International Journal of Sustainable Built Environment (2013) 2, 153–171

Gulf Organisation for Research and Development

International Journal of Sustainable Built Environment

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Original Article/Research

The impact of sustainable building envelope design on building sustainability using Integrated Performance Model

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Received 22 September 2013; accepted 3 March 2014

Abstract

Sustainable design is a design approach put in place to promote the environmental quality and the quality of building indoor environment by reducing negative impacts on building and the natural environment. Also, it is a design philosophy that seeks to incorporate sustainable development concept in terms of initiatives and values into sustainable building envelope design. However, the problem remains as to what constitutes sustainable development concept required for sustainable envelope design. Therefore, this paper is aimed at examining the role of sustainable development concept in sustainable envelope design by investigating the impacts of sustainable envelope design on building sustainability using Integrated Performance Model. This was validated by comparing the energy efficiency performance from selected case studies of buildings with sustainable development concept and building envelope without sustainable development concept. It is expected that the incorporation of sustainable development concept in terms of initiatives and values will enhance the energy performance of building envelopment development and bring about building sustainability.

Keywords: Sustainable; Development; Performance; Building; Envelope

1. Introduction

The concept of sustainable development has evolved greatly since it was introduced by Brundtland Commission in 1987 (WCED, 1987). Now it is being used for various purposes in the society by professional. In the process of this development, different meanings have been used to define sustainable development concept. In all, there is a consensus that the environment, society and economic are the important factors for achieving sustainable development concept. Yet the concept of sustainable development is still unclear and difficult to understand. Many dimensions have been attributed to sustainable development concept and sustainable building design (Lombardi, 1999; Ding, 2005). The idea of sustainable development concept was discussed at United Nation Conference on environment and development held at Rio de Janeiro in 1992 (UNCED, 1992; Hughes, 2000). The Summit was the first international conference attended by world leaders on environmental issues to promote international cooperation for global agreements and partnerships for environmental protection (Harding, 1998). As such, numbers of important conclusions were reached at the summit and the Rio declaration where they highlighted 27 strategies

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Peer review under responsibility of The Gulf Organisation for Research and Development.

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2212-6090
http://dx.doi.org/10.1016/j.ijsbe.2014.03.002

for achieving sustainable development goal. In spite of this discussion and international deliberations, the concept of sustainable development is still complex, multi-dimensional and ambiguous to understand within the context of just environmental issues (Lombardi, 1999; Ding, 2005). There is still a challenge of defining what actually constitute sustainable development concept and values that can be used for sustainable design and assess the sustainable performance of the building envelope. Therefore, it is necessary to examine the role of sustainable development concept in sustainable envelope design by investigating the impacts of sustainable envelope design on building sustainability.

2. The role of sustainable development concept in sustainable enveloped design and building sustainability

The concept of sustainable development has been analysed in theory and application from different perspectives (Dasgupta, 2007; Tvaronavicius and Tvaronaviciene, 2008; Sobotka and Rolak, 2009). Zavadska and Antucheviciene (2006) defined sustainable development as "a set of indicators in the multi criteria analysis to include environmental, social and economic aspects of sustainability". Burinskiene and Rudzkiene (2007) provides information dealing with economic, ecological and social components of sustainable development with analysis focusing on the aggregated indicators on air pollution variation, income, energy consumption and selected social indicators. In their analysis, there exists the recognition for sustainable development with aggregated indicators (Roome, 2001; Schaltegger and Synnestvedt, 2002; Li et al., 2009). One of the important goals of sustainable development is to reduce the impacts of building development on the environment. Burinskiene and Rudzkiene (2007) explained the association between the increase in the economic efficiency and decrease in the environmental impact. One of the key indicators that reveal economic efficiency is the amount of energy consumed for production. The previous studies confirmed the causality between energy consumption and changes in socio economic structures (Schaltegger and Synnestvedt, 2002; Rutkauskas, 2008). Also, Stefan and Drago (2011) analyse structural indicators of economic efficiency and energy intensity as determinants of sustainable development for the selected 33 European countries. This means that the goal of sustainable development can be achieved through the combination of energy efficiency and economic efficiency. Recently, the concept of sustainable development has emerged as a new framework for achieving the sustainable development goal in building development and construction industries (Ding, 2005). The concept promotes the balance of economic, social and ecological systems for any development (Ding, 2005). It is firmly established in government policies, legislation and in most private organisation environmental policies (Harding, 1998). According to Cooper (2002) sustainable refers to as "capable of being maintained indefinitely within limits while development means the pursuit of continuous growth". This assertion contradicts the present scenario as most developments tend to destroy sustainability. However, Ofori et al. (2000) argued that as long as development continues to take place in the society, the economic growth and environmental issues will continue to be major issues for sustainability. Besides, Boughey (2000) argued that sustainability indicates economic growth which could continue without long time damage to the natural environment or general human well-being. This viewpoint indicates that economic growth will continue to thrive while the environment will never be deprived, or used, at all. However, it is highly unlikely that this will happen as economic growth requires the consumption of environmental resources to sustain its activities. In spites of all these views, the most recognised definition for sustainable development concept came from Brundtland Commission report on the environment and development conference held at Rio de Janeiro in 1992 (UNCED, 1992; WCED, 1987). Sustainable development concept was defined as "development that meets the needs of present generations without compromising the ability of future generations to meet their needs and aspirations" (UNCED, 1992; WCED, 1987). The four aspects as emphasised in the report are to: eliminate poverty and deprivation; to conserve and enhance natural resources; to encapsulate the concept of economic growth, social as well as cultural variations into a development; and finally, to incorporate economic growth and ecology into decision making. Thus suggests that many factors are involved in achieving the sustainable development goals. HKU (2010) describes environmental sustainability as ecosystem integrity and bio diversities, economic sustainability centred on growth, development, accessibility, stability and equity, while social sustainability centred on community wellbeing. Lautso et al. (2004) emphasises the environmental sustainability, economic efficiency and social sustainability as central to comprehensive sustainable development. It means that sustainable development deals with the concepts of environment, futurity and equity, with the emphasis that the welfare of future generation must be considered in any decision making process. However, economic growth with an emphasis on aspects such as financial stability and material welfare creation is the ultimate goal to secure rising standards of living and increase the capability of providing goods and services to satisfy human needs. Furthermore, in order to achieve sustainable development, emphasis must be placed on energy and material efficiency (Dincer and Rosen, 2007), Just as the importance of efficient use of energy and resources to sustainable development and the society has been stressed (Goldemberg et al., 1988; MacRae, 1992; Dincer and Rosen, 2007). This means sustainable development does not just require that energy resources be made sustainable, but that they should be used efficiently. This shows the need to incorporate energy and resource efficiency into sustainable development of building envelope to ensure building sustainability. In spite of a different meaning ascribed to sustainable development, the concept has been widely accepted as the basic concept for sustainable design. Therefore, for the building envelope to be sustainable, important sustainable development factors such as ecological, energy, economic, social and environmental factors as discussed in this section must be considered.

2.1. The principles and philosophies of sustainable design

The designing of sustainable building that meets all sustainable requirements is often a challenge to the building professionals and building designers (WBDG, 2011a). In order to incorporate sustainable development concept into building envelope design, it is important that all stakeholders be involved in the sustainable building envelope design. Successful design of sustainable envelope must consider all competing sustainable development factors in order to achieve the goal of building sustainability. The problem of building sustainability in construction industry can be solved if the concept and principle of sustainable development were taken into consideration at early stage of building design (Baragatti, 2004; De Dico, 2005; Mohammed and Iqbal, 2005). Therefore, effort to achieve building sustainability through sustainable building envelope design should not be concentrated only on building performance assessment methods but also on the building envelope design types (Al-Hammond et al., 2007). Hence, the future of building development and its surrounding environment depend on the level of sustainable development initiatives and principles of sustainable practise incorporated into building envelope. Furthermore, sustainable design is a design approach put in place to promote the environmental quality and the quality of building indoor environment by reducing negative impacts on building and the natural environment (McLennan, 2004). Also, it is a design philosophy that seeks to improve building indoor comfort conditions and incorporate sustainability initiatives into building envelope design. According to McLennan (2004) the strategies involved in sustainable design include day-lighting, indoor air quality, passive solar heating, natural ventilation, energy efficiency, embodied energy, construction waste minimisation, water preservation and renewable energy. In addition to the above mentioned sustainable design strategies, McLennan (2004) suggested six (6) important principles of sustainable design that can be applied to sustainable building envelope design such as the Biomimicry Principle which emphasised learning from natural systems which means learning from nature; the Human Vitality Principle which promotes the need to respect people; the Ecosystem Principle which emphasises respect for place, the Seven Generations Principle which emphasises the respect for future; the Conservation Principle promotes the need to respect energy and natural resources and the Holistic Principle that is based on system thinking (McLennan, 2004). Therefore, sustainable design approach is a concept of sustainable development that seeks to ensure environmental quality, efficient use of resources such as efficient use of energy, water and material. The approach can be integrated into the four core processes of construction towards achieving sustainable construction. Moreover, the issue of sustainable development in building envelope was further explained in four interrelated areas of sustainable development such as the environment, equity, participation, and futurity as shown in Fig. 1. This issue was deliberated on at the Earth Summit held in 1992 at Rio de Janeiro in Brazil. The twenty-seven (27) principles highlighted for sustainable development practises were based on these four interrelated areas of sustainable development as shown in Fig. 1 (Jorge and Alberto, 2010).

