DESIGNING SYNCHRONOUS INTERACTIONS FOR THE FENESTRATION SYSTEM OF A PROTOTYPE SUSTAINABLE DWELLING

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Abstract. This paper presents an interactive fenestration system designed for the principal façade of a prototype sustainable dwelling. The system attains autonomous, responsive and interactive modes of operation, and is able to provide synchronous response to a wide variety of environmental conditions and user needs. The method to address the design of the system was to integrate electro-active materials and real time sensing and control technologies. The test was to implement a full-scale façade with the abovementioned capabilities. This presentation discusses the features, technologies and reasoning followed in the design and implementation of the façade.

1. Introduction

This paper presents the modes of operation and the technologies involved in implementing an interactive fenestration system. The innovative aspect of the system is that it interchangeably attains autonomous, responsive and interactive modes of operation in reply to a wide variety of environmental conditions and user needs. In the autonomous mode the façade adapts to the changing weather conditions to provide optimum performance without requiring explicit input by the users. In the responsive mode the façade adjusts its state to counterbalance any of the daily activities which may compromise the long-term optimization plan. Lastly, the interactive mode allows the façade to engage with external stimuli and human gestures in real time. The method to address the technical challenges in devising this interactive fenestration system was to integrate electro-active materials, sensors, actuators, and control processors into the physical apparatus of the façade frame and windowpanes. An autonomous, distributed control that employs risk-sensitive planning, manages the façade by executing a performance optimization strategy. The control reasons “on the fly”, tracks the system state, and performs reconfigurations. The test-bed for the proposed interactive fenestration system was the implementation of a full-scale dynamic system with the abovementioned capabilities that was used in the principal elevation of a prototype dwelling in Trento, N. Italy.

Unlike the standard inoperable curtain walls, the dynamic façade was envisioned as an operable building boundary able to supply multiple modes of interaction in parallel. This presentation exposes the features and the interaction modes of the façade and shows how the local context and the concern for ecological and technologically advanced methods of sustainability provided impetus to human centered design. After a brief reference to key background concepts, three fundamental interaction contributions are exposed, namely: interfacing between interior and exterior environment; interfacing between private and public domain; and supporting the expressive dispositions of the users. The technological solutions involved in implementing the innovative features of the interactive façade are presented immediately after, and the paper concludes with a discussion on the achievements of this particular fenestration system.

2. Background

Challenging the purpose of a standard inoperable curtain wall motivated the design of the interactive façade. Standard curtain walls aim to enclose air-and-sound sealed interior environments. They restrict the interaction with the public street, they neglect the urban context and they are energy intensive, since they require support by artificial lighting, cooling and heating. The practices that we followed in designing the dynamic façade for the prototype in Trento were influenced by our ethnographic studies on the role of building façades in the local architecture. In the context of Trento, the principal elevation of a building obtains a predominantly expressive character. Italians like to chat from window to window, or sit on the porch to observe the public street, while natural light and ventilation are highly valued interior qualities. The features of the interactive fenestration system aim to respond to these deep-rooted user expectations.

The integration of active material and control capabilities into building façades has been explored mainly as a “media system” involving large-scale public screens for advertisements, news, art installations, and for delivering community services (Haeusler, 2009). For example, Dalsgaard and Halskov (2010) explore media façades and how their scale, resolution, brightness, and exposure affect their dynamics of interaction, while Gehring and Kruger (2012) discuss the shared and collaborative properties of media façades and how they affect public space. The interactive fenestration system deployed in Trento follows a different approach mirroring the shifting design priorities during the recent environmental crisis of the Global Warming. With its combination of passive and active technologies and the capacity for real time management of its interior environment, the Trento prototype is an original example of adaptive/selective environment (Hawkes et al. 2002). Its dynamic façade (Figure 1) exposes a wide area of glass 2.60 m (height) × 6.90 m (length) to the southern sun, featuring a 3 × 9 matrix of operable, independently addressable windows 700 mm × 700 mm in size. Each windowpane involves an overlay of an electrochromic material and a polymer-dispersed liquid crystal (PDLC) film, enabling the precise adjustment of the incoming sunlight, heat, air, and view and providing an advanced alternative to the traditional systems of blinds, or louvered grilles. Gugliermetti and Bisegna (2003) offer a study on energy management with electrochromic technology, while Lampert (1998) presents a technical comparison of features and switching characteristics for electrochromic glass. Spruce and Pringle (1992) discuss the electro-optic properties of PDLC films, while Grosicka and Mucha (2006) provide a comparison of the performance of various PDLC samples.

