Developing a BIM-based process-driven decision-making framework for sustainable building envelope design in the tropics

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Abstract

There is a rising concern for sustainability in the built environment. Therefore, numerous sustainable building certification and rating systems are developed throughout the world. However, the current methods of measuring, predicting, and optimising the sustainable building design have relied on a number of disjointed analyses to meet the discrete requirements for various building systems. The recent development of Building Information Modelling (BIM) technology allows complicated building modelling to be digitally constructed with precise geometry and accurate information to support various building project stages. Thereby, this study aims to integrate decision-making (DM) for sustainable building envelope design with BIM functionalities by considering the tropical climatic contexts in Malaysia. Several regional sustainable building certification systems and related literature were reviewed to identify the importance of evaluation and DM criteria. The findings were then compared with various BIM tools in terms of their applications, functions and workflows, in order to formulate a process-driven BIM-based DM framework (DMF) for sustainable building design in Malaysia. The proposed DMF will address the difficulties of DM in the early design development process, and will also allow for specific trade-off analyses of sustainability and objective-based optimisation using BIM.
Keywords: GreenBIM, design process, AEC industry, sustainable architecture, tropical.

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1 Introduction

In the past 20 years, numerous certification and rating systems are available throughout the world for sustainable building, including LEED in US; BREEAM in UK; Green Mark in Singapore; and Green Star in Australia. Each of these systems requires different types of performance goals to evaluate and to benchmark the levels of green building revolution. Green Building Index (GBI) [1] and GreenRE [2] have been introduced to Malaysia in 2009 and 2013 respectively, both are sustainable building rating systems for non-residential new construction, residential new construction, and existing non-residential buildings. Some of the criteria in GBI and GreenRE actually used the benchmarks as stated in MS 1525 [3] such as overall thermal transfer value (OTTV) and roof thermal transfer value (RTTV).

The term 'sustainability' comprises a wide range of components: environmental quality, society well-being, and economic stability. These components often lead to conflict; therefore, it is very difficult to integrate these components into a single green rating [4]. However, the current design decision-making (DM) for sustainable buildings much depends on a number of disjointed analyses, to determine whether discrete requirements are best met with various building systems (e.g. HVAC, plumbing, lighting) or design features (e.g. landscaping, renewable energy generation, parking). Although many studies have pointed that the best opportunities for building sustainability improvement occurred in the early design or pre-construction stages, in the conventional architecture, engineering and construction (AEC) practice, surveys had found that the design DM for building sustainability occurred in the later stages [5, 6].

With the development of Building Information Modelling (BIM) technology, complex building modelling can be digitally constructed with both precise geometry and accurate information in order to support various project stages. Many researchers had stated the benefits of BIM in AEC industry such as accurate data environment, effective design process, accurate project cost estimation, time saving, and other benefits [7–11]. The additional functionality of BIM parametric modelling also allows conduct various analyses for design DM.

The applications of BIM for sustainable building design or GreenBIM model had been investigated widely recently. For instance, the data of BIM model can be utilised for green rating evaluation [12, 13]. BIM-based model can also be used for post-occupancy evaluation process [14, 15] and waste reduction of renovation projects [16]. Bank *et al.* [4] investigated the possibility of developing a decision-making (DM) framework for sustainable building design and operation by integrating BIM with System Dynamics. Kim *et al.* [13] aimed to develop Green BIM Template (GBT) for Green Building Certification Criteria (GBCC) in South Korea.

From the recent development on BIM-based sustainability or GreenBIM, it shows the importance of extracting data from BIM for sustainable building design DM. Hence, a decision-making framework (DMF) is needed to understand the extent and benefits of applying BIM in early stages of building design. A BIM-based DMF can give the designers a well-defined workflow to support the DM process using BIM based on regional sustainable building certification systems. Thereby, this study aims to integrate DM which comprises sustainable building envelope design and BIM functionalities with the consideration on the tropical climatic contexts in Malaysia. This study focuses on the early design or pre-construction stages which includes conceptual and schematic design as well as design development stages.

