International Conference on Whole Life Urban Sustainability and its Assessment
M. Horner, C. Hardcastle, A. Price, J. Bebbington (Eds)
Glasgow, 2007

Examining the Role of Building Envelopes towards achieving Sustainable Buildings

Irene Lee [a,*], Robert Tiong [b]

[a,*] School of Civil and Environmental Engineering, Nanyang Technological University, Singapore.
[b] School of Civil and Environmental Engineering, Nanyang Technological University, Singapore.

ABSTRACT

Buildings are long known to be a major resource consumer and contribute substantially to environmental deterioration. The building envelope, being the interface between the building and the environment, controls the interactions between them. It does so by firstly filtering out the undesirable external environmental elements and subsequently affecting the amount and rate of resource consumption and environmental deterioration by the building in order to regulate the interior conditions. This paper aims to investigate the ways in which the building envelope can impact upon the sustainability of the building and the magnitude of the impact through an extensive literature review.

The concept of building sustainability and sustainable building rating systems and guidelines are first reviewed. Criteria of sustainable buildings are established and grouped into 4 aspects, i.e. economic, environmental, social and functional. Based on these 4 aspects, the impact of building envelope on the building sustainability is examined. It was found that the building envelope has significant impact on the initial and running costs of the building. Also, it affects the energy efficiency and the indoor environment of the building significantly. Lastly, the building envelope was also found to be a significant factor of the functional performance of the building through its integration with other building systems.

In conclusion, the in-depth literature review conducted has confirmed that the building envelope is a major contributor to building sustainability and presents great opportunities in enhancing the sustainability of buildings. The concept of a sustainable building envelope is advocated. The paper also provides a framework which further research works on sustainable building envelopes can be built upon.

Key words: Building Envelope, Sustainable Building

1 INTRODUCTION

1.1 Background

Buildings are an important part of urban development as they provide the different types of spaces needed by humans for their various activities. Buildings' functionality, aesthetics, healthfulness, safety, environmental quality and economy are vital to the quality of life and productivity of their users (American Society of Civil Engineers 2004). However, in creating these spaces to meet human needs and requirements, buildings also impact greatly upon the natural environment.

Firstly, there is the impact of environmental consumption as buildings consume much resource in the form of building materials and energy throughout its whole life (Evangelinos & Zacharopoulos 2006). In Erlandsson & Borg (2003), it was reported that the building sector constitutes approximately 44% of the society's total material use. Nelms et al (2005) also reported an alarming percentage of more than 50% of Canada's primary resources are consumed by the building industry. And about the energy consumption by buildings, it was found to be between 30-50% of the country's total energy demand in Canada, UK and US (Erlandsson & Borg 2003; Nelms et al 2005; Dewick and Miozzo 2002; Raman 2005). Hence, buildings are major consumers of resources and energy.

Secondly, buildings contribute to environmental deterioration as a result of pollution from the consumption of energy, especially non-renewable energy (Evangelinos & Zacharopoulos 2006). In the US and Canada, it was reported that the building industry generates 25% of the country's solid waste (Kibert 2005; Nelms et al 2005). Also, buildings are found to be contributing between 36% to 45% of the carbon dioxide emissions and between 25% to 48% of the sulphur dioxide emissions in the UK and US (Dewick and Miozzo 2002; Kibert, 2005; Roaf, 2005). Thus, to say that buildings are the single largest source of terrestrial and atmospheric pollution is not an overstatement.

The impact of buildings on the environment has necessitated the need for "Green" or sustainable buildings which aims at reducing the energy and resource consumption and hence, resulting in a reduced amount of harmful pollutants. However, while doing so, sustainable buildings have to meet the functional requirements for the needs of human activities.

Buildings provide shelters against the undesirable exterior environment and create an interior condition that is suitable for humans' various activities (Yeang 2006; Lucuik et al 2005). Being the interface between the external environment and interior of the building, the building envelope controls the interactions between the building and its external environment by firstly filtering out the undesirable external environmental elements and subsequently affecting the amount and rate of resource consumption and environmental deterioration by the building in order to regulate the interior conditions.

In Institution of Structural Engineers (Great Britain) (1999), the building envelope is described as the “climate moderator” and “is the first line of defence against the impact of the external climate on the indoor environment”. Indeed, the concept of building envelope as the first line of defence is evident in the passive mode strategies used towards achieving sustainable buildings. It has been argued that passive mode strategies are important in achieving sustainable buildings (Daniels 1997 and Yeang 1999 cited in Kishnani 2002). Passive mode strategies can be adopted to provide natural light, natural ventilation and heating and/or cooling in the building (Amourgis 2006). Hence, the use of passive mode strategies will reduce the reliance on conventional mechanical devices and consume less energy (Steemers 2006; Kishnani 2002). Being the “first line of defence”, building envelopes are often made used of by many passive design systems. Examples are the orientation of main facades and openings, use of external shades and light shelves, use of low-conductivity materials, placement of fenestration and the colour of envelope exterior (Abel & Royal Academy of Arts (Great Britain) Summer Exhibition 2003) and Kishnani (2002).

