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Green BIM-based building energy performance analysis

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ABSTRACT

In the face of a rapidly changing climate and global energy crisis, this study proposes the concept of green building information modeling (Green BIM), and suggests the use of a decision-making cycle when performing building performance analysis (BPA) to obtain design proposals with optimized environmental effectiveness in response to local climate conditions when BIM is used as a basic tool from the beginning of the design process.

Taking building energy performance analysis as an example, in comparison with other domestic and foreign research, the important contributions of the study include: (1)

Based on a design decision-making perspective, a Green BIM-based decision-making cycle can integrate the practical steps of BIM and BPA. (2) Furthermore, this study also finds that meteorological data in a format that can be used in BPA is not easy to obtain. Nevertheless, virtual weather station technology developed using cloud technology can enable a building project to obtain simulated meteorological data relying on weather stations closest to the required criteria, and a cloud building energy analysis engine can be used to implement complex analysis involving large amount of data. As a result, the use of green-BIM technology and concepts can be promoted with greater ease.

When setting energy conservation targets, this study recommends that building energy usage intensity (EUI) be employed as an integrated performance indicator for energy consumption, and percentage of performance optimization be employed as a rating criterion. Nevertheless, the use of energy conservation targets is not essential; depending on the directions in which national governments would like to lead the industry and the maturity and feasibility of relevant technologies, other feasible high-performance benchmarks proposed in this study may also be used in Green BIM.

KEYWORDS
Building information modeling; building performance analysis; green building assessment indicators; energy usage intensity (EUI); virtual weather stations

1. Motivation and goal

In the face of a rapidly changing climate and global energy crisis, how to apply building information modeling (BIM) and related technologies to perform building life cycle information management applications, and thereby enhance construction efficiency and provide architectural solutions with lower building energy consumption, has become a key topic in building-related industries today. BIM has the two implications of information modeling and information management. The advantage of BIM is that it can realize building life cycle management (BLM) at each building life cycle stage, including the planning & design, building permit review, construction, and operation & maintenance stages, provide optimized application support and information management models, and can thereby update conventional architectural design methods. Furthermore, the development of building performance analysis software, such as Ecotect, CFD, and Vasari, has enabled the extension of BIM applications to the initial design assessment stage. As a consequence, with the availability of more precise meteorological and environmental information and site condition knowledge, building structural configuration analysis can include performance analysis and visualization. The integrated application of BIM and BPA technologies can thus enable the formulation of even more optimal design proposals.

2. Literature review

The chief categories of Green BIM research include building information modeling (BIM) and building performance analysis (BPA), as well as the integrated application of BIM and BPA to sustainable building design. Building Product Models, published by Eastman in 1999, defined building product model concepts, technologies, and standards, and set the stage for BIM [8]. Eastman's 2008 BIM Handbook defined BIM and related technologies, and provided BIM applications and illustrative cases for various types of participants (project owners, project

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managers, designer, engineers, and contractor, etc.) [9]. Articles summarizing BIM research topics and representative scholars include: BIM Parametric Modeling [18], BIM Standard Data Exchange Format [15], Applications of BIM Spatial Databases [17], An Integrated Approach for BIM Design and Analysis [23], Information Delivery Manual [7], Use of a BIM Platform in the Concrete Reinforcement Supply Chain [3], and BIM Facility Management [28]. The 2008 Green BIM-Successful Sustainable Design with Building Information Modeling book published Eddy Krygiel & Bradley Nies proposed the "Green BIM" concept for the first time, explored the influence of BIM on updating of design methods and various construction industry participants, and employed BIM in conjunction with BPA to promote sustainable design [16]. McGraw-Hill Construction (2010) suggests that Green BIM can employ energy modeling together with BIM tools to greatly enhance sustainable design results [21].