An autonomous, distributed high-level control system (Ono 2012, Graybill 2012) employs risk-sensitive planning to optimize the long-term performance of the façade. Computer simulations showed that this dynamic façade would improve the energy consumption in the range of 30% comparing to that of a conventional curtain wall.

Figure 1. Views of the dynamic façade from the exterior (left) and the interior (right).

The variance in the incoming sunlight depends on the number and distribution of the active windows. These are adjusted automatically to always supply levels of interior daylight above the standard values. In general, the interior daylight conditions are determined by the average illumination E_{ave}, the uniformity G_1 and the daylight factor D_{av}. Italian law adopts both a national law Circ. Min n° 3151 22/5/67 and the UNI EN 12464, which is a norm defining the lighting of workplaces. Although the minimum daytime value of illuminance E_{min} for residential buildings is 300 lux we raised this threshold to 500 lux to reach higher levels of visual comfort. Uniformity G_1 captures the smoothness of daylight distribution defined by the ratio E_{min}/E_{ave}. A satisfactory value is G_1 = 0,5. Lastly, the daylight factor represents a physical feature of windows, which is constant and set to D_{av}= 3. The dynamic façade achieves $E_{min} \geq 500$ lux with smooth interior daylight distribution $E_{min} / E_{ave} \geq 0{,}5$ while satisfying two provisions, namely: a) In an average luminous day 50 % – 75 % of the windows need to be active (*on*) to secure luminosity levels above the threshold value, and b) No four consecutive window cells can be concurrently active on the same row in order to secure smooth interior daylight distribution.

3. The Façade as Interface

Simon (1996) introduced an underlying symmetry in the problem of determining the association between an inner and an outer environment: “An artifact can be thought of as a meeting point, an interface between an inner environment and an outer environment”. The south façade of the Trento prototype is an interface that aims to satisfy environmental and functional factors and to fit harmoniously into the existing urban context. The façade attains autonomous, responsive and interactive modes of operation in reply to the environmental conditions and the dispositions of the inhabitants. Three missions of interface design were identified and challenged in particular: interfacing between interior and exterior; interfacing between private and public, and supporting individual expression.

3.1. INTERFACING BETWEEN INTERIOR AND EXTERIOR

Interfacing between interior and exterior aims at overcoming the extreme conditions and the variability of a local climate. During the process of mediation between interior and exterior, energy is consumed. The dynamic façade provides a flexible apparatus that modulates sunlight penetration, incoming heat and natural ventilation at the house interior. These features rely on the integration of electro-active materials, sensing, actuation, and control capabilities. The efficiency of the façade rests on the capacity to monitor and modify the solar transmission of individual windowpanes in real time. Simulation methods were used to project the façade performance in the local climate conditions (Figure 2). The autonomous control system compiles the available data related to the seasonal levels of sunlight, heat, humidity etc. and sensory feedback, to adjust the states of the electro-active materials as needed to optimize the long-term house performance.

In the autonomous mode the façade adapts its state based on the desired conditions without requiring supervision or input by the inhabitants. Hence, in the summer the windowpanes are adjusted to reduce the heating effect of incident solar irradiance, and in the winter, to expose the interior to the warm winter sun. Although autonomous functioning is based on an algorithmically calculated action plan, aiming at long-term goals, the façade is also engaged into synchronous interactions with the inhabitants. A parallel, responsive mode permits the adaptation of the façade if an optimization setting is overwritten by a short-term action. For example, if a resident opens many windows in a hot summer day the system would respond to the change of interior temperature by reconfiguring the façade settings (e.g., changing sunlight modulation pattern) to balance the heat loss.

