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Development of an Innovative Energy Modelling Framework for Design and Operation of Building Clusters in the Tropics

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Abstract

Efficient building design, and management of this through to the building's operation is critical as sub-optimal performance becomes difficult to detect and assess once in the operational stage. Building energy modelling can facilitate this through identifying operational drift away from the optimal building performance. However existing energy modelling tools fail to meet many of the needs to manage this process, due to the excessive complexity of modelling frameworks. Furthermore, models are not typically integrated with operational information from buildings to facilitate and maintain building performance in the operational stage. The aim of this project is to demonstrate an innovative energy modelling framework for clusters of buildings to improve their design, operation, compliance, data management and analytics. This case study considers new and existing buildings within the BCA Academy Campus in Singapore over three phases to compare and determine the potential for optimal building performance across the campus. Phase 1 creates a 3D masterplanning model used to store, visualise and compare key building parameters to enable advanced design and compliance planning. In Phase 2, more detailed building energy models are created for two proposed new campus buildings, which are used to simulate and analyse the impact of various design options, and guide optimal building design in line with BCA requirements. Phase 3 focuses on creating a highly calibrated detailed model of an existing building, where measured data is used to improve the level of accuracy between the model and the actual performance to with-in +/-5%. This allows for accurate simulation to assess and further improve the buildings performance virtually, ahead of making actual changes in the building.

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1. Introduction

There is increasing evidence regarding the mismatch between the optimal and actual energy performance of buildings as they transition from the design stage through to the operational stage, even in energy-efficient buildings [1]. This issue is becoming increasingly observed as buildings and cities integrate 'Smart' Technologies providing building owners with a higher level of data and transparency with respect to the performance of their buildings. It has been estimated between 25%-45% of energy consumed by HVAC systems in commercial buildings is wasted due to faults alone [2]. In tropical climates such as Singapore, where Air Conditioning is the typically the primary consumer of energy in buildings (up to 50% of consumption [3]), sub-optimal or faulty operation of these systems can have a significant impact in terms energy consumption and user comfort. Other causes of performance away from intended optimal design include inaccurate initial design assumptions, occupancy behavior influence and facility management [4]. In short, the absence of on-going monitoring and analysis can permit the continued sub-optimal performance of operational buildings, typically resulting in additional energy consumption, cost and/or poor user comfort.

Building Energy Modelling (BEM) is extensively used to assess building performance at the design stage (often for code compliance or voluntary environmental rating systems) as it offers an in-depth and accurate representation of the building parameter's dynamic interactions and resulting energetic performance. However, BEM can also play an important role in the building's operational stage in addressing the performance gap described. Creation of BEMs representative of the buildings actual operating conditions can be useful in identifying sub-optimal performance, system faults and can better determine the implications of proposed energy conservation measures (ECMs) and retrofit options to the building in terms of consumption, cost and comfort.

Despite these benefits, studies have shown that non-expert modellers rarely complete accurate, quality energy models for existing buildings during the operational stage due to (i) a lack of consistent standardized frameworks, (ii) the expense and time needed to obtain the required operational data and (iii) the lack of integrated tools and automated methods to assist in the modelling and analysis [5]. A collaborative project undertaken by IES and the BCA focused on demonstrating and assessing an innovate energy modelling framework which employs appropriate levels of models for different levels of analysis, from clusters of buildings down to individual building level with the aim of identifying performance issues and improving building(s) design, operation, compliance, data management and analytics. The project was based on the BCAA (Building and Construction Authority Academy) Campus, Singapore and was carried out in 3 Phases introduced below, with the different level of models as defined for the analysis discussed in the following sections described in Table 1.

- **Phase 1 Masterplanning at Community Level** which involved the development of a 3D masterplanning model for the BCAA campus to model, store, visualise and compare a range of key building parameters enabling collaborative analysis and management of building data for clusters of buildings (Level 1 models)
- **Phase 2 New Building Design Performance Evaluation** which focuses on the BEM and simulated analysis to optimise the design of two new buildings planned for the BCAA campus (Level 2 and 3 models)
- **Phase 3 Integration with BMS and CI2 Analysis** where a calibrated BEM was developed for one campus building achieve the next level of improving energy efficiency in existing 3-storey ZEB (Level 4 models)

Table 1. Model Levels description

Model Level	Description	~No. of Model Inputs
Level 1	Shell of the building represented as a single zone with simplified HVAC inputs	~25
Level 2	Level 1 + Number of floors added to model and defined as separate zones	~25-40
Level 3	Level 2 + each room added to model and defined as separate zones	>100
Level 4	Level 3 + sub-zones to account for HVAC system type and lighting control measures	>150

