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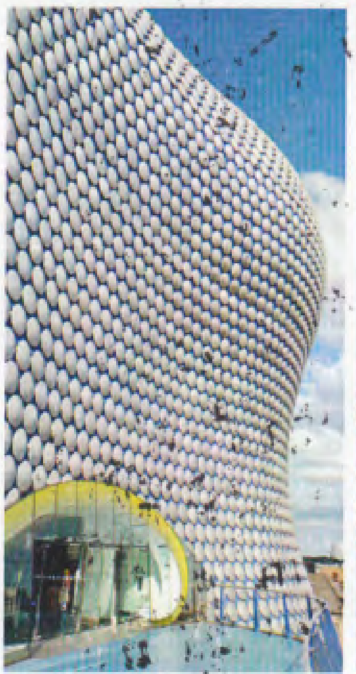
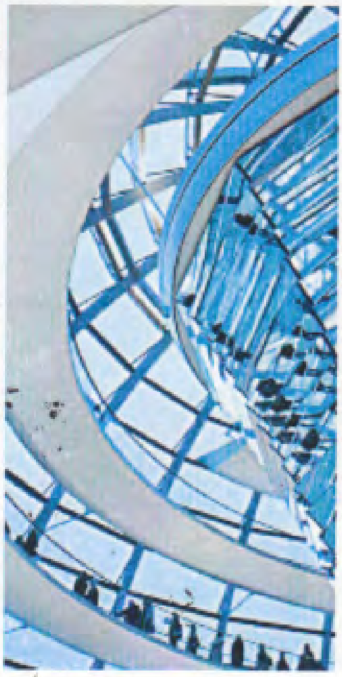

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Modular façade concept:

Opportunities for performance criteria integration

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Abstract

A building façade is a means of interaction, a building skin that can be characterized as "intelligent" or "adaptive" depending on the degree that regulates and adapts to the conditions between the inside and the outside environment. To meet a set of performance requirements, such as to provide visual and thermal comfort and also contribute to the energy savings, the notion of integration is increasingly used in façade design. This paper examines the potential of modular architecture to address the issues of integration of performance criteria.

A historical overview of prefabrication will first show examples of "system building" that highlight the role of building techniques and construction methods on modular façade design. With a focus on today's tendencies, this paper will examine a set of existing integrated façade concepts and systems with modular building service units. The façade systems will be presented based on their advantages and disadvantages concluding to the technical barriers and opportunities for integration.

After defining a set of functional requirements, goal of this paper is to describe a new design idea of an open modular façade concept that addresses the opportunities for integration already discussed. The modular façade concept consists of modules that represent each one of the selected performance criteria, such as the need for daylight, visual comfort with the use of shading systems and also energy production with photovoltaic cells.

1 Introduction

Over time, monolithic building shells have been progressively transformed into multilayered skins that tend to be lightweight and transparent. This trend results to decreased thermal mass that consequently results to increased peak loads. Design decisions, fabrication and assembly methods, as well as material selections need to be coordinated to ensure sufficient envelope performance. Collaboration of all groups involved, such as façade engineering specialists and industry is required from the early design stages. To address these issues, it is critical to embrace a holistic approach in façade design. This paper will examine the basic principles of integrated design and review the evolvement of façade design and modular architecture.

2 "Integrated" approach in façade design

Multilayered skins are characterized as single-skin, double skin or multiskin facades depending on their number of layers. A combination of single skin and mutliskin facades is an "alternating" façade [1] that incorporates the principles of both types into an overall system that tends to perform better than each type individually. The focus of this research will be the "integrated" facade which can be equipped with facade systems such as the heating elements in the interior space and decentralized ventilation units [2] (p. 100-101). By integrating building services into the facade, the construction period is shortened and space is more effectively used. Performance requirements such as lighting, heating, cooling, ventilation and energy generation can be comprised into the integrated facade on a basis of a modular facade design.

3 Basic principles on façade design integration

The performance criteria that could be integrated into the facade tend to lead to conflicts of objectives. For example, solar control in the summer automatically reduces the amount of daylight entering the space and the view to the exterior. Therefore, when designing a facade the primary goal is to define an optimum balance between the various requirements. The following diagram (fig.1) describes the role of the facade as an interface and shows by what means the conditions in the interior are affected by the exterior through the facade.