2 Methodology

Design DM for sustainable building envelope design is multifaceted; it requires energy consumption, PMV, daylighting, initial cost, and other aspects. DM is affected by many design variables such as window position, window-to-wall ratio, shading device geometry, type of glazing, wall material and so on. Therefore, DM for architectural optimal sustainable design involves searching for a multi-criteria optimal design solution set based on various sustainability indicators [4, 17, 18]. In this study, a BIM-based DMF for sustainable building envelope design was developed after considering certain aspects such as design process, sustainability indicators and functionality of BIM tools. Several regional sustainable building certification systems and related literature were reviewed to identify the importance of process and evaluation criteria for sustainable DM building envelope design. DM process and criteria then were compared and matched with BIM functionality and Level of Development (LOD). The finding of the study has established an objective-based process-driven DM framework (DMF) for sustainable building envelope design.

3 Development of BIM-based decision-making framework

3.1 Definition of sustainable design decision-making criteria

The review of several regional sustainable building certification systems and literature has highlighted the different DM criteria for sustainable building envelope design. All the criteria were then categorised according the different design variables: 1. Opening position, 2. Opening size, 3. Shading device, 4. Window glazing type, 5. Wall type and material, 6. Roof geometry, 7. Roof opening geometry, 8. Skylight geometry, 9. Skylight glazing, 10. Roof type and material. Different design variables require different sustainable design DM criteria by responding to the local climate. For instance, the position of window openings shall avoid facing east-west orientations in order to minimise direct solar heat gain; whereas the construction of building façade and roof shall maximise the use of regional and sustainable materials. The DM criteria and related references based on the various building envelope design variables are summarised in Table 1.

Table 1: Summary of sustainable building envelope design DM criteria.

Design variable	Sustainable design DM criteria	References
V1- Opening position	• Minimise east-west facing opening to avoid direct sunlight • Maximise north-south facing opening to capture prevailing wind • Maximise north-south facing opening to receive sufficient daylight • Provide good distribution of daylight	[2, 19–22]
V2- Opening size	• Minimise heat gain • Assure each space has sufficient operable opening area (WFR) for ventilation • Provide sufficient indoor air movement and air change • Provide sufficient indoor illuminance • Minimise daylight glare	[1, 2, 19, 20, 22–31]
V3- Shading device	• Use of solar shading to shade east-west facing opening • Optimise shading geometry • Minimise OTTV[1] / RETV[2] • Minimise heat gain • Use of shading device to control daylight quantity and quality • Minimise daylight glare • Use of PV as shading device	[1–3, 19–21, 24, 26, 31–45]
V4- Window glazing type	• Minimise OTTV[1] / RETV[2] • Minimise heat gain • Provide sufficient indoor illuminance • Minimise daylight glare	[1–3, 21, 24, 26, 28, 31, 33, 34, 41, 45–53]
V5- Wall type and material	• Minimise OTTV[1] / RETV[2] • Minimise heat gain • Use of green wall to reduce heat gain • Use of regional building material • Use of sustainable building material	[1–3, 28, 30, 41, 47, 49, 50, 51, 53–56]
V6- Roof geometry	• Use of roof overhang to shade east-west facing façade • Use of pitch angle to reduce incident solar heat gain (solar factor) • Optimise roof area for PV	[1–3, 47, 50, 57]
V7- Roof opening geometry	• Use of roof opening or solar chimney for stack ventilation • Provide sufficient indoor air movement and air change	[58, 59]
V8- Skylight geometry	• Shade the skylight from direct sunlight • Orientate the skylight to face north-south orientations • Provide sufficient indoor illuminance • Provide good distribution of daylight	[52, 60, 61]
V9- Skylight glazing	• Minimise RTTV[3] • Minimise heat gain • Provide sufficient indoor illuminance	[1–3, 49, 52, 62–65]
V10- Roof type and material	• Use of thermal insulation to reduce heat gain • Minimise RTTV[3] • Minimise heat gain • Use of regional building material • Use of sustainable building material • Use of green roof for cooling	[1–3, 41, 51]