Therefore, being the first line of defence against the external environment and an important contributor in passive mode strategies, the building envelope plays a significant role in determining the building indoor conditions and the energy consumption needed by the mechanical systems and hence, the resultant environmental deterioration by the buildings. In the light of the sustainability development trends, it is therefore necessary to re-examine the role of building envelope and consider its positive and negative impact on the sustainability of a building.

1.2 Objective and Structure of Paper

This paper will carry out an exploratory research on the role of the building envelopes towards achieving sustainable buildings. An extensive review of the literature will be conducted around the working hypothesis that the building envelope has significant influence on the sustainability of a building. This research aims to explore the ways in which the building envelope can impact on the sustainability of the building and ultimately, provides some insight on how the building envelopes should be designed, constructed and maintained towards achieving sustainable buildings.

The research will begin with reviewing the concept of building sustainability and its criteria. Next, it will examine the role of building envelope and attempt to provide a qualitative understanding of the building envelope parameters that affect the sustainability of the buildings. Lastly, the paper ends by discussing the emergent role of building envelope for building sustainability.

2 SUSTAINABLE BUILDINGS

2.1 Definition of Sustainable Buildings

There are many terms associated with sustainable buildings, such as green buildings, high-performance buildings, energy-efficient buildings, environmental buildings and eco-building (Kibert 2005; Lucuik et al 2005; *The Guidelines for Sustainable Buildings* 2002). Among these terms, green buildings are most often used interchangeably with sustainable buildings.

Few of the literature reviewed have offered any distinction between the two terms. In Lucuik et al (2005), the authors tried to distinguish the two terms, where it was briefly explained that comparing green buildings with sustainable buildings, “the concept of sustainable building is more relevant to larger projects or even geographical areas”. However, the authors also pointed out that “green definitions are edging into the territory (of sustainable buildings)”.

According to Raman (2005), sustainability in buildings means minimizing the consumption of resources, i.e. water, energy and materials and increasingly, it also entails maximizing the health, safety and quality of life of the building occupants. At the Stanford University, similar definition of sustainable buildings is adopted where they are referred to as “buildings that use energy, water, and other natural resources efficiently and provide safe and productive environment” (*The Guidelines for Sustainable Buildings* 2002). Kibert (2005) gave similar definition to green buildings. He defined green buildings as “healthy facilities designed and built in a resource-efficient manner, using ecologically based principles”.

Hence, the review of the literature shows that the definitions provided for sustainable buildings and green buildings are similar, i.e. both emphasize on the efficient use of resources from the external environment while providing a quality internal environment for the building users. For this paper, the term “sustainable buildings” will be used.

Following from the definition, the next section discusses the application of the concept of sustainable buildings.

2.2 The Multi-faceted Nature of Building Sustainability

Underlying the definition of sustainable buildings are different concerns by various stakeholders. The efficient use of resources is generally an environmental concern and the provision of safe, healthy and productive spaces are social, functional and economical concerns. These different concerns give rise to the multi-dimensional nature of the sustainability of buildings and are often in conflicts. Based on the well-known Bruntland Report, which defines sustainability development as meeting the needs of the present generation without compromising the ability of future generations to meet their own needs, to achieve sustainability of buildings would thus mean balancing between the different concerns. This is also agreed by Raman (2005), Bakens (2005) and Yang, Brandon & Sidwell (2005).

The application of the sustainable building concept is further complicated by the different perceived values of the different concerns by the diverse stakeholders. The involvement of numerous and wide variety of stakeholders is a result of the different concerns presented in the sustainable building concept (Bueren 2001). The implication is that problems and solutions are subjected to different judgment and preferences and thus the optimum balance between the different concerns of sustainable buildings are not likely to be obtainable. Hence, it is advocated that an integrated development process involving all stakeholders is vital towards achieving sustainability in buildings (Lucuik et al 2005; *The Guidelines for Sustainable Buildings* 2002).

As seen, the application of the concept of sustainable buildings is not as straightforward as it seems. To facilitate the implementation of sustainable building concept, there should be a set of agreed criteria of building sustainability among the various stakeholders. The next section reviews the current sustainability efforts related to the development of building sustainability criteria.

2.3 Criteria for Sustainable Buildings

It is obvious that a multi-criteria approach needs to be adopted for the multi-dimensional nature of building sustainability. This is also the stand taken by most of the building sustainability rating systems and guidelines.