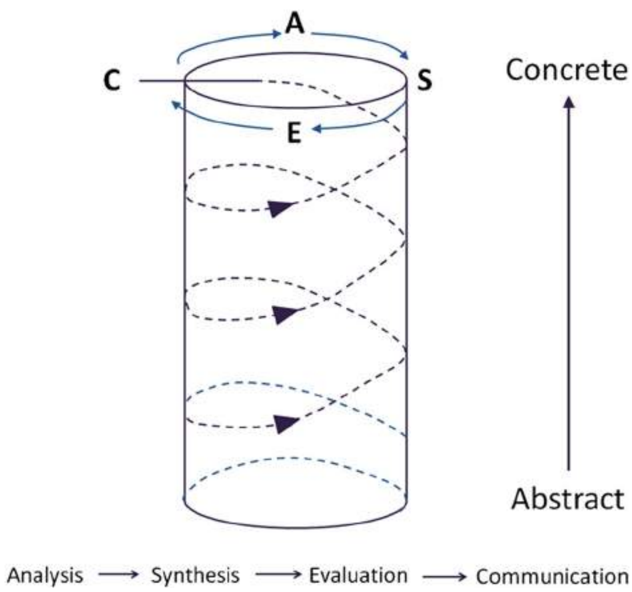
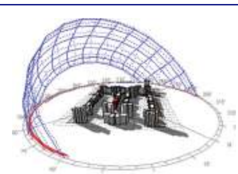
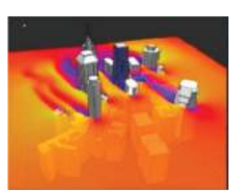
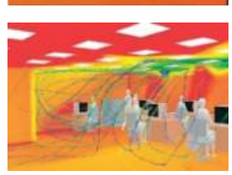
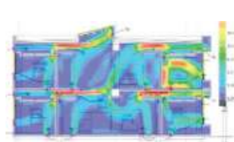
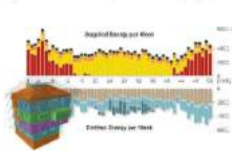


Figure 1. Asimow's decision-making cycle [5].

Apart from use in obtaining 3-D geometric information, BIM can also be used to formulate that part of non-geometric information that can be easily transmitted to building performance analysis software. The integration of BIM and BPA software can promote the use of rational decision-making cycles and optimized development in architectural design. Controlling actions (such as analysis, synthesis, evaluation, and communication, which are considered part of the process of analysis) and design processes can be marked as a series of problem-solving

Table 1. BPA software.

Software tools	Application example	Supported file formats	Visualization items	BPA
Ecotect Analysis [10]		DXF/3DS/RVT-gbXML/SKP-OBJ	Solar radiation, shadows, natural lighting, thermal simulation and analysis, building energy load analysis	Exports to Green Building Studio, can perform reporting of carbon emissions, water usage, and costs
Autodesk Vasari [29]		DWG/DXF/DGN/SAT/SKP	Wind rose data analysis, solar radiation, thermal simulation, energy load analysis, wind tunnel analysis	Energy load analysis (composition / monthly load), carbon emissions and cost reporting
Bently Hevacomp [14]		DXF/DGN/DWG/ IFC/ SKP/3DS/CIS2/gbXML	Energy analysis, three-dimensional visualization of external shading, indoor sunlit areas	Calculation of building heating and cooling loads, calculation of pipe and duct system dimensions, carbon emission analysis
Tas building modeling and simulation tool [17]		CAD/ gbXML/ INP/IDF	Daylighting, wind tunnel analysis, simulation of hot zones	Carbon emissions, energy consumption analysis, cost analysis, indoor comfort indices
Graphisoft Eco Designer STAR [12]		gbXML/PHPP/ iSBEM/VIP-Energy	Meteorological data analysis, energy load analysis, thermal bridge analysis	Building energy load analysis, energy optimization settings, renewable energy programs

steps [22]. Examples include Asimow's decision-making cycle (Fig. 1) [5] and other derivative design process models [4], [25], [11]. Decisions taken during the early part of the design process will have a major influence on building performance throughout the building life cycle. Design methods based on BIM can enable the assessment and comparison of different design proposals during the early design stage, which can effectively improve a construction project [24]. Because of this, building performance analysis (BPA) has become an indispensable link in the design decision-making cycle and optimized development. BIM system software companies are also incorporating BPA tools within the scope of their software development and integration efforts, and hope that they can help designers and other personnel to precisely control building performance within a 3-D operating environment in order to achieve sustainability. Examples include Autodesk's Ecotect Analysis [10] and even easier-to-use Vasari [29], Bently's Hevacomp series [14] and Tas building modeling and simulation tool [27], and Graphisoft's Eco Designer Star [12]. Tab. 1 summarizes and compares software programs, supported file formats, visualization items, and performance analysis items. The compared BPA items include natural and artificial lighting, indoor lighting, overshadowing and shading analysis, solar radiation and thermal performance analysis, wind ventilation analysis, acoustic analysis, visual access, energy load, and carbon emission analysis.