These four interrelated areas were defined based on their implications for sustainable development. These include:

- Futurity principle emphasises intergenerational equity and the need to minimise environmental resources for future generation through resources recycling and reviewable process.
- Public participation is an important strand that defines sustainable development and its role in influencing sustainable design decisions. It involves the participation of building and construction expert in sustainable devolvement decision making.
- Environment emphasised the preservation of ecosystem, energy conservation and resources conservation for future building and envelope development.
- Equity promotes equality between the present generation and future generation by ensuring equal access to natural and environmental resources.

The theory illustrated in Fig. 1 explains the sustainable development principles that can be incorporated into sustainable envelope design and assessment. This explains the connection between sustainable development values that comprises sustainable principles, sustainable design strategies, sustainable envelope design and building sustainability. This connection requires balancing all the sustainability factors such as economic, energy, environment, social etc. for building envelope sustainable design decisions (Department of Trade and Industry, 2006). Thus suggests the need to examine the sustainable practises and strategies for achieving sustainable design for building sustainability in construction industry.

2.2. The interactions and connections between sustainable building envelope design and building sustainability

In an effort to analyse the influence of building envelope design on building sustainability, it is important to address the fundamental role of sustainable development concept in building sustainability. Building envelope is the main component in building responsible for building ability to protect the indoor environment from external environmental impacts. It is the interface between the external environment and indoor environment. Building envelope protects the indoor environment, comfort conditions against

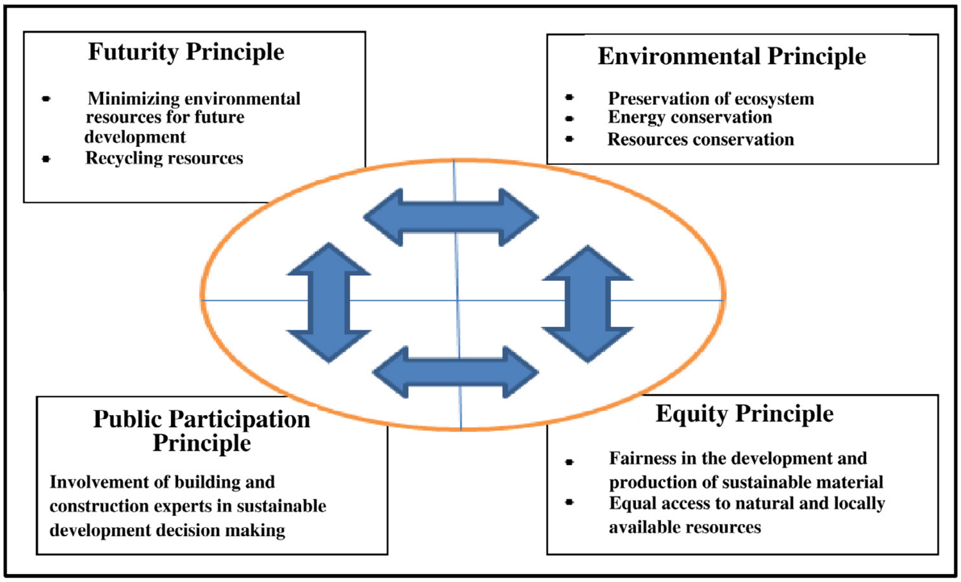

Fig. 1. Modified model of sustainable development for building envelope.

adverse environmental effects and subsequently regulates energy consumption, resource consumption and environmental degradation (Irene and Robert, 2007). Apart from its protective and regulatory functions, building envelope controls solar and thermal flow, as well as moisture flow in and out of the building. It also controls the indoor air quality, fire, wind, rain and acoustic effects on building. This suggests the need to make building envelope sustainable as an alternative approach for achieving building sustainability through sustainable envelope design. However, there is a need to look into the impacts of environment on building envelope as related building sustainability. Fig. 1 explained the principles and requirements for building envelope sustainable performance and building

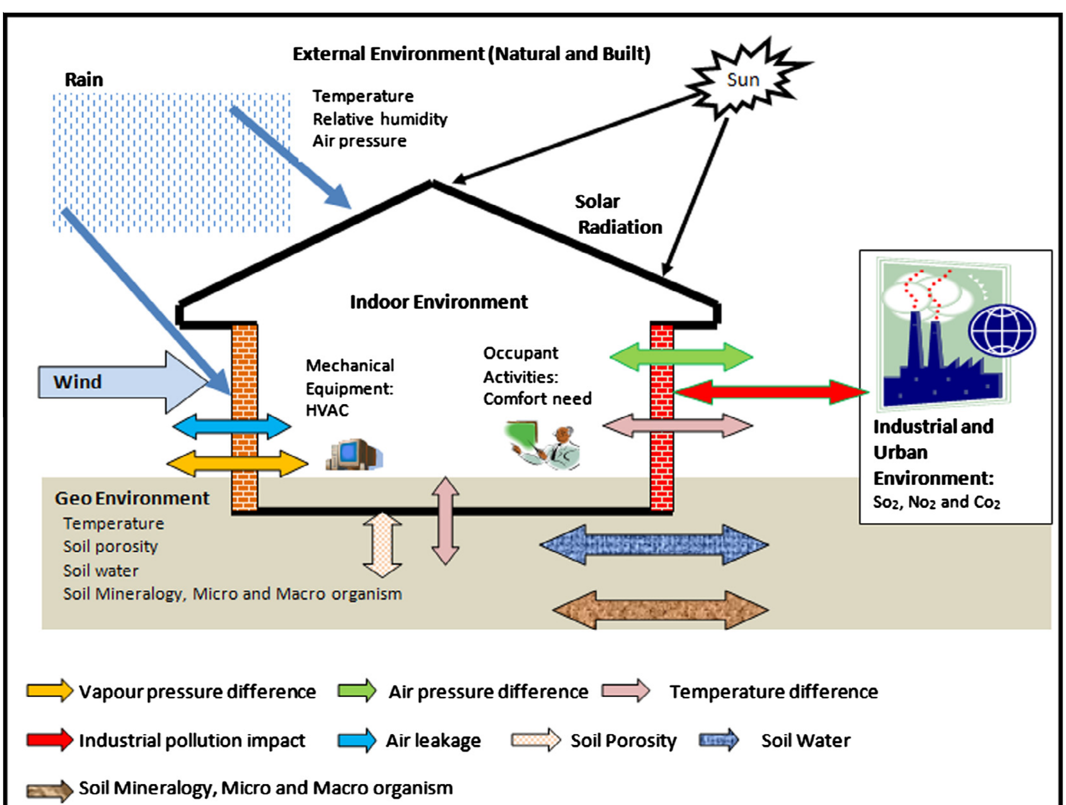

Fig. 2. Environmental loads on building envelope.

sustainability. More specifically, the Fig. 2 illustrates the regulatory and protective functions of building envelope in building. These regulatory activities of the building envelope help to achieve building sustainability. Building envelope protects the building against environmental impacts such as wind, rain, temperature difference; vapour pressure difference, industrial pollution, solar radiation and soil temperature (Green Building, 2011). Environmental impact is an important sustainability factor that influences other sustainability factors such as energy efficiency, material efficiency, and external benefit of building in terms of comfort conditions.

Also, shown in Fig. 2, building envelope provides regulatory functions such as thermal control, moisture control, and indoor air quality control against the environmental impacts on the building system thereby protecting the indoor environment of building (WBDG 2011a; NIBC, 2009). Besides, in the process of carrying out these functions against environmental impacts, building envelope interacts with three parts of building. The three parts of building include: exterior environment, interior environment and the envelope system itself (Hegger et al., 2008; Cyberparent, 2011). These three (3) parts interact with the physical system of building in the process of separating the interior environment from the exterior environment (Green Building, 2011). As potential line of defence against environmental impacts which influences other sustainability factors, it is important to make building envelope sustainable. This requires being able to assess the sustainable performance of the building envelope in terms of sustainable development criteria and principles stated in Fig. 1 using appropriate assessment method. However, there is need to incorporate life cycle assessment mechanism into the existing assessment methods for important life cycle parameters' assessment such as embodied energy, life cycle cost etc. in order to undertake the sustainable performance assessment and design of the building envelope. Moreover, the aim of making building envelope sustainable is to reduce building resource consumption and environmental degradation. Being the largest component of building, building envelope influences building resource consumption and environmental degradation (Manioglu and Yilmaz, 2006). As highlighted by Stansfield (2001) building envelope can help in achieving building sustainability by reducing environmental impacts on building as well as building impacts on the environment. Also, according to Manioglu and Yilmaz (2006) building envelope reduces the level of supplementary mechanical energy needed in building being the barrier between the interior of building and the external environment and main determinant of indoor climate. Thus shows that there is a significant environmental impact on building envelope that can influence building sustainability. Also, building envelope provides indoor conditions suitable for human activities (Yeang, 2006; Lucuk et al., 2005) and protects building against undesirable external and internal impacts such as pollution, climate change, temperature, humidity, HVAC load, lighting load etc. as illustrated in Figs. 2 and 3. Moreover, achieving building sustainability is a major challenge for building industry in view of many factors influencing building sustainability as shown in Fig. 3. Apart from external and internal environmental factors which had significant impacts on building sustainability, other factors influencing building sustainability include: building envelope, thermal processes, building elements and material properties.