In McCreadie (2004), 41 sustainability tools, including those for evaluating building sustainability such as LEED and BREEAM were reviewed. It was found that all the tools contained environmental theme and most of them also contained social or economic themes or both. In the report by Levett-Therivel Sustainability Consultants (2004), the social, environmental and economic dimensions of sustainability are considered as core issues.

Table 1 summarises the issues considered in some building sustainability rating system and guidelines in relation to the three dimensions of building sustainability.

From the table, it can be seen that the economic dimension of building sustainability is concerned mainly with minimizing the whole life costs of the building, especially the on-going costs. This will allow for maximum investment returns as indicated in the SINDEX software tool developed by Langston (2005). Good maintenance and operation strategies will be vital in keeping the on-going costs low. This can be seen from the rating systems, United States' LEED and Singapore's Green Mark Scheme, where points are allocated to buildings which have good or innovative maintenance and operation management and strategies. CIB also included the adoption of a life-cycle costing approach as one of its 7 principles of sustainable construction (Kibert 2005). This shows that sustainable buildings should incur minimum total building costs, i.e. the initial and on-going costs, in order to maximize investment returns.

For the environmental criteria, the main objective is to reduce resource consumption and environmental deterioration. Sustainable buildings should consume resources in an efficient manner and impact on the environment minimally. From the various building sustainability rating systems and the guidelines in Table 1, the suggested solutions include the efficient use of energy and water, selection of appropriate materials and products, reuse and recycle resources, optimization of site potential.

As for the social dimension of building sustainability, there is generally less consensus about it as compared to the economic and environmental dimensions (Levett-Therivel Sustainability Consultants 2004). Nevertheless, from the summary of review on the building sustainability rating systems and guidelines in Table 1, an obvious theme emerged. Building users demand quality for their buildings. This means a safe, healthy and comfortable indoor environment. This is supported by Leung et al (2005) where it was found that building users are willing to pay more for the extra indoor comfort they perceived. For example, the authors found from literature reviewed that tenants are willing to pay between US$32.15 to 38.47 more in their monthly rent for the noise level in their houses to be reduced by half. Also, in order to have healthier indoor environment, building users are prepared to pay at least US$17.84 more to reduce the amount of harmful substances in the indoor air. Therefore, socially, a sustainable building has to provide a safe, healthy and comfortable indoor environment.

Table 1: Economic, Environmental, Social and Functional Issues considered some Building Sustainability Rating Systems and Guidelines

	Economic	Environmental	Social	Functional
Building Sustainability Rating Systems				
Leadership in Energy and Environmental Design – Existing Buildings (LEED-EB)	• Innovation in operation, upgrades and maintenance	• Sustainable sites • Water efficiency • Energy and atmosphere • Materials and resources	• Indoor environmental quality	
Sustainable Building Tool (SBAT) (Gibberd 2005)	• Local economy • Efficiency of use • Adaptability and flexibility • Ongoing costs • Capital costs	• Water • Energy • Waste • Site • Materials and Components	• Occupant comfort • Inclusive environments • Access to facilities • Participation and control • Education, health and safety	
Green Mark by the Building & Construction Authority of Singapore (Green Mark for Existing Buildings 2006)	• Building management & operation	• Energy efficient performance • Water efficient performance	• Indoor environmental quality performance & environmental protection	
SINDEX (Langston 2005)	• Maximise wealth (investment returns)	• Minimise resources (energy usage)	• Minimise impact (loss of habitat)	• Maximise utility (functional performance)
Guidelines for Sustainable Building Practices				
7 principles of sustainable construction by the Conseil International du Batiment (Kibert 2005)	• Apply life-cycle costing	• Reduce resource consumption • Reuse resources • Use recyclable resources • Protect nature • Eliminate toxics	• Focus on quality	
6 principles of building sustainability by WBDG Sustainable Committee (2006)	• Optimise operational and maintenance practices	• Optimise site potential • Minimise energy consumption • Protect and conserve water • Use environmentally preferable products	• Enhance indoor environmental quality	

In addition to the three criteria of building sustainability discussed, Langston (2005) suggested a fourth dimension, functional performance which as seen from Table 1, is often not considered by other building sustainability rating systems and guidelines. It is conventionally considered separately under a different field, i.e. building performance. Works related to this field include building performance evaluation such as Preiser & Vischer (2005) and the total building performance concept such as Rush & American Institute of Architects (1986). However, according to the definition of sustainability given in the Bruntland report (see Section 2.2), besides the three core dimensions, sustainability is also about meeting the needs of humans (both present and future). Hence, the inclusion of a functional dimension to building sustainability is logical and makes the approach to achieving building sustainability more holistic and complete.