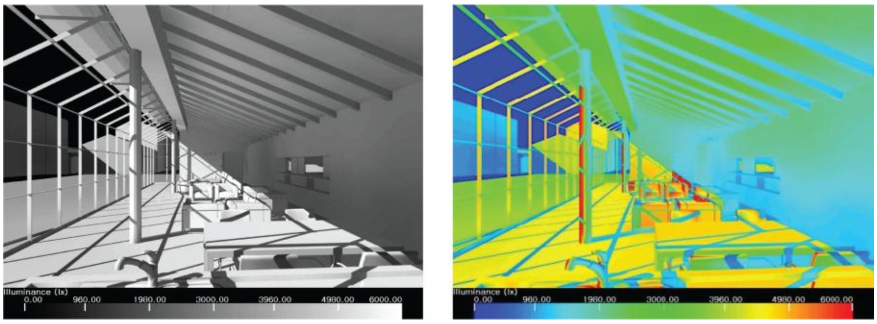

Figure 2. Solar radiation simulation indicating the angle and intensity of the incoming sunlight in the prototype, on June 21, at 1 PM, in Trento, N. Italy

3.2. INTERFACING BETWEEN PRIVATE AND PUBLIC

While servicing the adjustment of sunlight, heat and view the façade also determines the association between the private interior and the public exterior. As Lyndon and Moore (1996) note, the history of architecture could be approached as a struggle between the membrane and the frame: “Between solidly opaque and flexibly open, based partly on materials available, but more fundamentally on how definitively inside was to be separated from outside”. The modern, inoperable curtain wall is a contemporary expression of definitive separation between inside and outside. Inoperable curtain walls are energy intensive since they require support by artificial lighting and air-conditioning systems, they restrain user behavior and they neglect the urban context. The dynamic façade was envisioned as a flexibly open alternative. Its varying configurations affect privacy and transform how the prototype is perceived from the public street. Without prescribed states the façade functions as a programmable matrix of apertures, allowing the users to determine dynamically how to engage with the street and the neighbors.

Figure 3. A rendering showing the façade responding to sunrise, at waking time.

3.3. SUPPORTING INDIVIDUAL EXPRESSION

At any moment numerous façade configurations meet the efficiency requirements. This allows satisfying performance and individual preference related to privacy, visibility and view. Hence, the façade becomes a medium of self-expression mirroring the dispositions of the residents to the urban landscape. The variety of façade configurations was approached as a visual language, and it was mapped through the conventions of a generative grammar producing a large number of patterns based jointly on properties of symmetry and performance (Kotsopoulos et al., 2013). In this way, comfortable interior conditions are maintained while a range of distinct patterns is formed. The reconfiguration of the façade can also happen in response to the presence of a passer-by or to specific gestures that are tracked by the network of embedded sensors (Figure 4). The interactive mode allows the façade to react to gestures, events and conditions like the sunrise or sunset, etc. For example, on the transparent façade a patch of PDLC cells can conceal a moving person from the public view, while leaving the rest of the façade transparent (Telhan et al., 2010).

Figure 4. Early rendering showing the façade responding to user gestures.

4. Implementation of the Interactive Façade

In the interactive mode of the façade a state change is initiated in response to user gestures or external stimuli. In the autonomous/responsive modes the decision-making apparatus of the house outputs a series of constraints to configure with precision a façade state. The constraints are transmitted from the runtime decision-making system of the house to the low-level control of each window, and enable the required actions. A wireless network of sensors is employed by the runtime control to measure the parameters affecting comfort. These data are used to calculate the comfort levels and they are transmitted to the high-level control to update its procedures. The technologies involved in the implementation of façade are discussed next in more detail.

4.1. ELECTROACTIVE LAYERS

The physical process that is used in interfacing between interior-exterior and private-public, is electrically activated. Each window has a triple glazed pane 43 mm in thickness, involving an overlay of two electroactive materials. The first exterior glazing is a 6 mm in thickness SageGlass tempered pane, on which an electrochromic coating is applied. It is followed by a 12 mm Argon-filled gap and a second 6 mm in thickness clear tempered pane. An Argon-filled gap of 6 mm follows, and the third interior glazing is a 10 mm in thickness glass-pack involving two Isoclima-Isolite clear panes with a PDLC film applied in between (Figure 5).

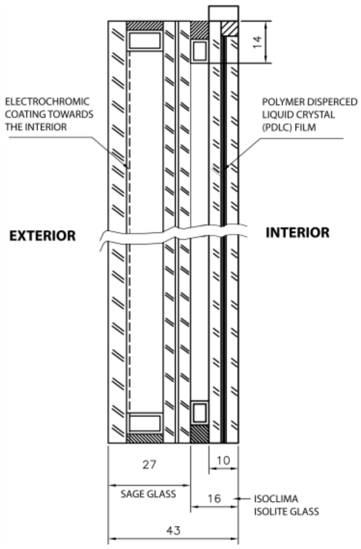

Figure 5. Section of the typical windowpane exposing the layering of materials.

