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Technological Interventions in Building Facade System: Energy Efficiency and Environmental Sustainability

Mohammad Arif Kamal

Architecture Section, Aligarh Muslim University, Aligarh, India

Abstract Building facades affect indoor thermal comfort. The dual effects of reducing building energy consumption and improving indoor thermal comfort can be achieved by adopting a passive design in a reasonable manner. High-performance sustainable building facades are exterior enclosures that use the least possible amount of energy to maintain a comfortable interior environment, which promotes the health and productivity of the building's occupants. The objective of the research is to investigate and understand the high performance building facade systems, especially employed in tall buildings in present day contemporary architecture. In this paper, a qualitative evaluation research method is used. The research methodology comprises of case studies, visual observation and data collection. The various modern trends in high performance building facade system employed in contemporary tall buildings around the world through five case studies have been analysed in this paper.

Keywords High Performance, Building Facade, Energy Efficiency, Environmental Sustainability

1. Introduction

The building facade is the interface between the external and internal environments of a building. Facade systems comprise of structural elements that provide lateral and vertical resistance to wind and other actions, and the building envelope elements that provide the weather resistance and thermal, acoustic and fire-resisting properties. It also has a large impact on occupant's interface with the surrounding environment; energy efficiency and the indoor environmental quality performance of a building, such as lighting and HVAC electricity loads; and peak load to maintain good lighting level and thermal comfort for the occupants. High-performance building facade systems involve selecting and deploying the right materials, advanced technologies, good detailing, and installation, all of which must be contextually and functionally appropriate. It refers to designing buildings and spaces (interior and exterior) using local climatic conditions to improve thermal and visual comfort. These designs provide protection from the summer sun, reduce winter heat loss, and make use of the environment (e.g. sun, air, wind, vegetation, water, soil, and sky) for building heating, cooling, and lighting. Due to the multiple important roles – i.e., aesthetics, thermal comfort, daylighting quality, visual connection to the outdoor environment, acoustic performance, and energy-related performances – building facades, especially glazing systems, have received much attention in research and development. This results in a wide range of products and technologies available to achieve high-performance facade systems.

2. Research Methodology

The objective of the research is to investigate and understand the technological interventions in high performance building facade systems, especially employed in tall buildings in present day contemporary architecture. In this paper, a qualitative evaluation research method is used. The research methodology comprises of case studies, visual observation and data collection. The study identifies the amount of energy consumed in buildings and the need for a sustainable built environment. The various modern trends in high performance building facade system employed in contemporary tall buildings around the world through five case studies have been analysed in this paper. These case studies illustrate how various technological concepts have been realized architecturally.

3. Energy Consumption in Buildings

Buildings consume about 40% of energy use and carbon emissions in the world. The total energy consumption of buildings especially for cooling purposes varies as a function of the quality of design and climatic conditions. Energy

* Corresponding author:
architectarif@gmail.com (Mohammad Arif Kamal)
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consumption is an important factor for today's living, the dependency on energy is primarily for achieving a comfortable life. Comfort achieved by the consumption of energy has its economic and environmental drawbacks. In hot climates, buildings with appropriate heat and solar protection and careful management of internal loads may reduce their cooling load down to 5 kWh/m2/year, while buildings of low-quality environmental design may present loads up to 450 kWh/m2/year [1]. The buildings use one-third of all energy consumed in India and two-thirds of all electricity. In India, the building sector represents about 33% of energy consumption with commercial and residential sectors accounting for 8% and 25% respectively [2]. Researchers have proved that global warming and climate change are two interrelated phenomena. Fossil fuels are burned to produce the cooling energy, which causes greenhouse gas emissions and hence global warming leading to climate change. By implementing energy reduction measures, we can reduce electricity demand and climate-altering emissions.