It should be noted that the four facets of building sustainability are not independent. They are, instead, interlinked and trade-offs exist among them. According to Bakens (2005), there are so far no clear performance indicators for building sustainability. There are unresolved issues about its measurements and the weightings that should be given to each criterion.

Nevertheless, the above discussions have provided a qualitative understanding of the different criteria required of sustainable buildings. In the following section, the impact of building envelope on the sustainability of buildings is examined based on these four criteria of sustainable buildings.

3 IMPACT OF BUILDING ENVELOPE ON THE SUSTAINABILITY OF BUILDINGS

3.1 Building Envelope and its Fundamental functions

The building envelope, according to Brock 2005, is the skin of a building which is supported by the skeleton of the building structure. Elder (2005) describes it generally as the building components that enclose conditioned spaces and through which thermal energy is transferred to or from the outdoor environment. These building components include the external walls, roof, doors and windows (Bolin 2006). The primary function of the building envelope is to provide shelter and security (Brock 2005; Bolin 2006; Leung et al 2005). This means that the building envelope provides solar and thermal control, moisture control, indoor air quality control, fire resistance and acoustic control.

In addition to this fundamental function, there are other requirements of the building envelope. Leung et al (2005) commented that the building envelope should also provide for the psychological needs of the building occupants. It should allow views to the outside and provide sufficient natural lighting so as to avoid the feeling of isolation by the building occupants. Also, the building envelope should possess aesthetic quality in order to project an attractive image of the building (Brock 2005; Bolin 2006; Leung et al 2005). Other requirements of the building envelopes include cost effectiveness (Bolin 2006) and minimum impact on local or global environments (Leung et al 2005).

Hence, it can be seen that, in addition to the provision of physical protection and shelter, it is generally agreed that building envelope can impact on the overall building socially, economically and environmentally, i.e. the sustainability of the building. In the next few sections, the impact is examined in greater details.

3.2 Economic Impact of Building Envelope on Sustainability of Buildings

As discussed, a sustainable building will seek minimum initial and running costs in order to maximize investment returns. The economic impact of building envelope is discussed in two aspects, i.e. the initial costs and the running costs.

The impact of building envelope on the building's overall initial costs is significant. As reported in the Centre for Window and Cladding Technology (1994), the building envelope is the single largest cost in the construction of many buildings.

In addition, the maintenance and operation costs of building envelope can be very substantial. As pointed out by Bourker and Davies (1997) cited in Chew et al (2004), a defective façade system would have a large financial impact on the building's total maintenance costs. There are two main reasons. Firstly, this is partially due to repairs and rectification works to the building envelope being costly. For example, the barriers and retarders between the interior finish and the exterior cladding usually are only a fraction of the overall cost of a building but to repair them when they failed can be very expensive (Brock 205). Beside repair works, rectification works on building envelopes are also costly. This is because general improvements to the building envelope, for example to rectify an acoustic problem, are often not possible or too difficult and expensive to implement after the building envelope has been designed and constructed (Unver et al 2004). Secondly, the incidence of component failure of building envelopes is high since the envelope is subjected to the most wear and tear from the external environment (Stansfield 2001). According to the findings of a survey conducted by the Quality in Traditional Housing reported in Al-Hammad, Assaf, & Al-Shihah (1997), about 50% of the 1000 different kinds of design faults identified were related to the building envelope. This explains why the insurance claims against architects involve the building envelope more often than any other building components as pointed out by Brock (2005). Furthermore, the premature failure of the building envelope can lead damages within the building and hence, incurring more maintenance and operation costs.

The building envelope is also the single largest building element in terms of size. This means it uses the substantial amount of materials and can impact significantly on the sustainability of the buildings, considering the costs associated with embodied energy of the materials. Indeed, as highlighted by Schwartz and Kayll (2005), the costs associated with the use of energy to extract, manufacture, transport, install and dispose of each of the building envelope components are beginning to be included in the life cycle cost analysis as an environmental cost.

Besides impacting on the whole life costs of the building, the building envelope can also influence the investment returns directly. The building envelope projects the image of the building. Thus, its aesthetic quality is of interests to developers as it is believed to contribute to the perceived market value of the building and therefore, contributes to the collective portfolio of the developers (Schwartz & Kayll 2005).

Therefore, it can be seen that the building envelope has significant economic impact on the sustainability of the building. This is supported by the life cycle cost analysis guidelines given by the Stanford University (2005) where the building envelope is classified as an area of high potential cost impact which can provide significant cost savings.