2. Phase 1 Masterplanning at Community Level

Phase 1 involved the development of a 3D masterplanning model for the group of BCAA campus buildings to enable the holistic, high-level performance analysis required to improve design and compliance planning at the community level. The models were created using an IES plug-in to Trimble's SketchUp software, where initial models can be created by importing GIS data and models formats (see Figure 1) to simplify the model creation process. The BEMs can be described as Level 1 models with a minimized number of inputs to define the building construction and ACMV system, which are sufficient for high-level planning, visualization and comparison of key building parameters for large clusters of buildings. As part of the modelling framework in this phase, the campus model was exported to the web to act as an integrated data repository to enable collaborative cloud-based storage and retrieval of building information between all of the stakeholders involved (building owners, facility/campus managers, urban planners, local authorities etc.). Figure 1 below describes the BEM process steps undertaken to achieve this, followed by information on the small scale masterplanning model developed for the BCAA campus at each step in the next sections.

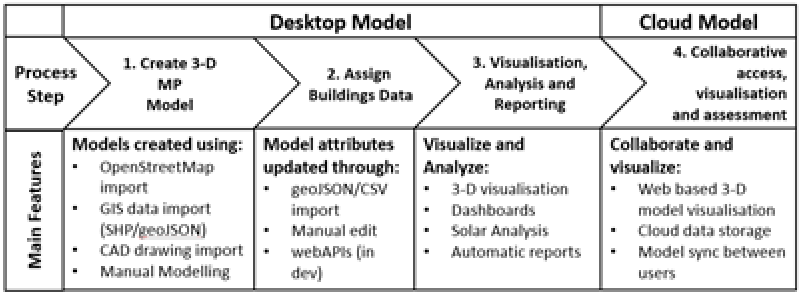

Fig. 1. Phase 1 Masterplanning BEM approach

2.1. Process Step 1 – Create 3D MP Model

The initial base model of the BCAA Campus was developed by importing buildings and other urban features from Open Street Map (OSM) to guarantee the correct geolocation. The exact footprint of the buildings was extracted from existing BIM models provided by BCA (BCAA buildings in brown in Figure 2) and coordinated with the data downloaded from Open Street Map.

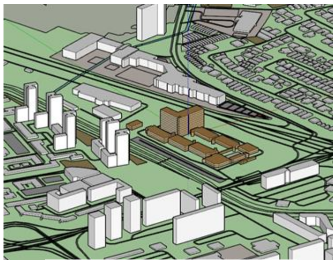

Fig. 2. BCAA 3D

2.2. Process Step 2 – Assign Building Data

This step focused on collecting and updating key building parameters (combining both measured and simulated data) in the model which drive the masterplanning analysis and visualisation in Step 3. Additional data such glazing, building use, ACMV, occupancy, energy consumption was added to each building block in the campus. Building data was imported from a number of sources or manually updated; for the BCAA model the data was partly gathered from BCA, and partly from imagery resources (Google Walk-through using Google Maps).

2.3. Process Step 3 – Visualization, Analysis and Reporting

Once steps 1 and 2 are complete the model can be used to easily visualise, analyse and report on the building performance for a range of parameters, which can also include solar analysis for the masterplan model based on actual solar conditions for the geo-located buildings. Examples of performance analysis for the BCAA campus model included comparison of building ventilation strategies, ACMV systems and space use (Figure 3).

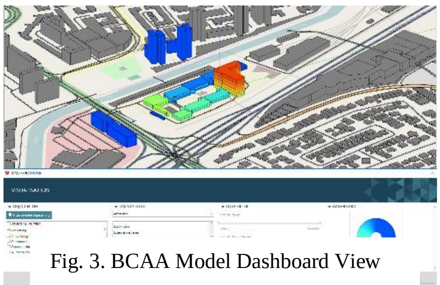

Fig. 3. BCAA Model Dashboard View

2.4. Process Step 4 – Collaborative access, visualization and assessment

For the final step, the model and associated data were exported to a central cloud-based repository to enable collaborative model visualization between all members of the project team; using this shared model similar higher level masterplanning analysis to that described in Step 3 can be carried out.