In all, building envelope design through an appropriate assessment method plays a major role in building sustainability since it regulates all other factors including building element performance, thermal processes, transmission processes and material properties shown in Fig. 3. Being the first line of defence against the undesirable environmental impacts on building and the impact of building on the environment has necessitated the need to make building envelope sustainable. As such, an Integrated Performance Model (IPM) was developed to assess the sustainable performance of the building envelope towards creating sustainable envelope design that can achieve building sustainability (Iwaro et al., 2012, 2013). Besides, recognising the significant of the sustainable building component design to building sustainability has led to the development of many assessing methods for sustainability assessment in building (Roderick et al., 2009; Reed et al., 2009). Assessment methods such as building performance assessment methods play a major role in sustainable performance assessment and sustainable building design. The major ones among them include Building Research Establishment Environmental Assessment Method (BREEAM) developed in 1990 for UK building and construction industry. This was the pioneer of all other building performance assessment methods developed by countries till today and the most widely recognised method for sustainable design rating and sustainability assessment (Larsson, 1998; Ding, 2008; Reed et al., 2009). The method uses credit awards system and it has been regularly updated to include assessment of buildings such as existing offices, supermarkets and industrial buildings (Yates and Baldwin, 1994; Crawley and Aho, 1999; Lee, 2013). Since then, there are growing interests in the development of building performance assessment methods all across the world. Thus led to the development of High Environmental Quality (HQE) in 1996; Leadership in Energy and Environmental design (LEED) in 2000; CASBEE (Japan) in 2001; Green Globe (Canada) and Green Star (Australia) in 2002, LEED (India) 2005; GBC (Poland) and LEED (Emirates) in 2006; Green Star (South Africa) in 2007; BREEAM (Netherlands) and LEED (Brazil) in 2008 (Reed et al., 2009). However, even though many methods have been launched, Studies have shown that there is need to incorporate important sustainability factors such as such as economic, social and environmental as well as comfort. These are the significant parameters required for building sustainable performance assessment and design (Soebarto and Williamson, 2001; Ding, 2004, 2008; Sinon, 2010). Besides, while building sustainability continue to be a major

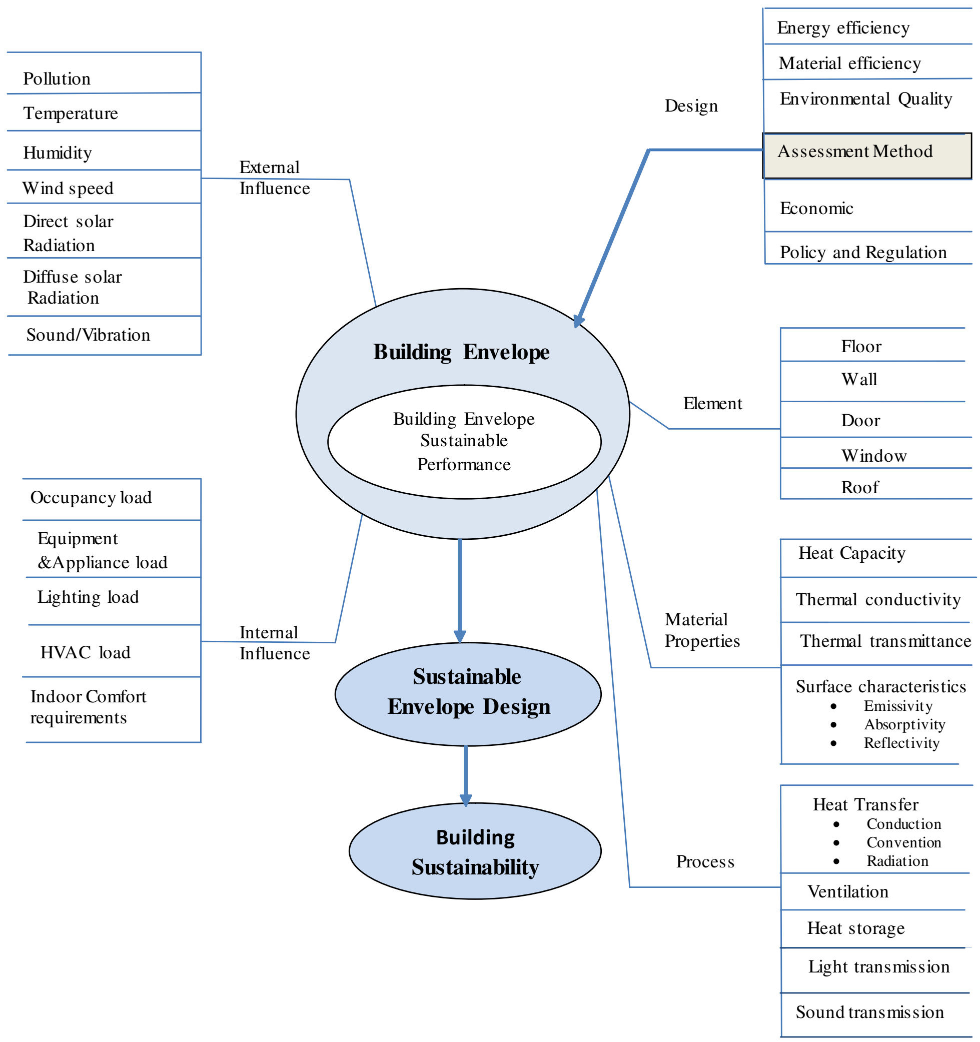

Fig. 3. The connection between building envelope and building sustainability.

concern of professionals in the building industry (Holmes and Hudson, 2000, 2002; Segnestan, 2002; Myers et al., 2008; Reed et al., 2009; Pinter et al., 2010, WBDG, 2011), there has been little focus on the potential and sustainable performance of building envelope. Moreover, due to regional variation, the existing assessment methods may not be applicable for other regions with different climatic conditions and geographic areas such Trinidad and Tobago and the Caribbean. This indicates the need to develop a new comprehensive and integrated approach that can assess the sustainable performance of building envelope as an important step in sustainable envelope design and achieving building sustainability.

3. Brief description of the Integrated Performance Model

The Integrated Performance Model (IPM) is a residential building envelope sustainable performance assessment method and sustainable design rating system. The IPM was developed by Iwaro and Mwasha (2011b) and Iwaro et al. (2012, 2013) for residential building envelope to fill the gap between existing building performance assessment methods and the current demand for building sustainability in Trinidad and Tobago. The Model was developed to integrate sustainable performance values into a single framework. The IPM's framework combined four major evaluation frameworks such as Life Cycle Cost (LCC), Life Cycle Assessment (LCA), Life Cycle Energy Analysis (LCEA) and Multi Criteria Analysis (MCA). The IPM framework was developed based on six (6) major sustainable performance criteria: economic efficiency, material efficiency, external benefit, regulation efficiency, energy efficiency, and environmental impact and fifty-seven (57) sub criteria identified for this study. The process of selecting sustainable envelope design alternatives starts with the definition of envelope design requirements based on the input from policy makers and building stakeholders, such as client, builder, engineer and architect etc. This input is used to define the criteria to be evaluated and identified design alternatives. Also, an integrated framework was developed for the sustainable envelope design problem since the sustainable performance assessment of building envelopes involves considering many sustainability factors. As such, the framework quantifies life cycle performance data for energy efficiency through Life Cycle Energy Analysis (LCEA) sub index, material efficiency, regulation efficiency, environmental impact and social impact criteria through Life Cycle Impact Assessment (LCIA) sub index and economic efficiency performance data through Life Cycle Cost Analysis (LCCA) sub index in IPM. These modelling processes as described above are illustrated in the model flow chart shown in Fig. 4. The performance values derived from these sub-indexes are transferred to Integrated Performance Index to generate sustainable performance values for the envelope alternatives. The envelope alternatives are to be assessed based on the overall sustainable performance values. However, the above process requires computing weight for each criterion to be used for the sustainable performance assessment. The Weight is computed through Criteria Relative Important through Objective Rating Technique (CRITORT) (Iwaro et al., 2013). CRITORT was used to generate objective weight for the criteria based on the performance information from the criteria. Also, the sustainable performance values generated through Integrated Performance Index for the criteria were used to compute the overall sustainable performance value for each alternative under consideration.