This study takes building energy consumption as an example in showing how Green BIM can be applied to integrated design procedures. The tasks that assessment of building energy consumption must accomplish include (1) selection of energy conservation targets, (2) acquisition of representative meteorological data, (3) determination of major factors influencing building energy consumption and setting of their parameters, (4) selection of an appropriate energy consumption analytical engine, (5) visualization analysis and plan optimization, and (6) confirmation of green building assessment indicator usability.

3. Approach and method

As summarized above, Green BIM emphasizes how building information modeling can be used as a basic tool from the beginning of the design process to perform BPA in response to local climate conditions. In addition, a decision-making cycle consisting of design and analysis processes can optimize design and generate candidate proposals offering environmental effectiveness, and ultimately achieve the goal of environmental sustainability. Fig. 2 shows a flowchart of the decision-making cycle in Green BIM.

During the assessment stage, testing was performed to check the fit of the BIM software and ensure that the virtual weather station technology and energy load analysis engine complied with standards. This study recommends the use of Autodesk's Vasari [29] BPA software. Energy load analysis involves the following key elements:

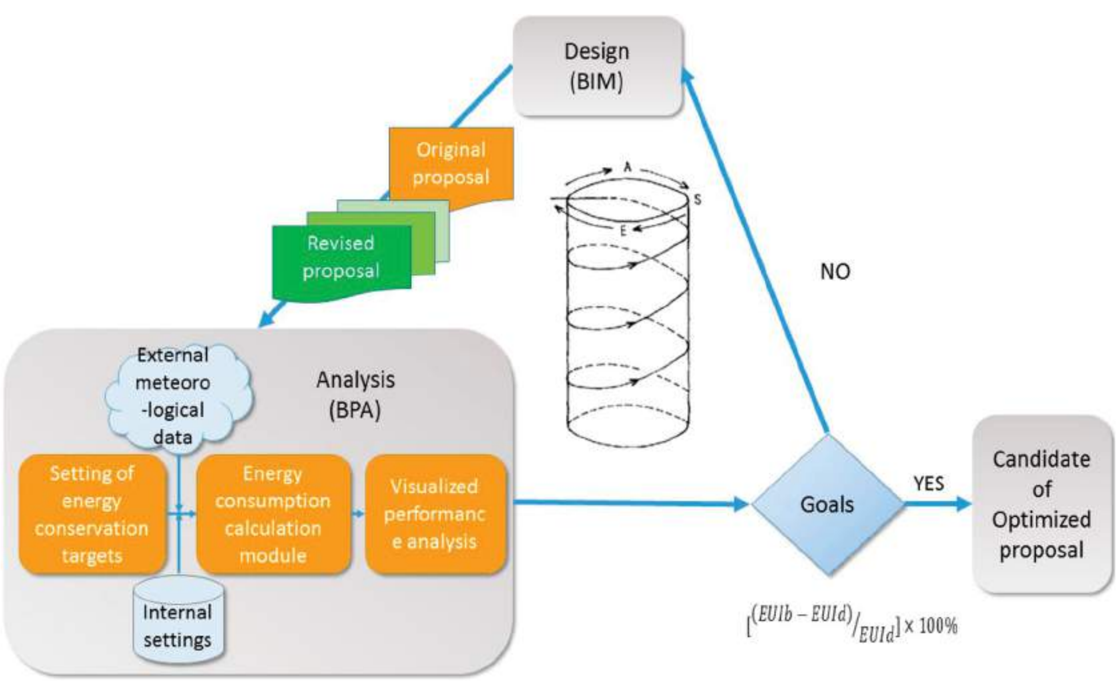


Figure 2. Green BIM decision-making cycle model.