3. Phase 2 – New Building Design Performance Evaluation

Phase 2 of the project focused on optimising the design of propose two new buildings planned on the campus and used Level 2 and 3 BEMs for the different stages of analysis required. The two new buildings are proposed for the BCA Campus are referred to as:

a) Super Low Energy High Rise building (SLEB)
b) Zero Energy Mid Rise building (ZEB 2.0)

The initial analysis focused on the positioning options for the new builds due to their potential impact on the energy performance of the Zero Energy Building (ZEB) that is located due west of the proposed development. Photovoltaic (PV) panels are located on the roof of the ZEB building and any obstructions could potentially affect the current electrical generation performance. Level 2 models (developed in the IESVE) requiring a limited number of inputs were deemed appropriate to examine the impact of the building position options. The option 1 model is illustrated in Figure 4, and the BEM simulation results provide a sufficient indication of the effects of the different building position options presented:

- Existing condition - 1% of the roof is shaded
- Positioning Option 1 - 22% of the roof is shaded
- Positioning Option 2 - 7% of the roof is shaded

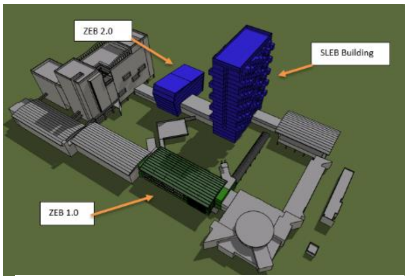

Fig. 4. New Buildings Positioning – Option 1

The next stage of analysis was to determine optimal design solutions to meet aggressive energy performance targets set by BCA for the new buildings:

- SLEB to achieve less than 100 kWh/ m² per year and minimum a 40% energy savings compared with minimum code requirements as established in the Green Mark NRB-2015 standard and achieve energy efficiency index (EEI) of less than 100 kWh/m_2/yr
- ZEB 2.0 to achieve “Net Zero Energy” status

To achieve this analysis at the level of detail required, Level 3 IESVE baseline BEMs were established as a benchmark to compare design performance in accordance with the mandatory requirements of Green Mark NRB-2015 standard. These models took into account the basic building geometry (building footprint and height) with floor spaces configured as per BCA usage information (space type allocation and floor area), including a range of assumptions on internal gains and operational schedules. Through collaboration with the BCA, revisions were made to the input data and revised results were prepared to form the final accepted baseline models. Using these models, extensive tests (ECMs) were then performed on the BEMs focused on the following areas:

- Envelope performance
- Lighting fixtures and controls
- Building equipment (receptacle and elevator loads)
- ACMV system efficiency options
- On-site renewables

Guided by the results of the individual ECMs for each area, an optimal combination of multiple ECM’s were determined for each building resulting in the savings versus the baseline model as detailed in Table 2. This level of detailed results provides sufficient information on the building design options and their subsequent impact on performance. The results establish that the majority of the performance criteria set-out by BCA can be met and exceeded by combining certain measures. However, it was found that the zero energy targets for the ZEB 2.0 settings, in particular the extensive operating hours, are not ideally conducive to a "Net Zero Energy" building without extensive renewable power generation which would likely need to be sourced off-site to meet the targets set-out.

Table 2. SLEB and ZEB 2.0 ECM optimal combination results

Test Number	Measure	Annual Energy Use MWh	Energy Use Intensity EUI kWh/m2	Savings vs Base %
SLEB	Baseline	3,013	180	
	Test includes no infiltration, improved façade performance with high performance glass, LED lighting, occupancy sensors, daylight harvesting, energy star rated equipment, elevators with VVVF regenerative drives, DOAS units with active chilled beams, high efficiency chillers, demand control ventilation, high temperature-low lift cooling, elevated space temperatures and PV Panels	1,423	85	52.8%
	% renewable contribution to energy savings			6.70%
ZEB 2.0	Baseline	1,010	124	
	Test includes air tight building, improved façade performance with high performance glass, LED lighting, occupancy sensors, daylight harvesting, energy star rated equipment, elevators with VVVF regenerative drives, DOAS units with active chilled beams, high efficiency chillers, demand control ventilation, enthalpy and passive desiccant heat wheels, high temperature-low lift cooling, elevated space temperatures and PV Panels	330	40	67.3%
	% renewable contribution to energy savings			21.1%

4. Phase 3 – New Building Design Performance Evaluation

The final phase of the work concentrated on assessing and identifying opportunities to achieve optimal building performance in an existing operational building. The 3-storey ZEB campus building was used as the primary case study for this phase of the work. The ZEB's current operational performance was assessed through the creation of calibrated Level 4 BEM, where operational faults and/or opportunities for ECM or Retrofit improvements to optimise the performance were then identified.