3.1. Development of an Integrated Performance Index (IPI)

In addition to the above modelling processes shown in Fig. 4, the Integrated Performance Assessment Matrix (IPAM) was used to assess the overall sustainable performance of each alternative in order to select the most sustainable envelope alternative with highest overall sustainable performance value. The Integrated Performance

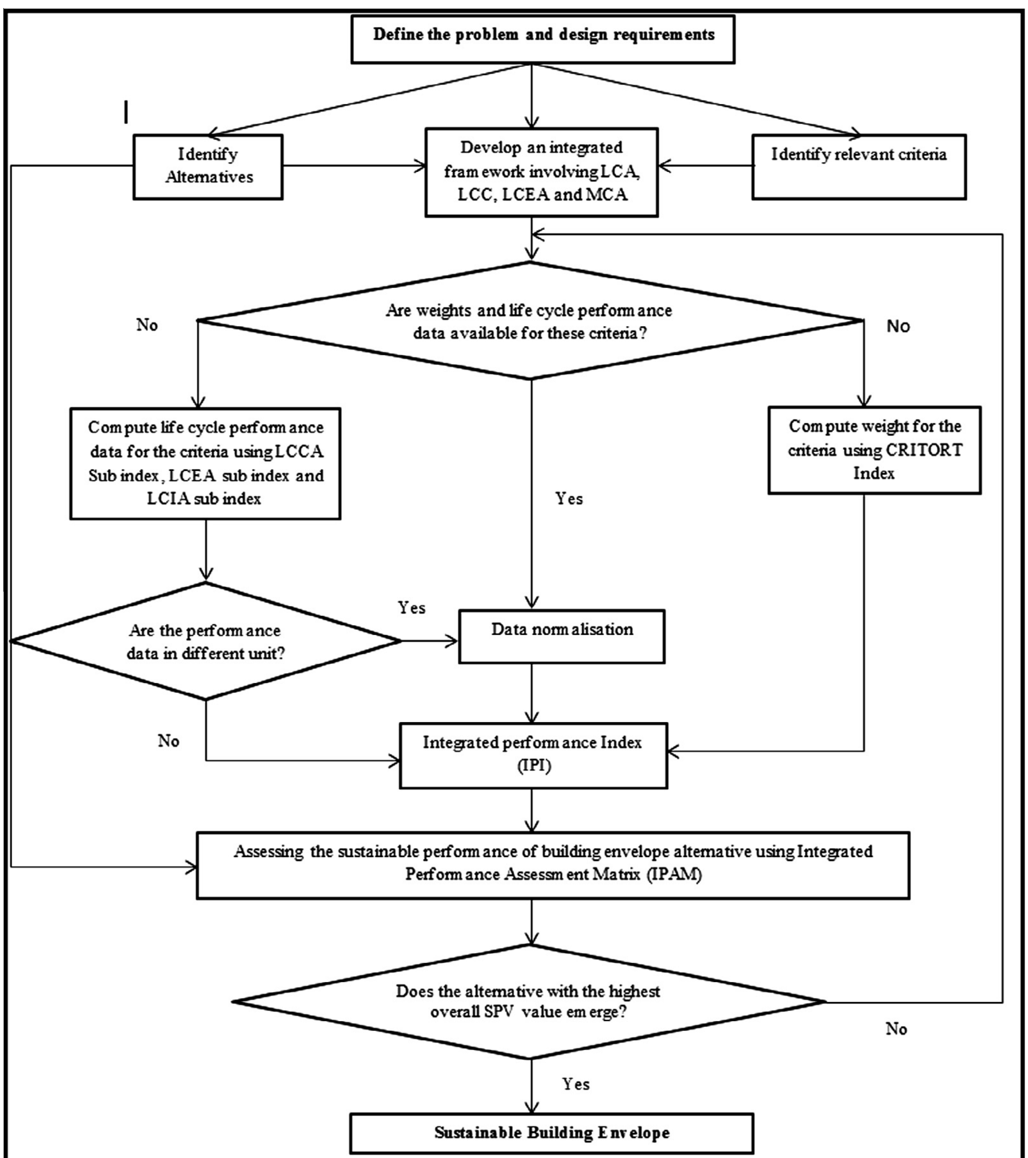

Fig. 4. Model flow chart.

Index (IPI) was developed by combining all the sub-indexes developed to estimate criteria performance values and sub-indexes developed to compute weight for the criteria (Iwaro and Mwasha, 2011b; Iwaro et al., 2012, 2013). The computation of Sustainable Performance Value (SPV) for each envelope alternative was done through IPI incorporated into IPAM as shown in Table 1. The IPAM is a multi-criteria evaluation matrix where the actual sustainable performance assessment of envelope design alternative is done. The sustainable performance assessment of the envelope was done by applying the weights (W_T) generated from weighting method to the normalised criteria performance values (P) generated from the criteria performance sub-indexes. Hence, the Sustainable Performance Value (SPV) for building envelope design alternatives is modelled using IPI index through equation 1.

$$\mathrm{IPI}_i = \sum_{j=1}^{n} P_{ji} W_{Tj} \quad (1)$$

Where $P_{ji} = f$ {EC, EN, ME, EI, EB, RE} ($j = 1,2,3 \ldots n$)($i = 1,2,3 \ldots$,m), EC – Economic Efficiency, EN – Energy Efficiency, ME – Material Efficiency, EI-Environmental Impact, EB – External Benefit and RE – Regulation Efficiency. Also, $\mathrm{IPI_i}$ denotes the Integrated Performance Index for envelope design alternatives as denoted by i. Also, W_{Tj} stands for the weight for each criterion j, while P_{ij} represents the Life cycle performance values computed for envelope design alternatives, i based on the criteria performance values j. This means that the higher the value of P_{ji} and W_{Tj} the better is the sustainable performance of that alternative. Also, the higher the overall sustainable performance value from the IPI index, the more sustainable is the alternative as shown in Table 1.

4. Model application using a case study of a single family residential building envelope

The model application was carried out by applying it to case studies of building envelope designs developed for a residential building project. The case studies show the realistic scenario of a sustainable building envelope selection problem. The proposed sustainable building envelope design was meant for the Housing Development Corporation (HDC) single family units' project to be located at Union Hall, San Fernando, Trinidad and Tobago. The Ministry of Housing and Environment (MOHE), Trinidad and Tobago has initiated a project on designing sustainable building envelope. The design for single family residential units specifies that the envelope should be sustainable, able to withstand extreme weather and climate conditions and ensure energy efficiency. Like in Trinidad and Tobago, the temperature condition could be as high as 37 °C which is an extreme weather condition. Furthermore, major consideration should be given to cost efficiency. As such, three different building envelope design alternatives were proposed for MOHE from which one is selected for this single family unit's project. Therefore, in order to address the challenge of sustainability, the Integrated Performance Model was used to appraise the sustainable performance of these three proposed envelope designs. This facilitates the selection of the best sustainable envelope design alternative that satisfies the clients' needs. Table 2 shows the major elements of the building envelope and summaries of the material used for the building envelope design alternatives.

4.1. Data quantification and modelling for IPM application

Based on the literature reviewed and the outcome from the sustainable performance criteria survey conducted by Iwaro et al. (2011), where six main criteria and 57 sub criteria were identified for the sustainable performance assessment of the building envelope. Moreover, the computation of weights for decision making criteria requires that weight be computed for decision making criteria using Criteria Relative Important Through Objective Rating Technique (CRITORT) index (Iwaro et al., 2012, 2013). As such, the life cycle performance data were normalised into a common dimensionless unit since they were assessed in different units while the resulting statistic data were used for the weight modelling. The weights computed for each main criterion are depicted in Tables 3–5.

Table 1
Integrated Performance Assessment Matrix (IPAM).

	Alternative A		Alternative B		Alternative C		
	PV	SPV using IPI	PV	SPV using IPI	PV	SPV using IPI	Integrated Weight, W_T
Decision making criteria	P1	SPV_1	P1	SPV_1	P1	SPV_1	W_{T1}
	P2	SPV_2	P2	SPV_2	P2	SPV_2	W_{T2}
	P3	SPV_3	P3	SPV_3	P3	SPV_3	W_{T3}
	P4	SPV_4	P4	SPV_4	P4	SPV_4	W_{T4}
	P5	SPV_5	P5	SPV_5	P5	SPV_5	W_{T5}
	P6	SPV_6	P6	SPV_6	P6	SPV_6	W_{T6}
Overall sustainable performance value (OSP)	A=	OSP	B=	OSP	C=	OSP	

PV: performance value, SPV: sustainable performance value.

Table 2
Summaries of material and envelope elements used for the proposed building envelope design alternatives.