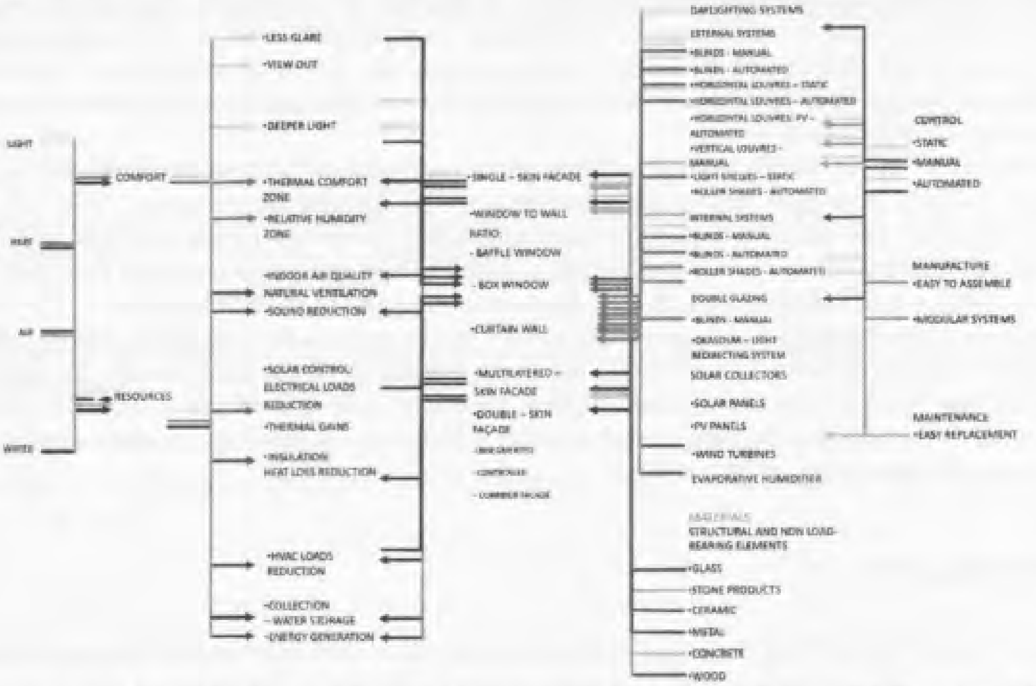

Figure 1: The façade as an interface. Skin types and technologies. Source: M. Konstantoglou

4 Modular Architecture

4.1 Basic Principles

Modular design basic principles are fundamentally related to prefabrication rules and systematically define the relationships between the individual modular elements. These principles apply to both the architecture of the core of the building and the facade design.

4.2 Systems

Systems define the relationships between the individual elements in terms of their geometrical organization and their modes of connection. Modular facade systems coordinate building envelope' s load bearing and non load bearing elements in order to specify their location and relationships. Building systems are designed as either closed or open systems [3]. In closed systems all elements are coordinated and connected in such a way that they can not be exchanged or altered. Because the individual elements can only be used within the particular system, the range of design options that closed systems offer is quite limited. Open systems compared to closed systems are not building specific. Elements in open systems can be combined in a variety of ways allowing for a wide range of construction projects. Standardization of the elements dimensions, materials and functions allows for use of products from different manufacturers.

4.3 Modular building envelopes

Based upon their structural principles, facades can be divided into two main categories, structural and non-structural facades. Structural facades transfer all loads from the roof and also ensure the bracing of the construction. Structural facades that transfer all loads from the roof, can either be single layer or multi-layered that might consist of structural, insulating and facing layers. Non-structural facades are usually closed systems independent of the building's structural system. A typical example of the non-structural facade type is the post-beam construction [4] (p.45).

5 Evolvement of façade design and fabrication

As soon as the first building skins fulfilled basic functions the notion of integration was introduced. Small punched openings in massive stone or clay structures provided daylight and allowed visual connection to the outside. Examples of traditional and vernacular architecture express the need for integration and adaptation to the external conditions [5]. Wood screens in Indian temples allow for ventilation and cooling without compromising the view to the exterior while window shutters of Italian palazzos protect from direct solar exposure. The idea of layering and interactivity of the shell is highlighted in the traditional Japanese house where paper-faced exterior walls and sliding doors permit daylight in.

The evolvement of the building envelope from massive introvert structures into lightweight transparent shells is highly affected by the technological achievements in glass production and load-bearing skeletons. From times when glass was still a rarity, like in the Middle Ages when openings were the primary source of energy loss, to the 19th century and the Industrial Revolution that enabled the construction of Paxton's Crystal Palace, façade design has undergone tremendous changes. Because of its mode of construction, Crystal Palace has been a landmark in the history of prefabrication, "a turning point, through which the development of building history started on a new course" [4] (p.20).