The electrochromic glass provides an energy efficient interface between interior and exterior environment. This glass can be in obscured or in clear state. The obscured state enables the windowpanes to absorb unwanted solar heat and glare while preserving view. The clear state allows maximizing the incoming sunlight and heat. The electrochromic coating consists of five layers of ceramic material. Two transparent conductor (TC) layers sandwich an electrochromic (EC) layer, an ion conductor (IC) and a counter electrode (CE). Applying a positive voltage to the TC in contact with the CE causes lithium ions to be driven across the IC and inserted into the EC layer, causing the glass to attain its obscure state. Reversing the voltage polarity forces the ions and electrons to return to their original layer, causing the glass to return to its clear state. This reaction is enabled by a low voltage power supplied during the entire transition time from one state to another. The power consumption ranges from 0.4 W/m^2 (average), to 2.5 W/m^2. The transmittance value (τ) to the visible light varies from 62% for idle glass to 2% for obscured glass without ever compromising visibility. The U factor indicating insulating performance is high, ranging from 0.29 for idle glass to 0.28 for obscured glass. Figure 6 shows temperature simulation results with the electrochromic panes in clear (left) and in obscured (right) state: Left, if the windows are in clear state and the exterior temperature does not fluctuate intensely (curve a), the interior temperature reaches a higher peak than the exterior temperature (curves b, c, d); Right, if the windows are in obscured state and the exterior temperature elevates sharply (curve a), the interior temperature remains lower than the exterior (curves b, c, d).

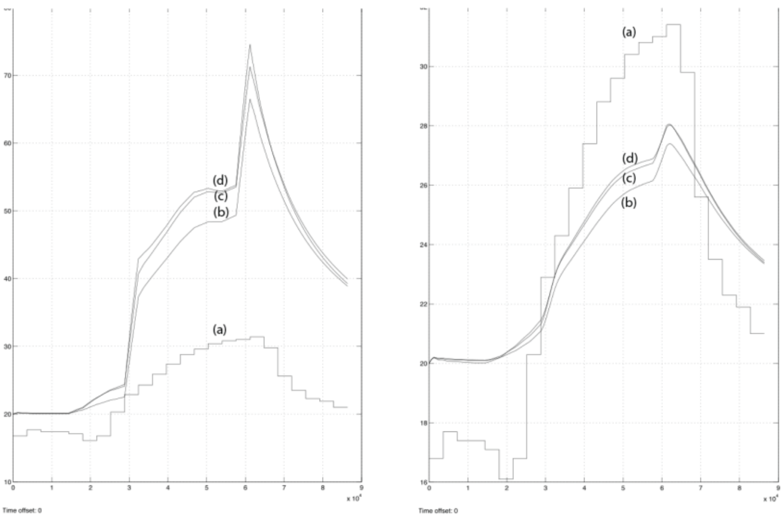

Figure 6. Results of temperature simulation during summer with all the electrochromic panes clear (left) and tinted (right). Curve (a) corresponds to the exterior temperature. Curves (b), (c) and (d) correspond to the interior temperature in the three modules of the prototype.

The PDLC film regulates visibility and it is used to interface between the private and the public domain. The PDLC film by Innoptec that is used on the façade consists of two outer layers of polyester film (PET), coated on the inside surfaces with a transparent conductive layer. The total thickness of the film is 365 (+/-10) μm. Electrical bus bars are placed all alongside two opposite edges of each panel. The PDLC film switches between a translucent state in which visibility is blocked, and a clear state when alternating electric field is applied to the bus bars. The two states correspond respectively to a random alignment and a well-ordered alignment of the liquid crystal molecules of the conductive layer. The unpowered state of the PDLC film is opaque. Constant application of the alternating field is required in order preserve the film in its transparent state. The operating ranges of the film are 60 VAC (50 Hz) from -10°C to +50°C. The power consumption is <7 W/m^2. The transmittance value (τ) to the visible light is >70% when the PDLC is in transparent state and <1% when is in opaque state. Light haze <7% appears in the transparent state. The U factor value, indicating the insulating performance, is poor (U_g = 0.7).