Envelope elements	Material used		
	Alternative A	Alterative B	Alternative C
Roof frame	Timber frame	Steel frame	Steel frame
Roof finishes	Red clay roof tiles	Corrugated galvanised aluminium roofing	Galvanised aluminium roofing sheet
External wall	4″ × 8″ × 12″ thick hollow vertical core concrete block with 1/2” reinforcement	4″ × 8″ × 12″ thick hollow horizontal core clay block with 1/2” reinforcement	6″ × 8″ × 12″ thick hollow vertical core concrete block with 1/2” reinforcement
External wall finishes (wall insulation)	12 mm plastered (both sides) with ceramic wall tiles for bathrooms	12 mm plastered and painted both sides with ceramic wall tiles for bathrooms	12 mm plastered and painted both sides with ceramic wall tiles for bathrooms
Windows	Sliding Aluminium glazed window (4″ × 4″) and 4″ Louvred windows with solar shading and side fins	4′ louvred windows with glazing and Aluminium casement glass window with solar shading and side fins	Steel casement french type glazed windows (4 × 4), steel casement type glazed window (2 × 4) with solar shading and side fins
External doors	Aluminium panel filled with Styrofoam; Hardwood patterned door	Hardwood framed and glazed panelled doors; Panel wooden door	Steel panel door with steel framework
Floor	3000PSI concrete structure- 65BRC. 100 mm thick reinforced concrete slab overlay	3000PSI concrete structure- 65BRC. 100 mm thick reinforced concrete slab overlay	3000PSI concrete structure- 65BRC. 100 mm thick reinforced concrete slab overlay
Floor finishes	1” thick ceramic tiles (12″ × 12″)	Terrazzo tiles (12″ × 12″) 1″ thick ceramic tiles (12″ × 12″)	(12″ × 12″) Floor Wood tile
Ceiling	Suspended Acoustic ceiling boards; low sheen emulsion paint to ceiling	Suspended wood tile ceiling	Suspended gypsum ceiling boards
Envelope gross floor area (M^2)	70.0	78.1	81.5

4.2. Life cycle performance modelling of sustainable building envelope design alternatives

In an effort to compute life cycle performance value for decision making criteria shown in Table 5, their life cycle performance data were obtained through IPM life cycle modeling. This involved modelling life cycle performance for each sustainable envelope design alternative based on the main criteria and sub criteria incorporated into IPM. The following sub-indexes incorporated into IPM index as detailed in Iwaro et al. (2012, 2013) were used: Life Cycle Cost Analysis (LCCA) sub index, Life Cycle Energy Analysis (LCEA) sub indexed, Life cycle material analysis (LCMA) sub index, Life cycle Benefit Analysis (LCBA) sub index, Life Cycle Environmental Impact Analysis (LCEIA) sub index and Life Cycle Regulation Analysis (LCRA) sub index. Consequently, the life cycle performance assessment questionnaire was developed to measure the life cycle performance of subjective criteria such as external benefit, material efficiency, subjective component of energy efficiency criteria, subjective component of environmental impact criteria and subjective component of regulation efficiency criteria under each envelope design alternative. Also, there was direct measurement of life cycle performance for objective criteria using GraphiSoft Eco Designer computer simulation software (GraphiSOFT, 2013). It is a technology developed to perform reliable energy evaluation of BIM model within ArchiCAD based on BIM geometry analysis and accurate hour by hour weather data of the building's location. The criteria involved in this category included objective components from energy efficiency, environmental impact and regulation efficiency criteria. In this case of economic efficiency criteria, the envelope alternative's life cycle cost was modelled using life cycle cost analysis index. As such, the life cycle cost for the three building envelope sustainable designs were assessed for the proposed Housing Development Corporation (HDC) single family units to be sited at Union Hall, San Fernando, Trinidad by the Ministry of Housing and Environment. The life cycle cost performance data obtained are presented in Table 6.

Moreover, in an effort to model the life cycle energy efficiency performance of the three envelope designs, GraphiSoft Eco Designer computer software was used to simulate the operational energy consumption of the proposed sustainable designs for the HDC's buildings. This helps to forecast the average household electricity consumption. The data obtained from these simulations are presented in Table 7 while the simulation results from Eco Designer were compared with the actual electricity consumption from a private single family residential home selected from the St. Augustine, north area of Trinidad. The life cycle energy performance modelling for sustainable envelope design alternatives involves modelling the initial embodied energy, recurrent embodied energy, operation energy, and demolition energy using life cycle energy analysis index (Iwaro et al., 2012, 2013). The initial embodied energy was modelled for each envelope alternative based on

Table 3
Statistical variance of the main criteria life cycle performance data.

Main criteria	Alternative A	Alternative B	Alternative C	R_{ij}
$[P_{ij} - (P_{ij})_{mean}]^2$				
External benefit	0.000000	0.000004	0.000009	4.3×10^{-6}
Energy efficiency	0.000049	0.000001	0.000049	3.3×10^{-5}
Environmental impact	0.000004	0.000001	0.000004	3.0×10^{-6}
Material efficiency	0.000009	0.000001	0.000004	4.7×10^{-6}
Regulation efficiency	0.000009	0.000001	0.000009	6.3×10^{-6}
Economic efficiency	0.000004	0.000001	0.000004	3.0×10^{-6}

m is number of alternative = 3, R_{ij} = statistical variance.

Table 4
Statistical variance entropy of the main criteria.

Main criteria	R_{ij}	In R_{ij}	$-(R_{ij}$ In $R_{ij})$	E_j
External benefit	4.3×10^{-6}	−12.357	0.000053	2.958E-05
Energy efficiency	3.3×10^{-5}	−10.319	0.000341	1.903E-04
Environmental impact	3.0×10^{-6}	−12.717	0.000038	2.121E-05
Material efficiency	4.7×10^{-6}	−12.268	0.000058	3.237E-05
Regulation efficiency	6.3×10^{-6}	−11.975	0.000075	4.186E-05
Economic efficiency	3.0×10^{-6}	−12.717	0.000038	2.121E-05

E_j = statistical variance entropy, n is number of criteria = 6.

Table 5
Computation of the objective weights, Wo for decision making criteria.

Main criteria	E_j	$1-E_j$	Objective Weight, Wo
External benefit	2.958E-05	0.99997	0.166671
Energy efficiency	1.903E-04	0.99981	0.166644
Environmental impact	2.121E-05	0.99998	0.166673
Material efficiency	3.237E-05	0.99997	0.166671
Regulation efficiency	4.186E-05	0.99996	0.166669
Economic efficiency	2.121E-05	0.99998	0.166673

coefficient of embodied energy and quantity of building envelope material used. Also, the recurrent embodied energy was modelled based on the initial embodied energy while demolition energy was modelled based on the initial embodied energy as obtained from parametric study conducted for this study. Besides, the annual operation energy was quantified for envelope design alternatives using GraphiSoft Eco Designer computer simulation software. This simulated energy consumption was imputed into life cycle energy analysis index to model the life cycle operation energy. The energy consumed by buildings in running their daily operation is referred to as operational energy such as cooling, heating, appliances etc. Since building envelope is the major component of building, the energy consumed by building in running its operations is also applicable to building envelope. As such, the life cycle energy performances of the three building envelope sustainable designs were assessed. The data obtained from these assessments and simulations as presented in Table 7 indicated that envelope alternative B recorded the highest electricity consumption per gross floor area of 69.654 kWh/m^2. It means that it has the lowest energy performance in terms of energy efficiency when compared to other envelope design alternatives.

4.3. A typical private single family residential building at St. Augustine area of Trinidad

To validate the simulated results from the three building envelope designs proposed for the HDC's one storey single family units in Union Hall with actual data, a typical private single family residence was selected at the St. Augustine area of Trinidad. The electricity consumption data were collected from this building through daily metre reading for one week and projected per annum. Hence, the electricity consumption estimated for the private single family residential home was 4896 kWh/yr as shown in Table 8. The results of the simulation conducted for the three building envelope design alternatives in Table 7 were 4757 kWh/yr for alternative A, 5440 kWh/yr for alternative B and 5612 kWh/yr for alternative C. These results were fairly comparable to actual electricity consumption of 4896 kWh/yr obtained in Table 8. The external environmental and climatic conditions for St. Augustine and San Fernando areas of Trinidad are the same.

The simulated energy consumption for alternative A was 4757 kWh with percentage variation of 2% lesser than the actual energy consumption value of 4896k Wh/yr. The simulated energy consumption for alternative B was 5440 kWh with percentage variation of 10% higher than the actual energy consumption value of 4896 kWh/yr. Likewise, energy consumption for Alternative C was 5612 kWh with percentage variation of 12% higher than the actual energy consumption value of 4896 kWh/yr. These values were considered comparable while the percentage variations could be attributed to some default values used in EcoDesigner software. Moreover, the data obtained for operational energy, embodied energy along with subjective life cycle energy performance value were

Table 6
Modelled life cycle cost for envelope design alternatives.