Its roof was constructed out of countless identical modules that were defined from the maximum size of glass that could be mass-produced. Alongside iron structures, concrete was introduced into the mass and serial production industry. Le Corbusier, in 1914 developed the "Dom-ino House Project",that introduced the idea of integration in façade design with prefabricated windows and doors on a system-based structure of concrete columns and flat slabs. The first industrially produced building panels were manufactured in Germany in 1926. The "System Stadrat Ernst May", consisted of the wall panel (three layers of concrete), the window panel, the non-reinforced spandrel and the reinforced lintel panel (fig.2). A significant role in industrial building production played Jean Prouve from the 1930's onward. His concept idea of façade construction consisted of load-bearing posts, infill elements and sealing profiles has been the precedent of the post-rail construction systems. (fig.2). In the 1960's architects such as Gunter Behnish who developed the "System Behnish" his own prefabricated concrete prototypes, saw in prefabrication and rationalization of design the opportunity for new forms of architecture [4] (p.21-29). Renzo Piano and Richard Rogers complete in 1977 the Pompidou Centre that looks like a "building as a construction kit" [4] (p.37). Its extrovert envelope expresses how building form is dominated not by a single system, but rather by a set of systems with various technical standards.

In 1981, architect Mike Davies, proposed the idea of the polyvalent wall, in his article "A Wall for all Seasons". The polyvalent wall consists of a multi-layered compound element that provides sun and heat insulation while generating the required energy for the operation of these systems (fig.2). Davies's idea is based on technological achievements such as the electrochromic glazing and solar cells [6].

The concept of the polyvalent wall generated the term "intelligent" facade that refers to the ability of a building shell to adapt to the internal and external conditions [2] (p.89). Since the term intelligent facade can sometimes be misleading, "adaptive" facades were introduced to highlight how facades adapt to current weather conditions. Strategies for an adaptive facade aim to minimize the disadvantages of regular facades so that a high comfort level can be achieved.

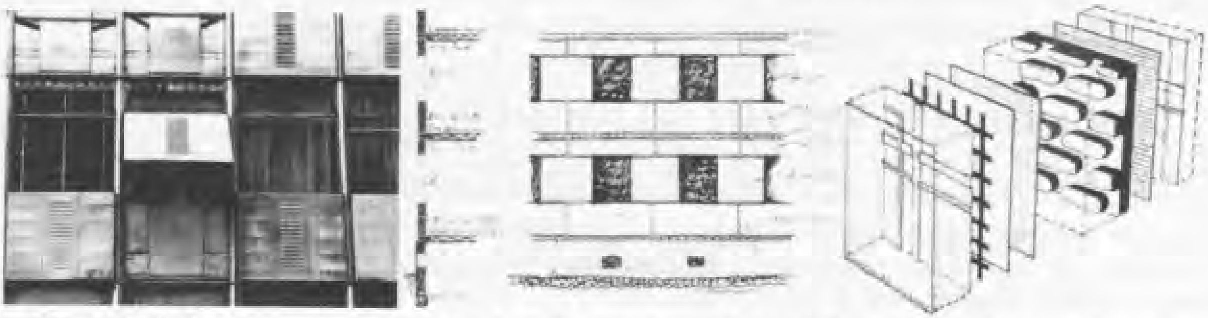

Figure 2: (left) Square Mozart (Paris), Jean Prouve, (center) Panel Construction System "System Stadtrat Ernst May", (right) Polyvalent wall, Mike Davies. Source (from left to right): www.artsblog.it, [3] p. 24, Facades, [2] p.89

Today, the examples of integrated facades with modular buildings units, continuously increase. In TEmotion, produced by Wicona, "glass" elements with shading are integrated with "functional" elements of building services and photovoltaic panels (fig.3). The functional requirements that TEmotion covers are daylighting, heating, cooling, ventilation (mechanical and natural), lighting (artificial), energy production and service management. All these performance criteria can be controlled by a central management system or by the user [8]. More of a concept idea than a product is the E^2 that aims to a type of buildings that produce more energy than they use. The performance criteria that Shucco integrated into E^2 are ventilation (mechanical and natural), heating, cooling and shading. Their components are placed at the floor edge in order to free up façade surface (fig.3). At the same time energy is produced by translucent solar panels. Decentralized control systems allow the users to achieve conditions of visual and thermal comfort. Because of its modular design the E^2 system can be integrated into different building types and patterns of use [9]. The idea of the Smart Box Energy Façade from Cepezed, consists of façade panels and a Smartbox (fig3). By incorporating the functions of heating, cooling and ventilation the decentralized unit Smartbox controls the room temperature and relative humidity. It is located at the edge of the floor and it can be combined with all various types of façade panels to form the Smartbox Energy Façade. Because of its placement and its decentralized character, space meant for centralized system pipes and shafts becomes available, control losses are minimized and control is granted to the user [10].