The electrochromic glass and the PDLC film allow the option of variable tinting. The SageGlass allows controlling the tint level within a four-valued scale 0%, 6%, 20% or 100%, and the PDLC film permits variable tinting based on sensory input. Figure 7, left, presents examples of various degrees of visibility caused by variability in tinting. Figure 7, right, presents the basic combinations of fully activated windowpanes, namely: a. PDLC layer is active and electrochromic layer is inactive; b. both PDLC and electrochromic layers are active; c. both PDLC and electrochromic layers are inactive; d. PDLC layer is inactive and electrochromic layer is active; e. exterior window view with both the PDLC and electrochromic layers active.

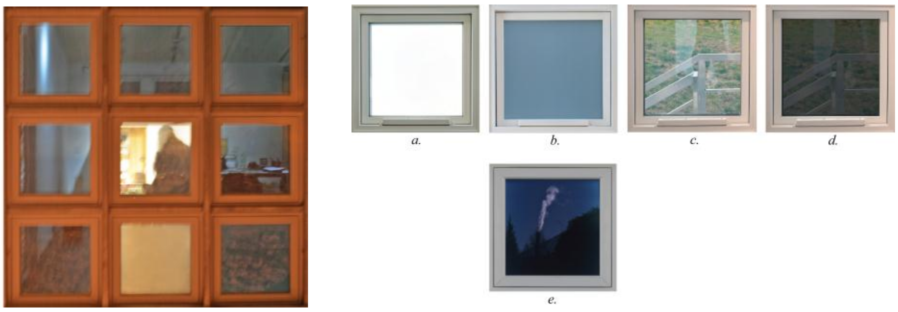

Figure 7. Left: Window pattern involving active electrochromic and PDLC layers. Right: Basic combinations of states. a, b, c, d present window views from the house interior, while e presents a view from the house exterior.

4.2. ACTIVATION AND CONTROL

The real time interaction with individual windowpanes, the adaptation of their state to the environmental conditions and the activities of the residents, and their ability to engage with external stimuli, are not typical attributes of the electrochromic and the PDLC technologies. They are custom features developed in our laboratory. Since these materials exhibit diverse optical, thermal and power-consumption characteristics and have varying response times, their activation processing required arrangement. The electrochromic panes are characterized by slow transition speed between the idle and obscured states. It takes 3 to 5 minutes for the SageGlass pane to tint over 90 percent of its range in warm weather, 5 to 10 minutes in moderate weather, and longer in cold weather. Conversely, PDLC is characterized by fast transition speed <0.1 sec between the opaque and transparent states.

At all times, the windows are managed in a concerted manner by the high-level control without interfering with each other. At a local level, each window is driven by its own low-level control and custom electronics that enable its operation. The on/off controlling of each electrochromic pane happens through a low-level controller. The operation of the PDLC layer happens through a relay circuit. The communication of the low-level and the high-level control is achieved through RS232 serial ports. A distributed control network including 1 master node and up to 122 slave nodes is used. Each slave node involves an electronic chain actuator (C20 TOPP), a relay circuit, a sensor unit, and a communication module. The microprocessor on the slave node processes the incoming commands sent from the master node and transmits the control signal to the function modules.

4.3. SENSING AND CONNECTIVITY

A wireless network of sensors (WSN) services the need for distributed monitoring of the interior and exterior environment. Each window is equipped with a photocell measuring the amount of light that the windowpane is exposed to, while an IR sensor detects the presence of the residents. An accelerometer takes measurement of the window angles and the electronic chain actuator compares the desired and measured angles and controls the opening angles with ±2.5° of accuracy. A relay circuit turns the PLDC film on or off, while an integration module controls the tint state of each windowpane. The sensors support the decision-making layer, assist the efficient management of the interior environment and enable the façade to be responsive in real time. Sensory feedback for the façade is collected in a central location where it becomes accessible by the high-level control algorithm. The various types of sensors deployed in the prototype and their sampling rates are listed in Table 1.

TABLE 1. Sensor types deployed in the prototype.