3.3 Environmental Impact of Building Envelope on Sustainability of Buildings

As discussed in Section 2.3, a building that is sustainable aims to reduce resource consumption and environmental deterioration. The building envelope, being the largest-size single building element and the most important parameter of the passive system (Manioglu and Yilmaz 2006) influences significantly on the resource consumption and environmental deterioration by the building.

Being the largest-size single building element, the building envelope uses much material for its different components. The building envelope can help to reduce the building's impact on the environment by recycling. As pointed out by Stansfield (2001), most materials used for the external cladding is recyclable. Hence, building envelope designers can help in achieving building sustainability environmentally by ensuring that each sub-component comprises similar materials so that recycling is easily achieved.

The building envelope is responsible for separating the interior of the building from the external environment. Hence, it is the basic determinant of the indoor climate and consequently, affects the level of supplementary mechanical energy needed

(Manioglu and Yilmaz 2006). One example of how the building envelope can reduce the amount of mechanical energy needed is its thermal control potential. The design of the building envelope can affect greatly the amount of heat entering into and leaving from the interior of the building. The following describes some of the ways of how the building envelope plays an important role in thermal control and hence, subsequently its impact on the overall energy consumption of the building.

The building envelope should use an appropriate system. For example, the application of metal stud framing system on a wall can nearly double the heat loss (Elder 2005).

Also, proper insulation of the building envelope can reduce the cooling energy needed quite significantly. In Cheung et al (2005), it was found that by placing a 100mm thick insulation on the inside of the wall reduces the annual required cooling energy by 19.4 % in a hot-humid climate. In fact, the thicker the insulation added, the greater the reduction in the annual required cooling energy. However, it was also noted that the reduction in energy decreases for every increment in the thickness of the insulation.

The colour of building envelope also affects the solar heat gain and hence the cooling energy consumption of the overall building (Cheng et al 2005). In the study by Cheung et al (2005), it was found that a lighter colour building envelope will lower the solar absorption and that a 30% reduction in solar absorption can achieve a 12.6% savings in the annual required cooling energy.

The glazing system of the building envelope is an area of major heat loss or gain. According to Stansfield (2001), by improving the energy efficiency of the glazing systems will give “large and nearly permanent improvement to the energy efficiency of a building”. In Cheung et al (2005), although the authors did not put up a claim that is as strong as the one by Stansfield (2001), it was found that the glazing system can indeed help reduce the energy consumption. In the study, by replacing the glazing with a single layer Evergreen^{TM} with a reflective coating, it gave a maximum saving of 4.6% in annual cooling energy and 5.4% in peak cooling load.

Another way of which the building envelope can affect the overall energy consumption by the building is through its shading devices. According to Cheung et al (2005), the longer the shading, the greater the reductions in both annual required cooling energy and peak cooking load. However, the law of diminishing returns applies as with the same as the insulation, i.e. the reduction decreases as the length of the shading increases. Nevertheless, it was found that a 500mm overhang can achieve a saving of 100kWh/ year based on the study carried out.

Overall, in the study conducted by Cheung et al (2005), when these passive thermal building envelope design strategies, i.e. insulation, colour, glazing system and shading devices, are implemented together, the annual required cooling energy for the whole flat studied reduced from 2252kWH to 3056kWh, i.e. a saving of 31.4%. There was also a reduction of 36.8% in the peak cooling load from 6.2kW to 3.9kW.

Therefore, it can be seen that the building envelope has significant impact on the overall energy consumption by the building. Beside the potential to improve the energy efficiency of the building, the building envelope can also help in water efficiency. According to Bolin (2006), the building envelope can help in stormwater management. For example, a vegetated roof can be used to capture rainwater. The captured rainwater can be used filtered and then reused for landscape irrigation or toilet flushing. Hence, the building envelope can help improve the water efficiency of the building.

3.4 Social Impact of Building Envelope on Sustainability of Buildings

One of the criteria of sustainable building is to provide a comfortable and healthy indoor environment. Unver et al (2003) define comfort as conditions that allow the users to achieve their activities easily for a long time. The building envelope plays an important role to this as it "acts as a modifier of direct effects of climate variables such as the outdoor temperature, humidity, wind, solar radiation and rain" (Wong 2003). The ways in which the building envelopes affect the indoor environment are discussed in greater details in the following.

The thermo-physical properties of the building envelope determine the indoor temperature to a large extent. For example, the colour of the façade will affect the indoor thermal environment significantly. According to Wong (2003), light-coloured building envelope reflects light better than when it is dark in colour and contributes to lower surface temperature of the façade and thus, maintains a better indoor thermal environment. This is further supported by Cheng et al (2005) in which the results of their study showed that the darker the colour, the higher the maximum temperature and larger the diurnal swings. Another important attribute of the building envelope to the indoor thermal environment is its U-value which measures the transfer of heat through the building envelope. In their study, Oral & Yilmaz (2003) concluded that the U-value of the building envelope together with the building form (which is expressed as the total façade area to building volume) is an important factor influencing heat transfer through the whole building.