4. Environmental Sustainability in Buildings

Sustainability is a term used to describe the needs of the present without compromising the ability of future generations to meet their own needs. Architectural sustainability is linked to the much-quoted Brundtland commission report definition through an emphasis on limits to the carrying capacity of the planet, and they pointed to the UK's Building Services Research and Information Association (BSRIA) definition of sustainable construction as 'the creation and management of healthy buildings based upon resource-efficient and ecological principle' [3]. With an increasing population, the energy reserves are depleting at a very faster rate. The buildings need to be designed in a way that it consumes lesser energy produced from various conventional energy resources. In principle, sustainable buildings relate to the notion of climate-responsive design, which emphasizes natural energy sources to achieve building comfort through the interaction with the dynamic conditions of the building environment [4]. Sustainable architecture intends to face the need of future, without destroying the remaining resources of future generations. In case of buildings, sustainable design refers to flexibility, lone lifetime, stable stagnancy, efficiency of resources, and minimum energy [5]. Sustainable architecture is an approach to design where building technology is integrated with the concept design and has the potential to reduce the need for high-tech systems and reduce the energy consumption of buildings.

5. Building Facade Performance

Facades have traditionally served as a barrier between internal space and climate conditions of outside and its performance evaluation is undertaken based on the ability to distinguish internal and external spaces. Meanwhile, new design ideas regard the facade of building as a barrier to balance external and internal spaces [6]. When considering a material or system to use in the design of a building facade, one needs to bear in mind a number of performance requirements. There are also many performance factors which affect the design of building facades [7]. The major factors which are design determinants for the facade system in buildings are discussed as below:

5.1. Aesthetical Appeal

Etymologically, the facade is quite literally the face of the building. It defines its identity, and is often what the public would use to describe or to refer to a specific development. Consequently, the aesthetics of the building envelope is a fundamental aspect to consider. It needs to exhibit flair and refinement. Other than the overall shape of the envelope, which ties with the internal space planning and layouts, the architect should be able to work on qualities such as modulations, texture, colour, reflectivity, gloss level, as well as the possibility to incorporate holes or patterns on the surface for aesthetics, daylighting or natural ventilation. All of these parameters, in conjunction with each other, define the appearance of the building.

5.2. Structural System

Besides the aesthetics, the design team needs to consider the structural aspects of the facade design. The latter needs to be able to withstand wind load, live load, self-weight, seismic loads, snow load, as well as the building movements under various loading conditions, and all of the above should be accommodated for the full lifespan of the building envelope. Several considerations will influence the size of the building envelope framing members, including the type of system, material strength, testing, design code, modulations, loading and floor-to-floor height, amongst others.

5.3. Durability and Stability

Aesthetics alone is not sufficient if the latter does not last for an adequate period of time. The building envelope should be designed using materials and systems that are durable. The fa çade of a building is susceptible to multiple sources of aggression, including the sun, rain, temperature variations, and other weather conditions. Under the effects of these elements, cladding materials may fade, crack, chip, craze, chalk, debond, warp, become scratched, etc. It should be noted that regardless of how careful one is with the material selection process, no material or system can last for their intended lifespan without proper and regular maintenance.

5.4. Safety

In addition, the facade should be designed to be safe while in service. Besides strength, which is considered in the structural design mentioned earlier, the building envelope should be resistant to impacts, be they from building users, the general public, vehicles in and around the building, or the building maintenance equipment. In case of impacts of a foreseeable nature, the façade should not be damaged and should remain safe for users and passers-by. Recent unfortunate events have also highlighted the particular importance that one should lend to the fire behaviour of the façade. This involves not only testing and verifying the reaction to fire of the materials used, but also paying careful attention to the detailing and testing of the overall façade systems, since the use of certain materials in combination with each other, and the configuration of the façade elements and fire-stopping systems all contribute to achieving an acceptable behaviour in case of fire.

5.5. Weather Performance

One of the main functions of the building envelope is to shield the occupants from the weather. This includes preventing water penetration, as well as limiting air infiltration and exfiltration so as to ensure proper thermal performance and minimise the risk of condensation and mould growth internally. Restricting the passage of air through the façade helps avoid whistling noises, and improves the overall acoustic performance of the facade.

5.6. Acoustical Performance

The acoustic performance of the façade is an essential aspect to consider as well. Beyond limiting air infiltration, as mentioned above, the building envelope should also be designed to sufficiently attenuate external noise sources, in particular, traffic and mechanical equipment. The STC (Sound Transmission Class) or OITC (Outdoor/Indoor Transmission Class) values of the façade system can be estimated from past data, or preferably accurately determined through laboratory and/or site tests. The facade should also be designed in such a way as to prevent self-generated noises, such as those that can occur due to the friction of metal on metal parts.