Sensor Type	**Sampling Rate**
Indoor temperature / humidity	On the order of 15 min – 1 h
Outdoor temperature	On the order of 1 h
Motion	High; ”1 min/ on motion trigger
Airflow	High; ”1 min
Illuminance	High; ”1 min

Finally, establishing real time connectivity among each independent module of the façade is fundamental in attaining autonomous, responsive and interactive modes of operation. The house connectivity is based on an always-ON broadband technology. An HTTP server connects the house devices into a single system. The HTTP server receives requests from the façade and from the high-level control algorithm and returns the requested information, or initiates a desired state change.

5. Conclusions

This paper presented the features, technologies, and reasoning underpinning the design and implementation of an interactive fenestration system. The system regulates the connection between interior and exterior environment, determines the association between private and public domain, and supports individual expression by providing to the users the ability of synchronous interaction.

The presented programmable façade that was used on the principal elevation of a prototype sustainable house in Trento, N. Italy, challenges the purposes of a standard inoperable curtain wall and contests the tactic of studying interactive façades strictly as "media systems". The dynamic façade of the Trento prototype mirrors the architectural priorities during the age of the recent environmental crisis of the Global Warming. It provides a novel basis for the development of environmentally responsive and technologically advanced dwellings through the mediation of the dynamics between environments and people. The method to address the technical challenges of designing and implementing the particular interactive fenestration system was to integrate electro-active materials – such as electrochromic coatings and PDLC films – sensors, actuators and control processors into the physical structure of the façade's frame and windowpanes. An autonomous, high-level control system manages the state of the façade by executing a performance optimization algorithm.

The innovative aspect of the façade is that it interchangeably attains autonomous, responsive and interactive modes of operation in reply to the changing environmental conditions and the needs of the inhabitants. The autonomous mode permits the façade to adapt to the environmental conditions with objective to maintain the desirable interior comfort and to secure long-term optimization of performance without requiring explicit input by the users. The responsive mode allows the façade to adjust its state to counterbalance any activity may interfere with the long-term optimization plan. Lastly, the interactive mode allows the façade to engage with external stimuli such as user gestures. The façade operates in the above three modes in real time. Since there is no standard class of façade configurations satisfying all conditions, the adjustment of the façade remains dynamic. While the high-level control system triggers appropriate configurations based on a long-term optimization plan the façade updates its state to accommodate real-time events and user demands.

Three missions of interface design were identified and challenged in particular: interfacing between interior and exterior, interfacing between private and public, and supporting individual expression.

Interfacing between interior and exterior allows – from an energy conservation point of view – to effectively overcome the extremes and the variability of the local climate at minimum energy cost. Each state of the façade affects the conditions of interior comfort by regulating the percentage of the incoming sun-heat, the level of interior daylight, and the pattern of airflow penetrating the house. The individually addressable windows, incorporating wireless sensors, actuators and layers of electrically activated materials, respond to the weather and allow harvesting light and heat from the sun. Computer simulations showed that the dynamic façade would improve the long-term consumption of energy in the range of 30% comparing to that of a conventional curtain wall.

Interfacing between the private and public domain allows – from a social interaction point of view – to negotiate the boundaries between inside and outside in flexible and visually compelling ways. Without prescribed states the façade functions as a matrix of reconfigurable apertures that permit the residents to determine how and to what degree will engage with the public street. This capability enables interactions that challenge the purpose of a standard, inoperable curtain wall. The habits of the local community were a key factor in determining this feature of the interactive façade. In the context of Trento, the principal façade of a building obtains a predominantly expressive character. Hence, the ability to activate the principal façade of the prototype acknowledges the new potential of today's technologies to cater these deep-rooted public demands for privacy and spontaneous social interaction.

Finally, supporting individual expression allows – from user interaction point of view – to satisfy personal dispositions. Since at any circumstance numerous façade configurations meet the performance requirements, it becomes possible to satisfy performance while satisfying aesthetic preference. Along these lines, the variety of possible façade configurations was approached as a visual language and it was mapped through the conventions of a generative grammar that produces a large number of façade patterns, on demand. The façade pattern language includes patterns that are generated based jointly on properties of symmetry and daylight performance. In this way, comfortable interior conditions are always maintained, while a wide range of distinct patterns is formed. And while the angles and the states of the windows are optimally configured, the façade can still respond to external stimuli, such as human gestures or daily events like the sunrise or sunset, etc., based on individual preference. Hence, the façade stands as a dynamic medium of self-expression, constantly mirroring the transitory dispositions of the residents into the urban landscape.

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