OTTV[1] = applicable for buildings with AC area > 1000m^2
RETV[2] = applicable for residential building
RTTV[3] = applicable for roof with skylight

3.2 Comparison of decision-making with Level of Development

Level of Development (LOD) in BIM had been defined by various previous studies in order to standardise the precision and suitability of a BIM for specific uses. LOD describes the steps of a BIM element to progress logically from the lowest level of conceptual approximation to the highest level of representational precision, which allows practitioners in AEC industry to articulate the content of a BIM at various project stages (Bedrick [66], BIMForum [67], Wood *et al.* [68]). In general, the LOD are defined as: 100 for conceptual design; 200 for schematic design with approximate geometry; 300 for developed design with precise geometry; 350 for tender and coordination; 400 for construction and fabrication; and 500 for as-built.

A BIM-based sustainable building envelope design DM needs to be process-driven according to BIM workflow. Therefore, the sustainable building envelope design DM process was defined by comparing the design variables with the BIM LOD. This study only focuses on conceptual or schematic design and design development stage of a project, thus LOD 100, 200 and 300 can only be selected for the comparison. The match-up of the design process with the selected BIM LOD is presented in Table 2.

Table 2: Match up of design process with BIM LOD 100 to LOD 300.

LOD	Model content requirement [66–68]	Design variable
100	Non-geometric data, symbol or line work, area, height, volume, zone, location, orientation or other generic representation.	V1, V6, V7
200	Generic elements or assembly shown in three dimensions, with approximate quantities, size, shape, location, and orientation. Non-graphic information may also be attached to the elements.	V2, V3, V8
300	Specific system, object or assembly in terms of quantity, size, shape, location, and orientation. Non-graphic information may also be attached to the elements.	V4, V5, V9, V10

3.3 Formulation of BIM-based process-driven DMF

Based on the sustainable building envelope design DM criteria and the match-up with BIM LOD, a BIM-based process-driven DM framework (DMF) for sustainable building envelope design was formulated. Table 3 represents the BIM-based DMF for building façade and roof design according to schematic or conceptual design (LOD 100 and 200) and design development (LOD 300) stages.

Objective functions were determined for every design variables based on the DM criteria as defined in Table 1. For instance, to minimise the percentage of east-west facing window areas over total east-west facing façade areas is one of

Table 3: Integrated BIM and objective-based process-driven decision-making framework for sustainable building envelope design in Malaysia.