5.7. Thermal Performance

The thermal performance of the facade is equally important. In the tropics, the contribution of the building envelope to the heat load can be as much as 30%. Considering that in commercial buildings, cooling systems can contribute up to 50% of the total energy bill, improving the thermal performance of the facade also contributes to reducing the size of HVAC (Heating, Ventilation and Air Conditioning) systems, and lowering the energy cost of the building while in operation. A similar situation exists in temperate and cold climate, where heating constitutes a major part of the energy consumption of the building and can be significantly reduced by reducing the amounts of convective, conductive and radiant heat passing through the facade.

5.8. Sustainability

Apart from the thermal aspects, building envelopes should be designed in the most sustainable manner possible. A variety of measures can be taken towards this, including sourcing sustainable materials such as the use of recycled or recyclable materials (many facade materials, including glass, aluminium and steel, are infinitely recyclable), limiting or altogether avoiding the selection of components with high VOC (volatile organic compounds) content, ensuring that the materials chosen for the façade elements have been produced in ISO14001-certified factories, incorporating building envelope components that can generate energy (from solar, wind or other renewable sources), etc.

5.9. Cost Effectiveness

Last, but not least, cost is a major consideration in the design of a facade and in the selection of materials and components. On a high-rise building, in particular, the cost of the building envelope could be in the range of 20% of the total construction cost of the building, or even more, since for taller developments, the ratio of façade area to Gross Floor Area increases as the building height increases. In many cases, regrettably, the cost is the ultimate deciding factor, beyond aesthetics and other considerations listed above. Judicious material choices and precise engineering can have a dramatic impact on cost and are thus crucial steps in the design process.

6. Effect of Facades on Efficiency

The facade makes up the majority of the building's envelope separating the interior and exterior environments; it is the single most important factor in the energy efficiency of the structure. The facade's efficiency is significantly dependent on the building's location and orientation to the sun, as well as the materials and construction methods used in the facade. The design of high-performance buildings begins with determining the optimal shape and placement of the building according to its intended use and other limitations. Next, the use of glazing on the facade must be optimized for thermal efficiency, lighting, and solar heating. The glazing defines the amount of sunlight that reaches occupants, the amount and type of glaze required on each face depends on heating and lighting needs, the path of the sun, and the position of nearby shading elements. Insufficient natural lighting creates a need for artificial lighting fixtures and increases energy costs. In cold environments, insufficient solar heating can also increase the air conditioning loads. Too much sunlight creates comparable effects, making additional shading devices necessary to manually limit sunlight exposure and increasing cooling loads due to excessive solar heating. Although glazing allows sunlight to enter a building for lighting and heating purposes, it also tends to decrease the thermal performance of the facade because glass provides less insulation than walls. By positioning glazing to optimize solar lighting and heating, the percent area of the facade covered by glazing can be reduced to mitigate heat loss. Double and triple glaze constructions and glazing frames that are thermally broken should also be used to reduce heat conduction across the envelope and minimize thermal losses. Because glazing has such a strong impact on energy efficiency, it is imperative that glazing and shading devices be positioned to ensure that heat fluctuations are minimized, reducing A.C. and lighting energy usage [8].

7. Climatic Considerations for Building Facade

The basic methods for designing high performance building facades include: orienting and developing geometry and massing of the building to respond to solar position; providing solar shading to control cooling loads and improve thermal comfort; using natural ventilation to reduce cooling loads and enhance air quality in climates that allow this; and minimizing energy used for artificial lighting and mechanical cooling and heating by optimizing exterior wall insulation and the use of day-lighting. In choosing specific design strategies, consideration should be given to the conditions of the climate zone to minimize environmental impacts and reduce energy consumption.

