capacity of building skins to harvest energy, offering promising potentials for Performance^2. This five-story residential building is located in Hamburg, Germany, and features microalgae that reacts to daylight and solar heat in a bio-reactive process to capture renewable energy. The façade is an active component of a closed-loop system, providing energy for a portion of the building's heating demands [24]. 129 panel bioreactors (PBR) are located along the southeast and southwest elevations mounted in front of opaque insulated exterior walls. Each PBR comprises microalgae suspended in a nutrient-rich fluid medium (containing recovered CO_2) between two laminated insulated glazing units. As PBR are exposed to daylight, microalgae undergoes photosynthesis, increasing its biomass, producing biogas, and heat. The system supplies water and compressed air into the PBR through integrated aerators, which create turbulence to promote the algae's absorption of carbon and light. The heat generated by the microalgae, plus the excess solar heat absorbed by the medium in the panel, is extracted with a heat exchanger and used for space heating and hot water. The resultant biogas is converted into Methane offsite, which can serve as a means of generating electricity [25]. Using principles of photosynthesis, whereby the algae consumes CO_2, the technology works to reduce the carbon footprint involved in heating a building in this climate. The design of the system reveals a thorough understanding of a biological process, its applicability, and the technical feasibility of incorporating such a process at a building scale.

A future manifestation of this prototypical façade system could aim to integrate the PBR within the thermal envelope since the materials of a well-insulated glass façade assembly are already in use. This would eliminate the redundant opaque insulated façade behind the panels, opening the possibility to experience them from the interior. In this configuration, challenges and opportunities emerge for the design of the panels to respond to spatial and programmatic considerations, acoustical isolation, and to address the need to avoid heat gain in the summer season. Another new challenge would be to redefine the design and discretization of the façade such that the overall skin and the components could be more informed by the process and the medium used rather than taking the rectangular panel for granted.

Tapping into the phenomenological and formal qualities of the biochemical process could lead to the design of animated façade compositions. As light levels increase, more microalgae grow, making the façade gradually greener. Working with varying shades of green would register time-based transformations in response to solar exposure, resulting in degrees of translucency and color saturation that can be experienced from within or be used for solar shading. Furthermore, the aeration technique has the potential to display choreographed patterns of air bubbles within the double façade. All of these possibilities could help establish a visceral relationship through experience by raising awareness of the process, promoting deeper emotional connections and a meaningful understanding of sustainability.

3.5 Hygroskin Pavilion by Institute for Computational Design and Construction

The Hygroskin Pavilion stands as an example of attaining controlled kinetic transformation by harnessing the anisotropic and hygroscopic characteristics of wood in response to changes in humidity [26]. Intrinsic material properties are used in lieu of extrinsic mechanical hardware to induce motion in response to external stimuli. In addition to employing a biodegradable renewable resource, the approach takes advantage of the kinetic potential of thin wood veneer, reducing energy consumption. As humidity levels rise, the pores of the pavilion open, allowing for light and air to pass through. Beyond its operability, the geometry of the pavilion and the apertures themselves -- in both open and closed conditions -- have been integrally considered as a unique and interesting formal arrangement, sparking curiosity and intrigue in visitors.

However, this environmental response is slow and without the possibility of human override, and its full potential, when applied to a specific climatic and cultural context, is yet to be realized. One aspect to be considered for further development is to adapt the skin to a building envelope where it would address more needs such as response rate, reversibility, and durability. The compelling way in which the skin behaves creates possibilities to explore the articulation of movement and timing to compose kinetic arrangements that might add to its appreciation. Related to this, we see additional opportunities for human engagement, perhaps through misting, which could trigger kinetic transformations in the skin.

3.6 Wind Veil by Ned Kahn

The work of artist Ned Khan embraces natural phenomena as a medium. The Wind Veil in Charlotte, North Carolina is a gridded kinetic array of hinged aluminum panels that move freely on one axis [27]. As the wind activates the panels, the six-story façade appears to move when viewed from the exterior, gracefully rendering perceptible the natural wave patterns of wind currents. The skin covers a parking garage, which benefits from both the shading afforded by the panels and from the free movement of ventilation air between them [28]. As light passes through the interstices, it produces a dappled light quality, reducing glare, but also elevating the otherwise mundane experience of parking a vehicle, all without the use of digital or human input. While the Wind Veil is not a weather-tight enclosure, nor has it been generated through an energy analysis, it is nonetheless effective at improving thermal and light conditions on the interior while also creating a remarkable and memorable experience for humans both inside and outside the skin, and one which ignites an appreciation for the omnipresent yet often unseen natural phenomenon of wind. This ability of the skin to provide a means for humans to tune into the rhythms of the environment, coupled with its capacity to perform functions of shading and natural ventilation, point toward the productive synergy inherent in considering Performance^2 when we design for efficiency and simultaneously for experience.

In its current state, the shimmering panels are designed with formal considerations in mind but could be expanded to have a nocturnal presence. In addition to this, it could incorporate other enhancements such as wind or solar energy harvesting technologies, augmenting the capability of the skin to respond to wind currents and solar radiation. In addition, this system could be adapted to thermal envelopes where the panels could remain functional as a porous shading device while retaining a capacity to respond in relation to the wind.