Besides impacting on the temperature of the indoor environment, the building envelope can affect the indoor comfort visually. According to Rush & American Institute of Architects (1986), it is important to allow for views to the external and natural lighting in order for the building occupants to feel comfortable psychologically. The building envelope properties such as the direction of façade and its transparency ratio will be important to create visual comfort in the interior of the building (Unver et al 2003).

Therefore, it can be seen that the building envelope can affect the indoor environmental quality of a building and hence affect the sustainability of the building in the social aspects.

3.5 Functional Impact of Building Envelope on Sustainability of Buildings

Being functionally sound is one of the criteria of sustainable buildings. Buildings are created primarily to support the activities of its users. According to Rush & American Institute of Architects (1986), there are 6 performance mandates that a building has to fulfil. They are acoustical performance, thermal performance, visual performance, indoor air quality performance, building integrity performance and spatial performance. These performance mandates are fulfilled through the integration of the various building systems such as the mechanical system, structural system, interior system, etc.

As it functions as a filter to screen out the undesirable environmental elements such as heat, noise, air pollution and electromagnetic radiation, the building envelope can assist or hinder other building systems in fulfilling the overall building performance. As pointed out by Elder (2005), “without a good understanding of how the envelope performs, a complete understanding of the interactive relationships of lighting and mechanical systems cannot be obtained”. Thus, the overall building performance is affected by how the building envelope interacts, integrates and affects other building systems. In Rajagopalan (1999), how a particular building envelope system, metal curtainwall, integrates with other building systems to affect each performance mandate is investigated. The findings are summarized in Table 2.

As seen from Table 2, the building envelope affects each of the performance mandates and hence, is important to the overall functional performance of the building. This view is also echoed by the Centre for Window and Cladding Technology (1994) which remarked that the performance of the building envelope is paramount to achieve a building free of failures. As also highlighted by Kunzel et al (2005), the heat and moisture behaviour of the building envelope is an important factor to the overall performance of the building.

Therefore, the building envelop plays an important role in the fulfilment of the 6 building performance mandates through integration with other building systems.

Table 2: Building Performance Mandates and the various Building Systems (Rajagopalan 1999)

Performance mandates	Building Envelope System	Mechanical System	Interior System	Structural System
Acoustics	X		X	X
Thermal	X	X	X	X
Visual	X	X		
Indoor Air Quality	X	X	X	
Building Integrity	X			X
Spatial	X	X	X	

4 DISCUSSIONS

4.1 Emerging Role of Building Envelope towards achieving Sustainable Buildings

As seen from the in-depth review of the literature above, the building envelopes have significant impact on the 4 criteria of sustainable buildings. Underlying this significant impact is a highly potential building sustainability contributor. The building envelope presents many opportunities to enhance the sustainability of the building. The fundamental role of building envelope as the filter of undesirable environmental elements has to evolve in the recent call for sustainable buildings. The building envelope can play a larger role in enhancing the sustainability of the buildings. Hence, this paper advocates a sustainable building envelope for a sustainable building.

The next section will present the concept of a sustainable building envelope and discuss the ways of achieving one in the bigger context of sustainable building.

4.2 Towards a Sustainable Building Envelope for a Sustainable Building

Following from the discussions in Section 3, a sustainable building envelope can be generally defined as one that contributes to the sustainability of building by maximizing the economic returns, minimizing the negative impact on the environment, maximizing the social benefits and maximizing the functional building performance.

It can be seen that the 4 aspects of sustainable building envelope can be conflicting to one another and trade-offs exists among them. For example, to minimize the impact on the environment, the building envelope can incorporate new technologies such as double façades to reduce the energy consumption by the building. Hence, the environmental impact is minimized. However, these new technologies are generally more expensive to implement. Therefore, the economic return is compromised. Furthermore, to achieve balance among the criteria is not an easy task as each criterion is valued differently by different stakeholders.

Nevertheless, there are some general guidelines on achieving a sustainable building envelope at each stage of its whole for a sustainable building.

The design stage of the building envelope is the most crucial as the decisions make at this stage has paramount influence on the later stages of the building envelope's whole life. For example, Unver et al (2003) highlighted that to decrease artificial lighting energy consumption, the building envelope parameters, direction of the façade and the transparency ratio are important and should be considered at the design stage of the building envelope. Also, Manioglu & Yilmaz (2006) pointed out that in designing the building envelope, it should be remembered that its thermal-physical properties can be used to control the operation period of the heating system.