An important metric for facades is the window-to-wall ratio, which is the proportion of glazed to opaque façade area. This ratio is a significant contributor to a facade's solar heat gain and energy consumption. In most cases, higher window-to-wall ratios result in greater energy consumption, since the thermal resistance of even a well-insulated glazed facade is typically lower than that of an opaque facade. Minimizing the window-to-wall ratio (energy code recommendations state that the window-to-wall ratio should not be larger than 40%) and specifically addressing building orientation (e.g. minimizing the window-to-wall ratio on east and west facades, and maximizing along the north orientation) should be implemented as design strategies for high performing facades. For hot and warm climates, increased window-to-wall ratios cause cooling loads to increase due to increased solar heat gain. For mixed and colder climates, higher window to-wall ratios increase heating loads, especially for buildings located in cold climates. An important strategy that improves the energy efficiency in any type of climate is to reduce the window-to-wall ratio by increasing the amount of opaque facade relative to glazing [9].

8. High Performance Building Facade System: A New Paradigm

A responsive facade system is considered a major component of high-performance building envelope that is capable of responding to environmental stimuli and aims to improve occupants' comforts and energy consumption [10]. Building facades perform two functions: first, they are the barriers that separate a building's interior from the external environment; and second, more than any other component, they create the image of the building. With the global energy crisis becoming increasingly serious, ensuring and improving indoor thermal comfort whilst reducing energy consumption during a building's operation stage are important goals [11]. At present, energy conservation in most buildings is focused on reducing energy consumption, whereas indoor thermal comfort is less frequently considered [12]. Building facades affect indoor thermal comfort. The dual effects of reducing building energy consumption and improving indoor thermal comfort can be achieved by adopting a passive design in a reasonable manner [13]. Building facades are directly exposed to the external environment. Different building facades are related to varying indoor comfort and energy consumption levels. A reasonable facade design helps reduce energy consumption and improve indoor thermal comfort [14]. Therefore, the passive design of building facades is an important aspect of managing building energy consumption [15]. High-performance sustainable facades can be defined as exterior enclosures that use the least possible amount of energy to maintain a comfortable interior environment, which promotes the health and productivity of the building's occupants. This means that sustainable facades are not simply barriers between interior and exterior; rather, they are building systems that create comfortable spaces by actively responding to the building's external environment, and significantly reduce buildings' energy consumption [16]. The recent technological interventions in building facade systems concerning climatic control and energy efficiency have been discussed through the following five case studies.

8.1. Al-Bahar Tower, Abu Dhabi, UAE

The Al Bahar Towers in Abu Dhabi has been designed by Aedas Architects. It is a responsive facade that takes cultural cues from the 'Mashrabiya', a traditional Islamic lattice shading device (Fig. 1). The Mashrabiya type double facade is on the south, east and west portions. The North facade left open due to minimized solar issues and to allow for a primary view to the city beyond. The responsive system opens and closes according to the solar path. The 'Mashrabiya' at Al Bahar Towers is comprised of a series of semi-transparent PTFE (polytetrafluoroethylene) umbrella-like components that open and close in response to the sun's path. Each of the two towers includes over 1,000 individual shading devices that are controlled via the building management system to create an intelligent second facade. This view shows the screen in its fully closed mode. The shading system operates as a curtain wall, located two meters outside the building's exterior on an independent frame. Each unit responds to the movement of the sun. However, in the evening, all the screens will open.

Figure 1. The view of Al Bahar Tower, Abu Dhabi, UAE

Each unit is comprised of a series of stretched PTFE panels and is driven by a linear actuator that will progressively open and close once per day in response to a pre-programmed sequence that has been calculated to prevent direct sunlight from striking the facade and to limit direct solar gain to a maximum of 400 watts per linear meter. The entire installation is protected by a variety of sensors that will open the units in the event of overcast conditions or high winds (Fig. 2). The benefits of this system include reduced glare, improved daylight penetration, less reliance on artificial lighting, and over 50% reduction in solar gain, which results in a projected reduction of CO_2 emissions by 1,750 tonnes per year. The effects of this system are tremendous: improving the penetration of daylight, reduce glare and less artificial lighting. By running the self-customized program, the Aedas team did a comprehensive solar analysis. The result shows that over 50% of solar gain has been reduced, which results in a reduction of CO_2 emissions of 1,750 tons per year. Also, the shading ability to filter light has allowed architects to be more alternative in the choice of glass [17].