Design Element Category	Project Stage									
	Schematic / Conceptual Design [LOD 100, 200]					Design Development [LOD 300]				
	Design Variable	Strategy	Objective Function	Decision-making	Tool	Design Variable	Strategy	Objective Function	Decision-making	Tool
Façade	Window size [WWR]	Solar Shading	% of E-W facing window areas over total E-W facing façade areas	The lower the better	Calculation	Glazing [VT, U-value, SC]	Thermal	OTTV (applicable for building with AC area > 1000m^2)	≤ 50 W/m^2	Calculation
	Window position		% of E-W facing window areas with sunshading devices over total E-W facing façade areas	The higher the better	Calculation	Wall material [U-value, solar absorptivity]		RETV (applicable for residential building)	≤ 25 W/m^2	Calculation
	Shading device geometry		SC of Shading Device	The higher the better	Refer to Guidelines	Shading Device SC		Building cooling load (if applicable)	The lower the better	Calculation
	Type of Wall	Natural Ventilation	% of spaces with window opening facing N-S directions for cross ventilation	The higher the better	Calculation		Natural Ventilation	Indoor wind velocity	0.5 - 1.0 m/s	CFD Simulation
			% of spaces with WFR ≥ 10%	The higher the better	Calculation			Indoor air change rate	0.35 ACH and ≥ 7.5 L/S	CFD Simulation
								Indoor air temperature	22.5 - 28.5 °C	Thermal Simulation
								Predicted Mean Vote (PMV)	0	CFD Simulation
		Dayligting	% of N-S facing window areas over total N-S facing façade areas	The higher the better	Calculation		Dayligting	% of the NLA with DF 1.0 – 3.5%	The higher the better	Daylight Simulation
			% of the use of light shelf over other shading devices	The higher the better	Calculation			Daylight uniformity ratio (min/avg)	≥ 0.5	Daylight Simulation
								Daylight Glare Index	Refer to Index	Daylight Simulation
		Other	% of green wall area over total wall area (if applicable)	The higher the better	Calculation		Other	Building Energy Index (BEI)	The lower the better	Energy Simulation
			% of solar shading device area optimsed for PV (if applicable)	The higher the better	Solar Simulation			Renewable Energy production (PV; if applicable)	The higher the better	Energy Simulation
								% of regional building materials over total project's material (based on cost)	The higher the better	Calculation
								% of sustainable building materials over total project's material (based on cost)	The higher the better	Calculation
								Construction cost	The lower the better	Calculation
Roof	Roof type	Solar Shading	% of E-W facing façade areas shaded by roof over total E-W facing façade areas	The higher the better	Solar Simulation	Roof material [U-value]	Thermal	% of roof area with U-value ≤ 0.4 W/m^2k (light weight) or ≤ 0.6 W/m^2k (heavy weight) over total roof area	The higher the better	Calculation
	Roof geometry		% of indirect (shaded) skylight area over total skylight area (if applicable)	The higher the better	Calculation	Skylight Glazing [VT, U-value, SC]		RTTV (applicable for roof with skylight)	≤ 25 W/m^2	Calculation
	Opening geometry		Solar Factor (SF) of the roof	The lower the better	Refer to Guidelines	Roof SF		Building cooling load (if applicable)	The lower the better	Calculation
	Skylight geometry	Natural Ventilation	% of spaces with roof opening / solar chimney for stack ventilation (if applicable)	The higher the better	Calculation		Natural Ventilation	Indoor wind velocity	0.5 - 1.0 m/s	CFD Simulation
								Indoor air change rate	0.35 ACH and ≥ 7.5 L/S	CFD Simulation
								Indoor air temperature	22.5 - 28.5 °C	Thermal Simulation
								Predicted Mean Vote (PMV)	0	CFD Simulation
		Dayligting	% of N-S facing skylight areas over total skylight areas	The higher the better	Calculation		Dayligting	% of the NLA with DF 1.0 – 3.5%	The higher the better	Daylight Simulation
								Daylight uniformity ratio (min/avg)	≥ 0.5	Daylight Simulation
		Other	% of green roof area over total roof area (if applicable)	The higher the better	Calculation		Other	Building Energy Index (BEI)	The lower the better	Energy Simulation
			% of roof area optimsed for PV (if applicable)	The higher the better	Calculation			Renewable Energy production (PV; if applicable)	The higher the better	Energy Simulation
								% of regional building materials over total project's material (based on cost)	The higher the better	Calculation
								% of sustainable building materials over total project's material (based on cost)	The higher the better	Calculation
								Construction cost	The lower the better	Calculation

the objective functions to avoid direct solar radiation heat gain in the tropics. Besides, related BIM functionalities or tools for every DM were determined based on the review of various BIM software such as Autodesk Revit, Integrated Environmental Solutions <Virtual Environment> (IES <VE>), Autodesk Ecotect Analysis, Design Builder and so on.

4 Conclusion

This study integrates DM for sustainable building envelope design and BIM functionalities with special reference to the tropical climatic contexts in Malaysia. Several regional sustainable building certification systems and related literature were reviewed to determine the importance of DM criteria. The objective-based DMF was defined based on BIM LOD and relevant BIM functionalities. It addresses the difficulties of DM in early design process, and allows for specific sustainability trade-off analyses and optimisation to be conducted using BIM. This study can be further developed as a BIM-based DM and optimisation tool.

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