3.7 HouseZero by Harvard Center for Green Buildings and Cities

HouseZero is home to the Harvard Center for Green Buildings and Cities in Cambridge, Massachusetts. As a renovation of a typical wood frame house, the building functions as an office and a data driven living laboratory for researching energy efficiency in buildings. Using advanced computational technology that enables the customization of performance, the building envelope responds to its real-time context by introducing outside air for natural ventilation [29]. It does this both in an automated way, using motor actuated windows, and by allowing humans to open windows individually. The automated system is equipped with sensors and actuators that function based on monitored meteorological conditions, CO_2 content, airflow, indoor room temperature, and outdoor temperature of the immediate surroundings. The skin utilizes additional energy saving features including a well-insulated and air-tight thermal envelope to reduce heat flow, a solar chimney to enhance ventilation, skylights to contribute to daylight autonomy, fixed solar shading over windows to reduce heat gain and glare, and a roof-mounted photovoltaic array to harvest solar energy. All of these contribute to its ability to maintain a comfortable interior environment using natural ventilation, harvesting solar energy, and reducing heating and cooling load through the skin [30].

As a research center, the program of the building informed the design, function, and intended use of the skin. Visitors and researchers can visualize heat transmission and airflow through the use of interactive augmented reality simulations. The promise of the project is thus not only its capacity to dynamically react to weather conditions using sensors, data, and automation, but that the skin and its performance can be understood in a didactic way. Researchers are able to continually monitor and learn from the building and its skin, and disseminate their findings on site and beyond.

The project stands as a prototype that incorporates computational technology into the performance of building envelopes and it is less concerned with formally reinventing the façade and its openings. The latter remains an opportunity for future building skin designs in a variety of contexts and scales, which could adapt and evolve the computational technology that HouseZero offers. Additionally, we see opportunities for learning from the context and the environment when applied to other programs beyond that of a research facility. The technologies in play could also be complemented by considering the skin as a deeper zone in which program can be extended, offering a spatial means of connecting to the world outside the skin, and perhaps inspiring viewers and visitors to become curious and engaged with the project.

4. Conclusions

The analysis of case studies aims at highlighting the performative aspects that each represents well, while offering insight on those that are not addressed, comparing them and speculating on their cross-pollination. Based on this analysis, we conclude that the vernacular examples of evaporative cooling and shading windows in hot arid climates, when considered collectively, outline principles worth integrating into other contemporary applications. The Al Bahr Towers skin uses weather prediction technology at an impressive scale to reduce cooling load and improve indoor daylight quality through automated shading, while simultaneously considering cultural context through its geometric patterning. However, it is important to note that other aspects found in the vernacular examples could be addressed to expand on the spatial and programmatic opportunities beyond either side of the skin. The vernacular examples define the quality of interior spaces and their relation to the exterior while responding to the cultural values in which the skin is located. The vernacular skins also shape the use of the space through perception and the activities surrounding the process of evaporative cooling.

While SolarLeaf stands as a pioneering example of hosting living organisms and harvesting renewable energy from their biological processes, the formal design and appreciation of the building skin through experience can be more fully addressed. Wind Veil shows this in an elegant way, as kinetic change and visual delight are perceived by using a simple material assembly to shade a structure, while simultaneously responding to wind fluctuations. Another example that sparks visual curiosity through the way in which the skin responds to natural phenomena is featured in Hygroskin, where apertures open and close using non-mechanized material properties in response to an environmental stimulus. These examples establish, through their performance, visceral connections with the environment, which could be an aspiration worth considering in all designs. However, they could borrow from the notion that building skins can be conceived as energy harvesters, so well exemplified by the SolarLeaf skin.

All projects have the potential to be richer in experience and functionality if temporal aspects are considered. We see that Wind Veil works with the transient conditions of wind currents while the building skin of KMC Corporate Offices offers an ever-changing exterior appearance as its living skin grows and transforms over time. Furthermore, it does this while serving as a means of shading interior spaces, with an automated irrigation and misting system that simultaneously cools the skin through evaporation. The idea of a skin that supports habitat is well exemplified through this project not only because it nourishes the vegetative skin but also because it invites human participation through visible gardening and mixing of social classes. And yet, the notion of change over time could be investigated further if this skin were placed in a context with seasonal cycles.

These considerations point towards designing skins as a way to promote a deeper understanding and appreciation of our environment and vice versa. Skins are then conceived as mediators to establish meaningful connections with our context instead of separating us from it. The skin of HouseZero balances energy efficiency and human engagement by integrating automatic aperture of the building skin using real-time weather and interior temperature monitoring, along with user operated openings. This enables a physical participation and connection with context through the building skin. Deepening that awareness further, the project incorporates interactive augmented reality as a didactic tool for inhabitants to visualize airflow and as a way to disseminate the results of their environmental research. By tapping into their didactic capacity, we can use building skins to play an active role in inviting meaningful participation from human users, and fostering a deeper understanding and stewardship of the environment.

We continue to see important advances in building skins through building science, improving thermal comfort, energy use, daylighting, and other quantifiable performance measures. At the same time, qualitative performance represents a complementary, rich, and much less explored avenue of investigation for designers of building skins. Our intent is not to focus specifically on what might define or differentiate a skin as, say, adaptive versus intelligent, but rather to develop a lens through which we can see, critique, appreciate, and thereby design with, the benefit of considering both the quantitative and qualitative aspects of a skin in tandem as Performance[2]. This recognizes the importance of prioritizing engineering that revolves around energy efficiency and strives for physiological comfort and reduced emissions, while also calling upon the strength of the experiential, social, communicative, inspiring, and beautiful capacity of skins to influence behavior. With such a powerful medium in play, we believe that designers should aspire to contribute to multiple discourses simultaneously to deliver more meaningful, engaging, and impactful building skins.

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