Envelope design option	Option A (TT$)	Option B (TT$)	Option C (TT$)
Pre-construction cost	38,709.00	57,544.00	60,035.00
Construction cost	229,046.70	272,054.93	320,211.92
Operating cost (annual recurring)	359,603.31	432,621.24	502,732.71
Maintenance cost (annual recurring)	215761.99	259572.74	301639.63
Operating cost (non-annual recurring)	202722.15	256266.08	285361.92
Maintenance cost (non-annual recurring)	135,148.10	170,844.05	190,241.28
Salvage/residual cost	16,949.45	20,391.06	23,695.68
LCC(TT$)	1164,041.80	1428,511.98	1636,526.78
Gross floor area(m^2)	753.50	840.66	877.26
LCC/GFA(TT$/$m^2$)	1,544.85	1,699.27	1,865.50
Economic efficiency	2500	1500	500
Efficiency scale	Life cycle cost/GFA(TT$/m2) (2000 < X > 0); economic efficiency (0 < X > 10,000)		

6.40TT$ = 1US$.

Table 7
Simulated energy consumption data for envelope design alternatives.

Envelope performance data	Simulated		
	Alternative A	Alternative B	Alternative C
Gross floor area(m^2)	70.0	78.1	81.5
Electricity consumption (kWh/a)	4757	5440	5612
Electricity consumption per gross floor area (kWh/m^2)	67.957142	69.654289	68.858896

incorporated into life cycle energy analysis index (Iwaro et al., 2012, 2013) to model life cycle energy efficiency performance for envelope design alternatives. The outcomes are depicted in Table 9 for further sustainable performance modelling. In terms of subjective assessment, alternative C emerged as the most energy efficient with a performance score of 14,844 as shown in Table 9. This is closely followed by alternative B with a performance score of 14,403 while alternative A is the least energy efficient. Moreover, when operational and embodied energy was quantified objectively, alternative C had the highest operational energy consumption of 1010.16 GJ and an embodied energy of 1924 MJ. This means that high energy consumption rate from alternative C makes it less efficient compared to alternative A with less energy consumption rate.

Also, according Table 9, alternative A recorded the highest energy efficiency value in embodied energy efficiency and operational energy efficiency with 2000 and 5500 life cycle performance score respectively when compared with other two alternatives. Therefore, alternative A emerged the most energy efficient envelope design alternative. Apart from obtaining the energy consumption of these three sustainable building envelope design alternatives, their associated carbon emissions were also simulated using GraphiSoft Eco Designer software as presented in Table 10. In the simulation results, alternative A was the most carbon emission efficient with 2800 performance score. It thus means that the energy efficiency performance of alternative A influenced its carbon emission efficiency performance and led to higher environmental efficiency. Also, alternative A emerged the most efficient in environmental impact subjective assessment with overall performance score of 12,892, followed by alternative C with 12,729 life cycle performance score. It thus means that alternative A is the most environmental impact efficient when compared with the other two alternatives in Table 10.

Moreover, in order to validate the simulated carbon emission values, the carbon emission associated with actual energy consumption of 4,896 kwh/yr obtained from a typical private single family residential building at the St.

Table 8
Daily reading of the electricity consumption from private single family residential.

Reading time (AM)	Day	Period	Energy consumption (kWh)	kWh used
9:30	Tue		28577	
9:30	Wed	Tue-Wed	28591	14
9:30	Thur	Wed-Thur	28603	12
9:30	Fri	Thur-Fri	28618	15
9:30	Sat	Fri-Sat	28635	17
9:30	Sun	Sat-Sun	28644	9
9:30	Mon	Sun-Mon	28660	16
9:30	Tue	Mon-Tue	28679	19
				102
Energy consumption per annum		102 kWh × 4 wks = 408 kWh/month = 4896 kWh/yr		

Table 9
Building envelope life cycle energy efficiency performance.

Index	LCEA component	Life cycle energy performance values		
		Alternative A	Alternative B	Alternative C
$LCEA_i$	Energy efficiency (Subjective)	13996.00	14403.00	14844.00
	Total Embodied energy(MJ)(Objective)	1592.12	1723.64	1924.01
	Embodied energy efficiency	2000	1500	500
	Operational energy for 50yrs(GJ)(Objective)	856.26	979.20	1,010.16
	Operational energy efficiency	5500	5000	5000
	Efficiency Scale	Energy consumed (2000 < X > 0) energy efficiency (0 < X > 10,000)		

Augustine area of Trinidad was calculated using a carbon emission factor for Trinidad and Tobago of 0.7666 KgC02/kwh (Matthew et al., 2011). The average carbon emission associated with the three stimulated sustainable envelope design alternatives was 3894 kg/a while the actual carbon emission associated with the household as quantified for private single family residential building was 3753 kg/a. This confirms the validity of the simulated values obtained for the energy consumption and carbon emission. Besides the life cycle performance data obtained for economic efficiency and energy efficiency criteria, the life cycle performance data for material efficiency, external benefit, regulation efficiency, and environmental impact criteria were obtained through Life Cycle Impact Assessment (LCIA) index (Iwaro et al., 2012, 2013). The life cycle performance data for the subjective components of these criteria were obtained through Life Cycle Performance Assessment Questionnaire while the objective components were obtained through the direct measurement and simulation of these criteria life cycle performances. Hence, the life cycle performance data obtained for the three proposed envelope design alternatives based on main and sub criteria performance are presented in Table 11.

The data involved in this model are both subjective and objective in nature. The subjective component incorporated into the model was to ensure that all aspects of sustainability which cannot be measured objectively were assessed. Moreover, based on the principle of additive utility theory, the theory emphasised the need to assess the sustainable performance of an element using the criteria weights and performance (OECD, 2003). As such, the life cycle performance scores in Table 11 were normalised by converting objective criteria to their respective efficiency using efficiency scale. The life cycle performance scores in Table 11 were combined with their respective weights from Table 5 in the Integrated Performance Assessment Matrix (IPAM) developed based on the Multi Criteria Analysis (MCA) Framework presented in Table 12 to model sustainable performance value for each sustainable envelope design alternative using the Integrated Performance Index (IPI) (Iwaro et al., 2012, 2013). The overall sustainable performance value for envelope alternative was derived through IPI by summing the sustainable performance values for all the criteria under each envelope design alternative. The higher the overall sustainable performance value obtained from Integrated Performance Index the better the sustainable envelope alternative. As such, the applicability of this model in selecting envelope design alternative with the best sustainable performance value was demonstrated.

The potential of achieving building sustainability through sustainable building envelope has been demonstrated in this paper. Based on the modelling outcomes depicted in Table 14, alternative "A" recorded overall sustainable performance value of 16,936, alternative "B" has 16,016 overall sustainable performance value while alternative "C" recorded 15,181 overall sustainable performance value. Thus means that Alternative "A" is the most preferred sustainable option with the highest overall sustainable performance score. Also, in consideration of

Table 10
Life cycle environmental impact performance values for building envelope alternatives.

Main criteria	Sub criteria	Life cycle performance values		
		Alternative A	Alternative B	Alternative C
Environmental impact (Objective data)	Energy efficiency (embodied and operational energy)	7500	6500	5500
	Carbon emission(kg)/annum) simulated	3515	4020	4147
	Carbon emission(kg)/50yrs) simulated	175750	201000	207350
	Carbon emission efficiency	2800	2000	1600
Environmental impact (Subjective data)	Environmental impact Efficiency	12892	12630	12729
	Efficiency Scale	Carbon emission (250000 < X > 0) carbon emission efficiency (0 < X > 10,000)		

Table 11
Life cycle performance data based on sub criteria.