The design of the building envelope will have impact on the way it is installed and constructed. The design should allow the building envelope components to be assembled in the factory as much as possible. This will enable wastage of resources to be minimized during the construction stage.

The operation and maintenance stage of the building envelope is important as it ensures that the building envelope continues to perform as it is designed for. How the building envelope should be cared for should be considered when designing it.

In summary, a sustainable building envelope should always consider its impact on the four criteria of the building sustainability in all stages of its whole life.

5 CONCLUSION

This paper does not aim to downplay the importance and influence of other building systems on the sustainability of buildings or to disintegrate the building as a product to focus on only the building envelope for achieving sustainable buildings. What it wishes to highlight is the impact of building envelope on the sustainability of buildings and the close connection between a sustainable building envelope and a sustainable building. The literature review conducted has confirmed that the building envelope is a major contributor to building sustainability and presents great opportunities in enhancing the sustainability of buildings.

This paper has also provided a framework based on the four criteria of building sustainability which further research works on sustainable building envelopes can be built upon.

REFERENCES

Abel, C., & Royal Academy of Arts (Great Britain). Summer Exhibition. (2003). *Sky high: vertical architecture*. London: Royal Academy of Arts.

Al-Hammad, A., Assaf, S., & Al-Shihah, M. (1997). The effect of faulty design on building maintenance. *Journal of Quality in Maintenance Engineering, 3*(1), 29.

American Society of Civil Engineers. Committee on Sustainability. (2004). *Sustainable engineering practice : an introduction*. Reston, VA: American Society of Civil Engineers.

Amourgis, S. (2006). Architectural design and passive environmental and building engineering systems. In M. Santamouris (Ed.), *Environmental design of urban buildings : an integrated approach* (pp. 36 - 45). London ; Sterling, VA: Earthscan.

Bakens, W. (2005). Sustainable building and construction: contributions by international organisations. In J. Yang, P. S. Brandon & A. C. Sidwell (Eds.), *Smart & sustainable built environments* (pp. 275 - 288). Oxford ; Malden, MA: Blackwell Pub.

Bolin, R. (2006, 18 May 2006). Sustainability of the building envelope. *Whole Building Design Guide* Retrieved 16 September, 2006, from http://www.wbdg.org/design/env_sustainability.php

Brock, L. (2005). *Designing the exterior wall : an architectural guide to the vertical envelope*. Hoboken, N.J.: John Wiley.

Bueren, E. v. (2001). Sustainable Building Policies: Exploring the Implementation Gap. In N. Maiellaro (Ed.), *Towards Sustainable Building*. Bari: Kluwer Academic Publishers.

Centre for Window and Cladding Technology. (1994). *Facade engineering : a research survey*. Claverton Down, Bath: Centre for Window and Cladding Technology.

Cheng, V., Ng, E., & Givoni, B. (2005). Effect of envelope colour and thermal mass on indoor temperatures in hot humid climate. *Solar Energy, 78*(4), 528-534.

Cheung, C. K., Fuller, R. J., & Luther, M. B. (2005). Energy-efficient envelope design for high-rise apartments. *Energy and Buildings, 37*(1), 37-48.

Chew, M. Y. L., Tan, S. S., & Kang, K. H. (2004). A technical evaluation index for curtain wall and cladding facades. *Structural Survey, 22*(4).

Dewick, P., & Miozzo, M. (2002). Sustainable technologies and the innovation - regulation paradox. *Futures, 34*(9-10), 823-840.

Elder, K. E. (2005). Building Envelope. In W. C. Turner (Ed.), *Energy management handbook* (5th ed., pp. xviii, 856). Lilburn, GA. New York: Fairmont Press; Marcel Dekker.

Erlandsson, M., & Borg, M. (2003). Generic LCA-methodology applicable for buildings, constructions and operation services - today practice and development needs. *Building and Environment, 38*(7), 919-938.

Evangelinos, E., & Zacharopoulos, E. (2006). Sustainable design, construction and operation. In M. Santamouris (Ed.), *Environmental design of urban buildings : an integrated approach* (pp. 63 - 74). London ; Sterling, VA: Earthscan.

Gibberd, J. T. (2005). Developing a sustainable development approach for buildings and construction processes. In J. Yang, P. S. Brandon & A. C. Sidwell (Eds.), *Smart & sustainable built environments*. Oxford ; Malden, MA: Blackwell Pub.

Green Mark for Existing Buildings. Retrieved 15 Dec, 2006, from http://www.bca.gov.sg

Institution of Structural Engineers (Great Britain). (1999). *Building for a sustainable future: construction without depletion*. London: SETO.

Kibert, C. J. (2005). *Sustainable construction : green building design and delivery*. Hoboken, N.J.: John Wiley.