A baseline Level 4 BEM model of the ZEB was created in the IESVE software based on an existing BIM model and available operation and maintenance (O&M) information. Model calibration was then accomplished by linking simulation inputs acquired from the buildings BMS to apply the actual operating conditions to the BEM, and then comparing simulation results with end-use data. ASHRAE Guideline 14-2014 sets the acceptable calibration tolerances for monthly calibration at +/- 5% for MBE (Mean Bias Error). Due to the calibration approach undertaken and the large volume of data available, a successful calibration was achieved with a 1.1% MBE variation between the actual building and the energy model energy usage (see Table 3 and Figure 5). Achieving this high level of calibration in the BEM enables accurate assessment of ongoing building energy performance and investigating future building retrofit options.

Table 3. ZEB monthly calibration results

Date	ENERGY MODEL (MWh)	BMS Data (MWh)	Mean Bias Error (MBE) Model Vs BMS %
Aug 01-31	14.6	14.9	1.6%
Sep 01-30	12.9	12.7	-1.4%
Oct 01-31	12.2	12.5	2.3%
Nov 01-30	13.2	13.6	3.1%
Dec 01-31	12.9	12.9	-0.2%
Summed total	**65.8**	**66.6**	**1.1%**

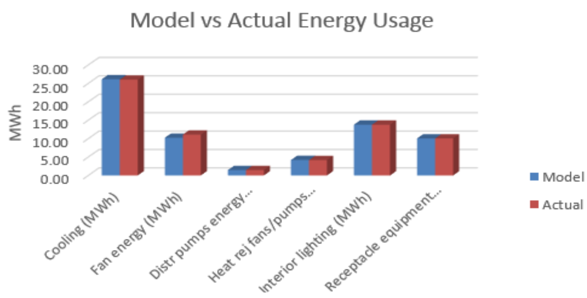

Fig. 5. ZEB calibration results per end-use

Using the calibrated ZEB model developed a number of potential data issues, sub-optimal performance and potential retrofit measures were identified with their effects and resulting savings simulated in the BEM. This included lighting savings of 12% if night-time lighting was eliminated and a fan energy saving of 7% if only operated when required. Figure 6 illustrates the results for a retrofit measure investigating the impact of replacing the existing ZEB chiller, where red indicates the current energy consumption per month, the blue bar shows the consumption of chiller with a supply temperature of 7ºC and the green is a chiller with a 11ºC supply temperature respectively.

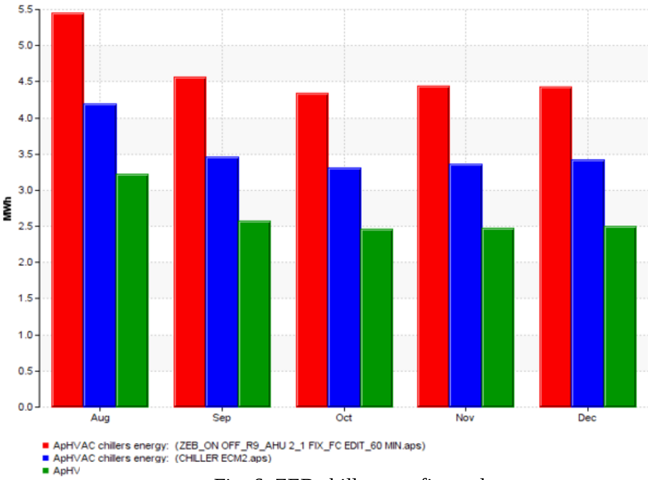

Fig. 6. ZEB chiller retrofit results

5. Conclusions

The paper presents the key findings from the project described to demonstrate the effectiveness of different levels of energy models for different performance analysis requirements aiming to assess and optimize building(s) design and performance. The framework described illustrates how complex BEMs with hundreds of inputs are not always required for energy performance analysis, and more simplified models with reduced inputs and data requirements can provide required guidance in terms of decision making at a group and individual building level for certain types of analysis. Where the Level 1 and 2 models are typically sufficient to provide adequate results to influence decision makers and enable high level planning and compliance tracking, Level 3 and 4 models are more relevant to situations where significant investment may be required (at either the design or operational stage) so more accurate savings and realistic results are required for decision making. These 3 and 4 models can also then be used to measure and verify (M&V) the performance of a new building, or the results of ECMs or retrofit measures in an existing building. Finally, the results from the Level 4 calibration of the ZEB building also signify the benefit the measuring and storing detailed BMS operational data to achieving high levels of BEM calibration, resulting in the ability to carry out accurate simulations to assess and improve the buildings performance virtually ahead of making actual changes in the building. Further work proposed will focus on defining the scalability of this framework to include a larger number of building types and community sizes, as well as more detailed experimentation on the differences in the accuracy of the results from models at each level.

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