Main criteria	Sub criteria	Life cycle performance values		
		Alternative A	Alternative B	Alternative C
Environmental Impact efficiency	Renewable resources depletion	1589	1605	1613
	Non-renewable resources depletion	1759	1572	1411
	Deforestation	1679	1449	1394
	Indoor air quality	1392	1876	2099
	Air pollution	1445	1519	1653
	Noise pollution	1701	1585	1575
	Material emission	1587	1516	1522
	Construction waste	1740	1508	1462
	Energy consumption (GJ)	858	981	1012
	Carbon emission (kg/50yrs)	175750	201000	207350
Energy efficiency	Building Envelope design	1202	1497	1604
	Energy conservation	1209	1508	1615
	Equipment and appliance	1858	1679	1725
	Wall insulation	1558	1452	1613
	Embodied energy (MJ)	1592	1724	1924
	Renewable resources depletion	1836	1818	1149
	Non-renewable resources depletion	1679	1546	2099
	Door & window frame	1392	1587	1653
	Operational energy (GJ/50yrs)	856	979	1010
	Window and door glazing	1701	1459	1404
	Labelling and certification	1561	1857	1982
Material efficiency	Low pollution effect	1489	1442	1445
	Embodied energy	1559	1300	1209
	Minimal emission	1357	1637	1701
	Indoor air quality	1944	1646	1561
	High moisture resistance	1453	1640	1679
	Material life span	1365	1537	1558
	Low maintenance	1472	1391	1371
	Durability	1651	1816	1858
	Minimum heat gain	1527	1253	1202
	Energy saving potential	1596	1442	1392
	Renewable potential	1823	1827	1836
	Recycling potential	1592	1690	1724
	Social image	1462	1655	1422
External benefit	Environmental ecological value	1155	1609	1337
	Environmental economical value	1522	1574	1499
	Local community economic	1725	1376	1711
	Landscape beautification	1613	1587	1596
	Environmental beautification	1411	1707	1489
	User productivity	1394	1621	1357
	Indoor air quality	2099	1578	1944
	Living Environment	1653	1481	1556
	Indoor environment	1575	1683	1527
Regulation efficiency	Regulation compliance	1371	1277	1527
	Moisture resistance	1858	1733	1559
	Air tightness	1558	1610	1472
	Energy consumption (GJ)	858	981	1012
	Heat loss/gain	1836	1341	1365
	Design flexibility	1679	1975	1592
	Construction quality	1392	1635	1823
	Carbon emission (kg/50yrs)	175750	201000	207350
Economic efficiency	Pre-construction cost/GFA (TT$/sf)	51.37	68.45	68.43
	Construction cost/GFA (TT$/sf)	303.98	323.62	365.01
	Operating cost/GFA (TT$/sf)	746.28	819.46	898.36
	Maintenance cost/GFA (TT$/sf)	465.70	511.99	560.70
	Residual cost/GFA (TT$/sf)	22.49	24.26	27.01

criteria performance and contribution to sustainable performance, energy efficiency criteria under alternative "A" emerged the most sustainable with the highest sustainable performance value of 3582 when compared with the other two alternatives. It means that alternative "A" has the lowest energy consumption, lowest embodied energy and possess better energy conservation strategies. Also, it means that alternative "A" recorded a better combined subjective

Table 12
Integrated performance assessment matrix.

Criteria	Alternative A		Alternative B		Alternative C		Weight
	LPV	SPV	LPV	SPV	LPV	SPV	
External benefit	15609	2602	15871	2645	15438	2573	0.166671
Energy efficiency	21496	3582	20903	3483	20344	3390	0.166644
Environmental impact	23192	3865	21130	3522	19829	3305	0.166673
Material efficiency	18828	3138	18621	3104	18536	3089	0.166671
Regulation efficiency	19994	3332	18071	3012	16438	2740	0.166669
Economic efficiency	2500	417	1500	250	500	83	0.166673
Overall sustainable performance value		16936		16016		15181	$\sum = 1.000$

LPV = Life Cycle Performance Value,
SPV = Sustainable Performance Value.

and objective life cycle performance from energy conservation strategies, wall insulation, certification compliance, energy efficient wall and window frame usage, embodied energy consumption and operational energy consumption. Therefore, according to the assessment outcomes presented in Table 14, the IPM model indicated that energy efficiency performance is a major determinant of sustainable performance of the building envelope. Also, the model's assessment in Table 14 revealed that the higher the energy efficiency performance of a building envelope design, the higher is the sustainable performance of that envelope design. Also, in terms of economic efficiency performance and contribution to sustainable performance, alternative "A" emerged the most sustainable alternative design with the highest sustainable performance value of 417 under economic efficiency criteria when compared to the other two alternatives. It means that alternative "A" possessed the lowest life cycle cost over the envelope life cycle span as related to annual recurring and non-annual recurring operating cost, maintenance cost, pre-construction cost, construction cost and residual cost. This is due to the fact that the lower the life cycle cost the more is the economic efficient of that alternative. Also, in terms of external benefit of the sustainable envelope design to the indoor occupants and external environments, alternative "B" recorded the highest sustainable performance value of 2645 with strong external benefit when compared with the other two options. It means that alternative "B" has better contribution to indoor air quality, thermal comfort, indoor temperature, environmental beautification, economical value of the building, heritage beautification etc. than alternative and "A" and "C". Moreover, under environmental impact criteria, alternative "A" emerged as the most sustainable alternative with the highest sustainable performance value of 3865 when compared to other two alternatives. It means that alternative "A" possessed materials that contributed the lowest impact such as carbon emission, energy consumption, waste and pollution to the environment. This is followed by alternative "B" and "C" with sustainable performance values of 3522 and 3305 respectively. Also, on material efficiency performance, alternative A emerged as the most sustainable alternative with the highest sustainable performance value of 3138 compared to other two alternatives. It means that alternative "A" possessed materials can easily be recycled, renewable, higher resistance to heat loss, minimal heat gain, high durability, and high energy saving potential, minimal carbon emission, high moisture resistance and low maintenance. This is closely followed by alternative "B" with sustainable performance values of 3104. Besides, in the case of regulation efficiency criteria, alternative A also emerged as the most sustainable alternative with the highest sustainable performance value of 3332 compared to other two alternatives. It means that alternative "A" design is the most compliance to ASHREA standard, compliance in terms of U-values, thermal properties specifications, better air tightness, high moisture resistance and most design with flexibility compared to alternative B and C. In overall, even though, the sustainable performance of the three envelope design alternatives were assessed and alternative A emerged the most sustainable building envelope design alternative with the highest sustainable performance value of 16,936 accrued from energy efficiency performance, economic efficiency performance, environmental impact performance, regulation efficiency performance, material efficiency performance and second place performance under external benefit criteria. It thus points to the importance of these criteria to sustainable development, sustainable design, sustainable envelope and building sustainability. Also, for any building envelope design to be made sustainable, all these criteria must be assessed. Also, the life cycle energy performance assessment though life cycle energy analysis technique (LCEA), life cycle environmental, external benefit, material, regulation performance assessment through life cycle impact assessment technique (LCIA) and life cycle cost assessment through life cycle cost analysis technique (LCCA) must be taken into consideration as done in this study.

5. IPM validation using energy efficiency approach

5.1. Energy efficiency performance assessment of sustainable building envelope design alternatives

In an effort to compute energy performance for sustainable envelope design alternatives, the GraphiSoft Eco

Designer computer simulation software was used to simulate the operational energy performance. As such, three sustainable building envelope designs were assessed for the proposed Housing Development Corporation (HDC) single family units to be sited at Union Hall, San Fernando area of Trinidad by the Ministry of Housing and Environment. The data obtained from this simulation are presented in Tables 7 and 13 while the simulation results from Eco Designer were compared with the actual electricity consumption from a private single family residential home selected from St. Augustine Area of Trinidad for validation purpose as discussed in Section 4.3. The results were fairly comparable to actual electricity consumption of 4896 kWh/yr obtained in Table 8. According to Tables 9 and 10, alternative A recorded the highest energy efficiency value in energy efficiency with 5500 performance score and life cycle energy efficiency performance score of 7500 when compared with other two alternatives. Therefore, alternative A emerged the most energy efficient sustainable envelope design alternative.

5.2. *Energy efficiency performance assessment of building envelope without sustainable design initiatives*

In order to compute the energy efficiency performance of building envelope without sustainable design initiatives the electricity consumption of twenty-six (26) Housing Development Corporation (HDC) single family units at Hillside Garden, Prince Town was tested to determine their energy saving potential. These HDC units were un-renovated existing structures with no sustainable initiatives. The results from this testing were compared with energy potential of the three proposed sustainable envelope designs for HDC single family units at Union Hall, San Fernando. Subsequently, the electricity consumption in these twenty-six (26) HDC single family units at Hillside Garden, Prince Town was monitored for 2 years. In the case of actual data collection, the monthly electricity consumption of the twenty-six (26) Housing Development Corporation (HDC) single family units was gathered through metre reading for 2 years between the period of 2011 and 2012. Besides, the actual electricity consumption from these un-renovated twenty-six (26) HDC single family units was compared with the simulated energy consumption from a single family unit selected from these un-renovated twenty-six (26) HDC using EcoDesigner software for validation purpose. In conducting the simulation to forecast energy consumption, a three dimensional model of a HDC single family unit selected from the twenty-six (26) HDC single family units, Hillside Garden, Prince Town was developed. The simulation's results were compared with the actual electricity consumption from the un- renovated twenty-six (26) HDC single family units for validation as shown in Table 13 while Table 14 shows the monthly electricity consumption data of the twenty-six (26) Housing Development Corporation (HDC) single family units gathered through metre reading for 2 years.

6. Results and discussion

The electricity consumption was gathered over the period of 2 years for twenty-six (26) (HDC) single family units at Hillside Garden, Prince Town. Based on the results obtained as depicted in Table 14, the average electricity consumption was approximately 6484 kWh/yr. This was the actual electricity consumption results obtained from these twenty-six (26) (HDC) single family units at Prince Town. Moreover, the actual average electricity consumption computed from Table 14 was used to validate the simulated results as shown in Table 13. Based on the simulation's result for a single unit at the Hillside HDC development, the electricity consumption was projected as 6059 kWh/yr while the actual electricity consumption for Hillside HDC single units at Princes Town was on average value of 6484 kWh/yr. The variation recorded in these values was approximately 6.5% which can be attributed to simulation effects. Moreover, based on the Eco Designer software simulation, the projected average electricity consumption for the proposed sustainable designs for HDC buildings at Union Hall was 5270 kWh/yr while actual energy consumption audited for a private single family residential building was 4896 kWh/yr. This difference may be accounted for by the 7% variance between the simulated and actual energy consumption data. However, the main

Table 13
The performance data of the proposed sustainable designs and existing HDC home.