Kishnani, N. (2002). *Climate, Buildings and Occupant Expectations: A comfort-based model for the design and operation of office buildings in hot humid conditions.* Unpublished PhD Thesis, Curtin University of Technology.

Kunzel, H. M., Holm, A., Zirkelbach, D., & Karagiozis, A. N. (2005). Simulation of indoor temperature and humidity conditions including hygrothermal interactions with the building envelope. *Solar Energy, 78*(4), 554-561.

Langston, C. A. (2005). *Life-cost approach to building evaluation*. Amsterdam ; London: Elsevier Butterworth-Heinemann.

Leung, T. M., Chau, C. K., Lee, W. L., & Yik, F. W. H. (2005). Willingness to pay for improved environmental performance of the building envelope of office buildings in Hong Kong. *Indoor and Built Environment, 14*(2), 147-156.

Levett-Therivel Sustainability Consultants. (2004). *Sustainable Urban Environment - Metrics, Models and Toolkits*: sue-MoT consortium.

Lucuik, M., Trusty, W., Larsson, N., & Charette, R. (2005). *A Business Case for Green Buildings in Canada*: Morrison Hershfield.

Manioglu, G., & Yilmaz, Z. (2006). Economic evaluation of the building envelope and operation period of heating system in terms of thermal comfort. *Energy and Buildings, 38*(3), 266-272.

McCreadie, M. (2004). *BRE Subcontract Assessment of Sustainability Tools*: Building Research Establishment Ltd.

Nelms, C., Russell, A. D., & Lence, B. J. (2005). Assessing the performance of sustainable technologies for building projects. *Canadian Journal of Civil Engineering, 32*(1), 114-128.

Oral, G. K., & Yilmaz, Z. (2003). Building form for cold climate zones related to building envelope from heating energy conservation point of view. *Energy and Buildings, 35*(4), 383-388.

Preiser, W. F. E., & Vischer, J. C. (Eds.). (2005). *Assessing building performance*. Oxford: Elsevier.

Rajagopalan, T. (1999). *Performance approach for the Evaluation of Metal Curtain Wall Systems Design.* Unpublished Master Dissertation, National University of Singapore, Singapore.

Raman, M. (2005). Sustainable design: An American Perspective. In B. Kolarevic & A. Malkawi (Eds.), *Performative architecture: beyond instrumentality*. New York: Spon Press.

Roaf, S. (2005). Benchmarking the 'sustainability' of a building project. In W. F. E. Preiser & J. C. Vischer (Eds.), *Assessing Building Performance*: Oxford: Elsevier.

Rush, R. D., & American Institute of Architects. (1986). *The Building systems integration handbook*. New York: Wiley.

Schwartz, J., & Kayll, D. G. (2005). *Building Envelope Performance: What to Expect when You are Expecting.* Paper presented at the 10th Canadian Conference on Building Science and Technology, Ottawa.

Stanford University, L. a. B. (2005). *Guidelines for Life Cycle Cost Analysis*: Stanford University.

Stansfield, K. (2001). Whole-life performance of facades. *The Structural Engineer, 79*(11), 15-17.

Steemers, K. (2006). Integrated builidng design. In M. Santamouris (Ed.), *Environmental design of urban buildings : an integrated approach* (pp. 310 - 318). London ; Sterling, VA: Earthscan.

The Guidelines for Sustainable Buildings. (2002).): Stanford University.

Unver, R., Akdag, N. Y., Gedik, G. Z., Ozturk, L. D., & Karabiber, Z. (2004). Prediction of building envelope performance in the design stage: an application for office buildings. *Building and Environment, 39*(2), 143-152.

Unver, R., Ozturk, L., Adiguzel, S., & Celik, O. (2003). Effect of the facade alternatives on the daylight illuminance in offices. *Energy and Buildings, 35*(8), 737-746.

WBDG Sustainable Committee. (2006). Sustainable. *Whole Building Design Guide* Retrieved 16 September, 2006, from http://www.wbdg.org/design/sustainable.php

Wong, N. H. (2003). *Thermal Performance of Façade Materials and Design and the Impact on Indoor and Outdoor Environment*. Singapore: National University of Singapore.

Yang, J., Brandon, P. S., & Sidwell, A. C. (2005). Introduction - bridging the gaps in smart and sustainable built environments. In J. Yang, P. S. Brandon & A. C. Sidwell (Eds.), *Smart & sustainable built environments*. Oxford ; Malden, MA: Blackwell Pub.

Yeang, K. (2006). Green Design in the hot humid tropical zone. In J.-H. Bay & B. L. Ong (Eds.), *Tropical sustainable architecture : social and environmental dimensions* (pp. xviii, 292). Oxford: Architectural/Elsevier.