Figure 2. Dynamic semi-transparent PTFE screens of Al Bahar Tower

8.2. The Pearl River Tower, Guangzhou, China

Pearl River Tower, located in Guangzhou, China is a green skyscraper designed by Skidmore, Owings & Merrill. The building is 309 meters tall having 71 stories (Fig. 3). It is a high-performance building that claims to be the most energy-efficient super – tall tower building in the world [18]. The building has double-wall insulation. The double envelope accommodates venting and solar shading devices within the cavity (Fig. 4). These design approaches facilitate thermal comfort and air quality, as well as day-lighting and energy savings.

Figure 3. The Pearl River Tower, Guangzhou

Figure 4. High Performance Active Facade Detail of Pearl Tower

Figure 5. Building Integrated Photovoltaic

The building has an embedded photovoltaic transistor system for solar energy. The Building Integrated Photovoltaics (BIPVs) in the Pearl River Tower act both as the building skin (spandrel panels) as well as the power generator (Fig 5). The wall surfaces are angled for maximum sun exposure. The building is designed in such a way that it funnels and pushes the air through wind tunnels at a great speed which is 1.5 to 2.5 times greater than the ambient wind speed. It has a curved glass facade that directs airflow through narrow openings in the facade that will drive large, stainless steel wind turbines to generate electrical energy. It generates 15 times more energy than the 'freestanding' wind turbines. The wind has a great impact on the design of tall buildings. When the air is allowed to pass through the building, the difference in pressure between the windward side and the leeward side is reduced. As a result, the forces on the building are also reduced. This approach allows for a reduction in the quantity of steel and concrete to maintain the building's stability. Therefore, it is a sustainable approach towards design as far as a structural standpoint is considered.

Moreover, vertical axis wind turbines are implemented in the building, which is capable of harnessing winds from both prevailing directions and greatly reduces efficiency loss. This building also employs geothermal heat sinks, ventilated facades, waterless urinals, integrated photovoltaic and daylight responsive controls. According to reports, the Pearl River Tower would help emit less carbon dioxide by approximately 3,000 tons and achieve an overall energy saving of 30.4 percent a year [19].

8.3. Q1 ThyssenKrupp Essen, Germany

ThyssenKrupp AG worked with TKQ architect consortium JSWD Architekten and Chaix & Morel to design a new seven-building corporate campus in Essen, Germany (Fig. 6). The German Sustainable Building Council (DGNB) has awarded the project a Pre-certificate in Gold based on the new German Certification for Sustainable Buildings. Unlike the fabric of Aedas's design, Essen's smart sun shading system is made of stainless steel slats in a featherlike pattern. It is one of many sustainable features of an 11-storey office building on the corporate campus of ThyssenKrupp. The shading system helps reduce solar gain while often leaving gaps that allow external views and let natural light enter, reducing the need for artificial light. "This is very important, because the greatest energy use in a building is electric energy, especially for lighting," says Jürgen Steffens, a partner at JSWD Architects. Because of the shading system and other green features, the building uses less than 120kWh/m^2 of energy a year, a low amount for a glass high-rise [20].

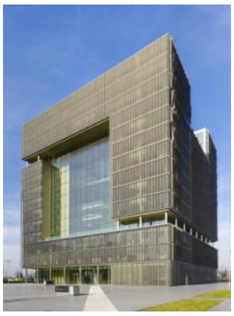

Figure 6. The Q1 ThyssenKrupp building in Essen, Germany

Figure 7. Perforated motorized sunscreen of Q1 ThyssenKrupp

The energy requirements are expected to be 20 to 30% below the statutory requirements. All of the buildings are simple glazed structures but their appearance is unique because of their second facade. The buildings are wrapped in automated sunshade systems with Type 316 stainless steel horizontal and vertical slats or custom perforated sunscreens (Fig. 7). These active motorized sunshade systems have moveable triangular, square and trapezoidal fins that are automatically adjusted with changing conditions to save energy. Used in combination with natural ventilation, the system eliminated the need for air conditioning [21].