Performance data	Simulated	Actual	Actual			
Envelope	Proposed sustainable Single family envelope (Union Hall)			Single family Unit (Hillside Garden)	Single family Units (Hillside Garden)	Private residential home
	Alternative A	Alternative B	Alternative C			
Gross area(m^2)	70.0	78.1	81.5	60.4	60.4	70.0
Electricity Consumption (kWh)/yr	4757	5440	5612	6059	6484	4,896
Energy efficiency (energy consumed scale ($8000 < X > 0$) energy efficiency scale ($0 < X > 10,000$)	4125	3250	3000	2500	2000	4000
Electricity consumption/area (kWh/m^2)	67.957	69.654	68.858	100.314	107.351	69.942

Table 14
Monthly electricity consumption of HDC single family units at Hillside Garden, Princes Town.

No.	Unit	From	To	Average (kWh)	Mean(kWh)	Max.(kWh)	Min.(kWh)
1	Household 1	25-Jan-11	23-Dec-12	5385.0	448.8	681.5	329.0
2	Household 2	22-Jan-11	23- Dec-12	4225.0	352.1	471.5	268.0
3	Household 3	22-Jan-11	22-Dec-12	5159.0	429.9	524.0	304.0
4	Household 4	25-Jan-11	29-Dec-12	8023.5	668.6	839.5	521.5
5	Household 5	23-Jan-11	27-Dec-12	5871.5	489.3	569.5	438.0
6	Household 6	25-Jan-11	25-Dec-12	8367.0	697.3	929.5	459.0
7	Household 7	22-Jan-11	27-Dec-12	7848.5	654.0	928.5	455.0
8	Household 8	21-Jan-11	27-Dec-12	7701.5	641.8	841.0	479.0
9	Household 9	25-Jan-11	27-Dec-12	3475.5	289.6	388.5	232.0
10	Household 10	25-Jan-11	27-Dec-12	3811.0	317.6	467.5	251.5
11	Household 11	20-Jan-11	28-Dec-12	4684.5	390.4	560.5	299.5
12	Household 12	27-Jan-11	28-Dec-12	3062.0	255.2	330.0	192.5
13	Household 13	20-Jan-11	28-Dec-12	8487.5	707.3	916.0	498.5
14	Household 14	29-Jan-11	28-Dec-12	7722.0	643.5	814.5	488.0
15	Household 15	25-Jan-11	28-Dec-12	8151.0	679.3	861.0	469.0
16	Household 16	22-Jan-11	28-Dec-12	5793.5	482.8	554.5	389.5
17	Household 17	23-Jan-11	27-Dec-12	8822.5	735.2	908.5	519.5
18	Household 18	24-Jan-11	27-Dec-12	8481.5	706.8	904.5	440.0
19	Household 19	26-Jan-11	27-Dec-12	7114.0	592.8	733.5	439.5
20	Household 20	22-Jan-11	28-Dec-12	8044.5	670.4	790.0	556.5
21	Household 21	22-Jan-11	28-Dec-12	5159.0	429.9	524.0	304.0
22	Household 22	26-Jan-11	28-Dec-12	8023.5	668.6	839.5	521.5
23	Household 23	22-Jan-11	28-Dec-12	3811.0	317.6	467.5	251.5
24	Household 24	26-Jan-11	23-Dec-12	4684.5	390.4	560.5	299.5
25	Household 25	28-Jan-11	23-Dec-12	8822.5	735.2	908.5	519.5
26	Household 26	29-Jan-11	27-Dec-12	7848.5	654.0	928.5	455.0

differences between the two HDC buildings used as case studies for this research, the proposed sustainable envelope designs for HDC building at Union Hall and Hillside HDC single units at Princes Town are their floor areas as shown in Table 13. On average floor area, the proposed sustainable designs at Union Hall are 22% larger than the typical single unit at Princes Town. If the electricity consumption is compared per square area, the three proposed sustainable envelope design units at Union Hall will have different consumption values, with A having approximately 68 kWh/m^2, B with 70 kWh/m^2 and C with 69 kWh/m^2. In comparison, the average electricity consumption per area for the typical single unit at Princes Town is 100 kWh/m^2. This figure is 31% higher than the projected figure for Union Hall as related energy consumption performance. This difference may be accounted for by the 22% variance in gross floor area between proposed sustainable envelope designs for HDC buildings at Union Hall and Hillside HDC single un-sustainable units at Princes Town. Also, it may be attributed to 31% variance in energy consumption between the proposed sustainable envelope designs for HDC buildings at Union Hall and Hillside HDC single units at Princes Town. In general, if the floor area is not considered, the average energy consumption of the existing Hillside HDC single family units is 13% greater than that of the proposed sustainable envelope designs at Union Hall. Thus means that the proposed sustainable envelope designs at Union are more energy efficient with higher efficiency values. In Table 13, the sustainable envelope design alternatives recorded energy efficiency value of 4125 for alternative A, alternative B with 3250, alternative C with 3000 efficiency value and single unit at Princes Town with 2500 energy efficient value. Thus suggests that buildings with sustainable envelope design will have higher level of sustainability in terms if energy efficiency performance when compared with building without sustainable initiatives such as Hillside HDC single units at Princes Town. Hence, the findings from this validation study confirm the outcome from IPM assessment where envelope design alternative A emerged the most sustainable envelope design alternative with the highest life cycle energy efficiency performance score in Table 12. In this validation study as well, the sustainable envelope design alternatives emerged the most sustainable with the highest energy efficiency performance when compared with Hillside HDC single units at Princes Town as shown in Table 13.

7. Conclusion and recommendation

In the above energy efficiency performance assessment, the building envelope with sustainable design initiatives recorded the highest energy efficiency performance score. The sustainable performance was significantly influenced by the energy efficiency performance of that alternative. These results revealed that the higher the energy efficiency performance of a building envelope design alternative the higher is the sustainable performance of that alternative and building sustainability. The results obtained from the sustainable envelope design impact analysis indicated that sustainable envelope designs proposed for HDC single units' project at Union Hall are more energy efficient and sustainable when compared with existing Hillsides HDC single family units at Princes Town. Thus shows the significance of sustainable design concept to building sustainability and the capability of sustainable envelope design to achieve building sustainability. Therefore, it is imperative that sustainable development concept that involves sustainable initiatives such as sustainable development concept's elements, life cycle analysis, and energy conservation strategies be incorporated into sustainable envelope design to achieve building sustainability. The sustainable envelope design as analysed in this paper will help in promoting green building and sustainable practise in building industry. However, in order to design sustainable envelope that achieves building sustainability the sustainable performance of the building envelope must be assessed. This requires the development of a comprehensive and multi-dimensional assessment method for the building envelope sustainable performance that can take into consideration all sustainable development concepts and values such as energy efficiency, environmental impact, economic efficiency, material efficiency, social impact and regulation efficiency criteria. Also, the application of IPM in this study has demonstrated the capability of IPM to assess, rank and select the best sustainable envelope design alternative taken into consideration the alternative life cycle performance. The IPM as developed for the sustainable performance assessment and design of the building envelope in this study has filled the gap between existing building assessment techniques, the sustainable performance assessment of building envelope and the increasing demand for sustainable development in the construction industry. The model provided a comprehensive assessment method specific to building envelope that can undertake sustainable performance assessment of building envelope in Trinidad and Tobago and the wider Caribbean region towards achieving building sustainability. Besides, this model provided a robust methodology for the assessment of the sustainable performance of proposed designs and existing residential building envelope. This methodology can be used to predict the overall sustainable performance of the whole residential building using building envelope with few data. It is therefore recommended that for any building envelope design to be made sustainable, all the sustainable performance criteria also known as sustainable development values such as energy efficiency, economic efficiency, environmental impact, regulation efficiency, material efficiency and external benefit must be assessed. Also, the four interrelated principles of sustainable development that emphasised the need to minimise environmental resources for future generation through resources recycling and reviewable process, involving the participation of building and construction expert in sustainable devolvement decision making, the preservation of ecosystem, energy conservation and resources conservation for future building and ensuring equal access to natural and environmental resources for future generation as demonstrated in this study must be considered as well for sustainable design of the building envelope. However, further verification and validation still need to be conducted on this model to ensure that the model is effective in assessing and design sustainable building envelope that can achieve building sustainability in extreme weather and climatic conditions.

Acknowledgements

The author acknowledges the contribution of the Ms. Newton Mandilee and Mr. Richardo Zico whom made the collection of the data used in this study possible.

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