Figure 3: (left) E^2 Façade System, (center) Smartbox, (right) TEmotion. Source (from left to right): www.schueco.com, www.cepezed.nl, www.interempresas.net

5.1 Conclusions

The notion of integration has always been part of the façade design. Nevertheless, examples of modular integrated systems are recent and relatively limited. A few case studies of performance data of modular systems highlight the fact that there is lack of knowledge and available guidelines. The IEA Annex 44 project [11] that aimed to give examples of integrated building concepts and available performance data summarized that the lack of holistic design lies to a series of reasons. According to the report, the barriers and opportunities for integration are related to the lack of available standard components as well as demonstrated technologies and concepts for different climates. Current technologies and building components do not easily connect to each other, while the lack of appropriate and optimized controls often leads to inefficient performance and user dissatisfaction.

6 Modular Façade Concept

The growing need for integration of performance functions in facade design has been the incentive for a concept idea that explores the possibilities of modularity. Its development involved a set of ideas such as the frame-based modules where components of different functions are located in the façade. Placement of the modules along the vertical axis is defined under the principles of the three zones division (spandrel, view and daylight zone). Posts divide the façade along the horizontal axis. Because of their potential, as reviewed previously, decentralized control units were located in the posts. Modules measuring 1m on both directions define the modular grid that was incorporated. The set of functions to be integrated into the façade include, daylighting, solar protection, ventilation, cooling and energy production. More specifically the 1x1 m modules mounted on the posts display a variety of features to be selected based on design preferences, building type and use (fig.4). The façade modules need to take care of both the local and global properties of the façade. These features include exterior louvers for solar protection and light redirection to the back of the room, interior venetian blinds for shading and glare reduction as well as interior roller shades. The opaque modules feature increased thermal mass for peak load reduction and photovoltaic panels for energy generation. Heating, cooling and ventilation can be achieved with the decentralized unit inside the post. Connections between the posts and the modules to be designed in a later stage need to be flexible so that modules can easily be changed and upgraded in later stages.

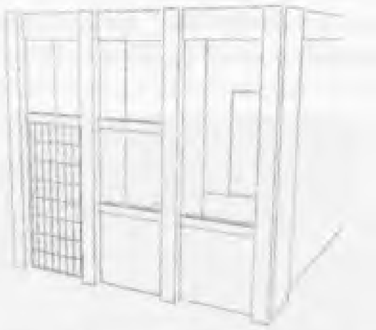

Figure 4: Modular façade concept idea

To examine the advantages and opportunities of the integrated modular façade system, a series of simulations were performed in the simulation program Comfen that supports the systematic evaluation of façade designs using EnergyPlus. The research question that was examined focused on the impact of integration and modularity on occupants' thermal and visual comfort and energy generation at the early stages of a project. More specifically, four comparative fenestration design cases were simulated in order to examine the transition from a standard case scenario to the "integrated" façade concept. The first scenario is a post-rail façade with posts every 1m and solar-E glass. In scenario 2, the façade is divided into three horizontal zones 1m apart.. Scenario 3 represents the modular façade concept with a series of integrated functions as shown in figure 5. Finally, scenario 4 presents the same geometric characteristics as scenario 3 with the addition of controllers for the louvers and blinds. The space that was modeled is a 3.8m wide by 6m deep office space in an office building. It was assumed that the space is occupied by two people.

Figure 5: Comparative fenestration design cases in Comfen. Technologies: **A**: thermal mass wall, **B**: interior venetian blinds, slat angle:30, slat width: 2.5cm, **C**: exterior horizontal louvers, slat angle: 0, slat width: 10cm, **D**: photovoltaic panels, $\mathbf{B_1}$: interior venetian blinds, control system: the shading system is on if irradiance on window 100 W/m^2, slat angle:30, $\mathbf{C_1}$: exterior horizontal louvers, control system: the shading system is on if irradiance on window 100 W/m^2, slat angle:0

6.1 Discussion

Results have shown that energy use for cooling and lighting has significantly been reduced in the modular concept idea (scenario 3) (fig.6A). Peak energy consumption on electricity in scenario 3 is about 100 MJ/m^2 less than the standard case (scenario 1) (fig.6A). Heat gains during the summer period (May-August) for scenario 1 and 2 are much higher than those for scenario 3. Their difference is less significant during the winter period (November-February). Overall, scenario 4 energy consumption is very close to scenario 3 and more specifically slightly higher for cooling. These results raise questions on the effectiveness of the controllers that were used. Further research will examine the effectiveness of the integrated façade's dynamic character.