8.4. The Doha Tower, Doha, Qatar

The Doha Tower designed by Ateliers Jean Nouvel, located in Doha, Qatar also uses a hybrid double facade arrangement (Fig. 8). In this instance, the Mashrabiya screen creates a very complete second skin and encloses the entire building. Except for the entrance, no large expanses of vision glass are maintained. Instead, the density of the screen is varied according to the solar orientation of the building.

Figure 8. The view of The Doha Tower, Doha, Qatar

The exterior skin of the Doha Tower is fixed or non-responsive. It is instead composed of four "butterfly" aluminum elements of different scales to evoke the geometric complexity of the Islamic 'Mashrabiya' while serving as protection from the sun (Fig. 9). The pattern varies according to the orientation and respective needs for solar protection: 25% towards the north, 40% towards the south, 60% on the east and west. The variation in the opacity of the aluminum screen addresses the variation in solar avoidance required on the facade orientations. Due to the round shape of the tower, some shading is required on the "north" facade as it will receive sunlight in the early morning and late afternoon hours [22].

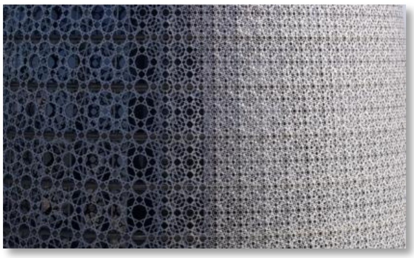

Figure 9. The 'Mashrabiya' like screen serving as protection from the sun

While the screen may appear quite dense from the exterior, the interior view shows the amount of sunlight that still enters the space. Additional blinds are provided on the interior to cut out glare and penetration when needed. The system relies on contemporary precision cutting methods in combination with the selection of solid aluminum plate to achieve a durable element that is easier to maintain than other finishes. The fixed Mashrabiya screen is situated more than a meter from the high-performance curtain wall. This is to allow for cleaning access to space. The metal grating at each floor provides additional shading for the glass. This view inside the air corridor and looking out gives a good appreciation for the density and texture of the exterior skin (Fig. 10). The diamond grating of the walkway allows for air circulation up the facade which is essential to prevent the entrapment of hot air at each level [23].

Figure 10. Mashrabiya screen as protection from direct solar radiation

8.5. The Capital Gate, Abu Dhabi. UAE

The Capital Gate, also known as the Leaning Tower of Abu Dhabi, is a skyscraper in Abu Dhabi that is over 160 meters tall, 35 stories high, with over 16,000 square meters of usable office space (Fig. 11). The Capital Gate is one of the tallest buildings and was designed to incline 18 degrees westward lean, holding the Guinness World Record for the "world's furthest leaning manmade tower." The building has a completely asymmetric shape. No two rooms are the same and all 12,500 panes of glass on the facade are a different size. A diagrid structural system was utilized in which all 8,250 steel diagrid members are of different thicknesses, length, and orientation and each of the 822 diagrid nodes is of different size and angular configuration. The sustainable agenda was high on the priority list in the design of Capital Gate in Abu Dhabi. It was recognized that the reduction in solar gain provided by the double facade system would be of great benefit to the building. For this reason, the designers used two distinct types of systems that worked with the specific conditions of the project that resulted from the offset of spaces from the vertical elevator core [24].

A diamond-shaped prefabricated curtain wall system is attached to the structural steel diagrid of the tower and forms the outside layer (Fig. 12). The interior layer uses a less expensive rectilinear glazing system. There are no shading devices used in the cavity. The cavity width is sufficient to provide access for cleaning. The lower office floors are protected by a large metal mesh canopy called "the splash" which starts at the entry-level as a sunshade over the car drop-off area and climbs the facade, terminating at the projecting pool level provided at the 19^{th} floor (Fig. 13). The mesh is supported on an architecturally exposed structural steel frame and is 90% open. The mesh allows for air circulation while blocking approximately 30% of the solar radiation from striking the curtain wall of the office spaces [25].