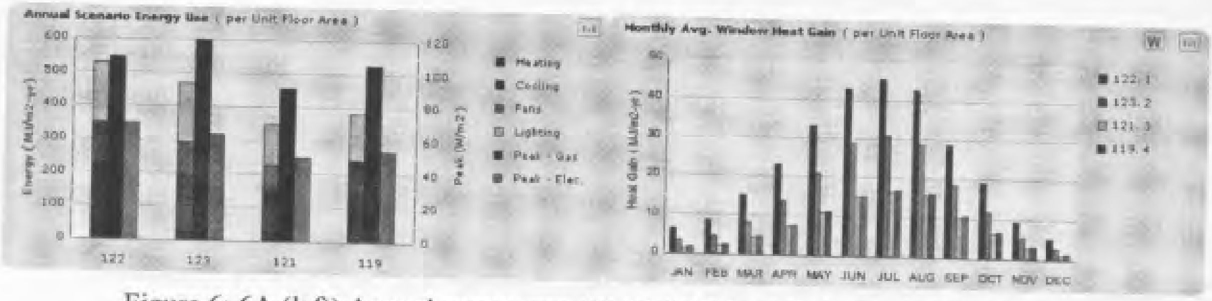

Figure 6: 6A (left) Annual energy use, 6B (right) Monthly Avg. window heat gain

Daylighting visualizations using Radiance in Comfen show that light distribution is uniform for scenarios 2 and 3 (fig.7). The horizontal exterior louvers at the upper parts of the window seem to be effective in redirecting light towards the ceiling. Images for the 4th scenario show strong light patterns, which probably means that the controllers for the two shading systems are not activated. Illuminance levels at the first sensor point are relatively low (around 100 lux) for scenario 3.

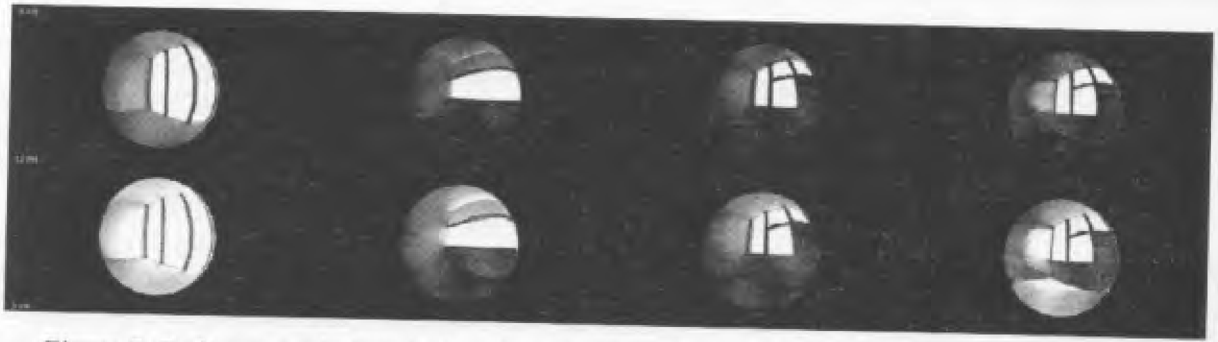

Figure 7: Radiance renderings in Comfen. Simulation period: December 21st at 9 am and 12 pm

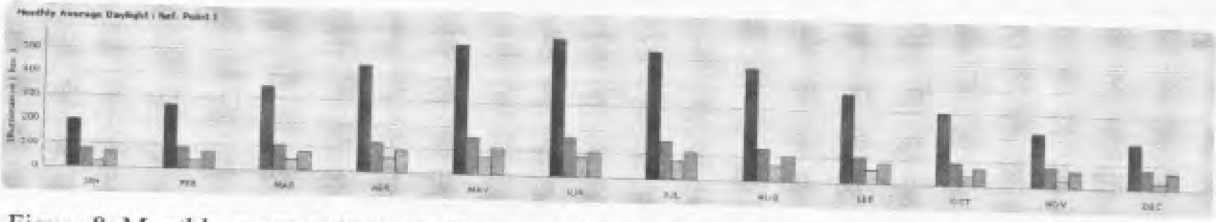

Figure 8: Monthly average daylight. Illumnance levels at sensor #1 (centered, 2.8 m from the façade)

6.2 Future work

Overall, the performance of the modular façade concept seems to be satisfactory as far as energy consumption and occupants' comfort is concerned. Future research will focus on the definition of the criteria for the location of modules in the façade. Modules and posts will be designed into more detail in order to specify their dimensions and modes of connection. To optimize its performance, and integrate dynamic characteristics, the use of appropriate control strategies will further investigated.

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