Figure 11. The Capital Gate, Abu Dhabi, UAE

Figure 12. The double skin curtain wall diagrid system of Capital Gate

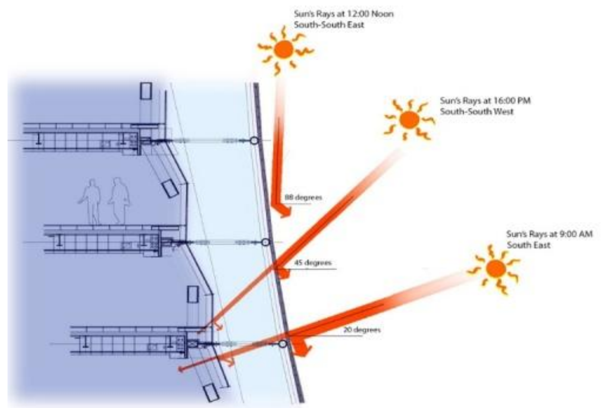

Figure 13. The double skin curtain wall diagrid system of Capital Gate

9. Integrated Facade Design Process

The integrated approach to facade lighting-HVAC building systems is to achieve optimum energy-efficiency and comfort. A sustainable integrated facade design process is intended to produce high performance buildings that are energy efficient, healthy, and economical in the long run, and use resources wisely to minimize the impact on the environment (Fig. 14). Properly designed windows play an important role in achieving these energy and environmental goals and contribute to the comfort, satisfaction and productivity of building occupants as well. The challenge in designing facades is balancing many issues and criteria

[26]. Control of physical environmental factors (heat, light, sounds) must be considered during the design process, as must design strategies that improve occupant comfort (thermal, visual, acoustic, and air quality). Therefore, sustainable facades must block adverse external environmental effects and maintain internal comfort conditions with minimum energy consumption. The location and climate thus are crucial factors in selecting appropriate design strategies for sustainable facades. Therefore High-performance sustainable building facades use the least possible amount of energy to maintain a comfortable interior environment, which promotes the health and productivity of the building's occupants. The existing practices in integrated facade design process are as follows:

- Designers rarely (i.e., never) design a façade using the codes
- Facade design typically defined by end of concepts phase
- Architect subcontracts out HVAC and lighting systems design
- Architect subcontracts out proof of energy code compliance
- Simulation tools used after the fact, rarely before

But the ideal practice for facade design process:

- Recognizes synergistic impacts of design on lighting and HVAC systems over 30- to 50-year life of building.
- Analysis focused on quantifying magnitude of trade-offs between facade-lighting-HVAC designs
- energy and non-energy trade-offs that affect occupant comfort.

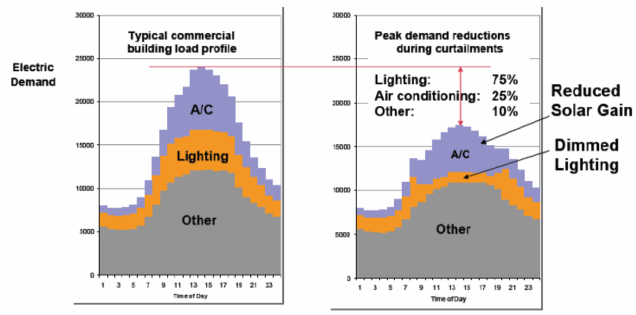

Figure 14. Energy and Demand management with Integrated Facades

10. Conclusions

Sustainable architecture pursues to lessen the negative environmental impact of buildings by raising efficiency and innovating the use of materials [27]. The facade is one of the most significant contributors to the energy budget and the comfort parameters of any building. As energy and other natural resources continue to be depleted, it has become clear that technologies and strategies that allow us to maintain our satisfaction with the interior environment while consuming fewer of these resources are major objectives for contemporary facade designs. The primary purpose of high performance sustainable facades is to provide a barrier between the interior and exterior environment, while creating comfortable spaces for building occupants and significantly reducing a building's energy consumption [28]. In recent years, architects and consultants have been coming up with an array of designs for digitally controlled sunscreens that move in response to shifting environmental conditions. The recent wave of concern about sustainability and reducing buildings' carbon footprints has spurred interest among architects in such systems. Design strategies for sustainable, high performance facades highly depend on the building's location and climate.

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