(1) Determination of the scope of the project in the building life cycle: The software simulated building energy load during the operational use stage, and its performance analysis and design optimization decision-making cycle focused on the design stage (including pre-design, preliminary design schematic design, including design development stages).

(2) Setting of energy conservation targets: In accordance with LEED [19] and Taiwan Power Co.'s Taiwan Power Cost and Price Tips [26], this study recommends that energy use intensity (EUI, annual power consumption per building unit area) be used as an overall indicator of building energy load, and the ratio of the baseline proposal's EUI value (EUIb) and the optimized proposal's EUI (EUId) to the EUIb value (percentage performance optimization) taken as rating or target during the determination of design settings.

$$\text{Percentage performance optimization} = [(EUIb - EUId)/EUIb] \times 100\%$$

(3) External meteorological data: While BPA software requires representative meteorological data as a basis for environmental modeling and energy calculations, the inadequate regional meteorological data available in the past hampered the application of BPA software. Due to breakthroughs in cloud-based virtual weather station technology, however, Green BIM need no longer be limited to application in certain regions. Autodesk's meteorological database contains meteorological data in the internationally-accepted TMY (typical meteorological year) format; this data is based on monthly averages for the most recent 30 years at each weather station, where one year of the most recent 10-year period in which monthly data closely approximate average values for the most recent 30 years is taken as a typical meteorological year. Employing TMY data for each weather station, Autodesk derives the corresponding data for virtual weather stations, which helps compensate for differences in data between real weather stations and shrinks the distance between meteorological grid points to less than 14 km, which boosts modeling accuracy [20]. Fig. 3 shows the distribution and density of meteorological data in California and Nevada; the yellow dots represent the locations of climate servers (close to 2,000), and the red dots represent TMY locations.

(4) Internal settings: In accordance with Anderson K. (2014[1]), factors influencing energy load during the building use stage include geometric shape information in the BIM model and non-geometric information required by BIM or BPA, including building type, activity types, user density, shell attributes (structural materials, thermal conductivity, insulation factor), and active systems (air conditioning and lighting) [1]. Parameter settings for these items must be entered in BIM or BPA software, and the parameter values input for the initial baseline proposal must comply with the lowest standards of local building codes. The settings input for the later optimized proposal must further be within the scope permitted by law.

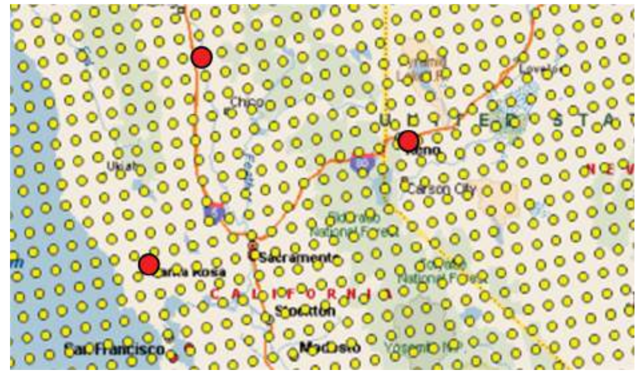


Figure 3. Distribution of meteorological data in California and Nevada.

(5) Energy consumption calculation module: As shown in Fig. 4, the Vasari software uploads the model's internal settings, including geometric information and non-geometric information, and meteorological data to Green BIM Studio in the gbXML format, which uses the DOE-2 engine to perform energy load analysis. The DOE-2 energy load analysis engine passed ANSI/ASHRAE Standard 140 testing and certification in 2008. ANSI/ASHRAE Standard 140 refers to the "Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs" issued by the American Society of Heating and Air-Conditioning Engineers (ASHRAE). [13]

(6) Visualized performance analysis: Following computation, the cloud DOE-2 simulation engine will return visualized building performance results, which include virtual performance and various numerical analysis and statistical charts.

(7) Analysis and revision: Hotspot tracking and adjustment of control variables can be performed in accordance with the results of analysis, and a modified proposal obtained.

(8) Candidate of optimized proposal: A modified proposal meeting energy conservation targets can serve as a candidate optimized proposal.

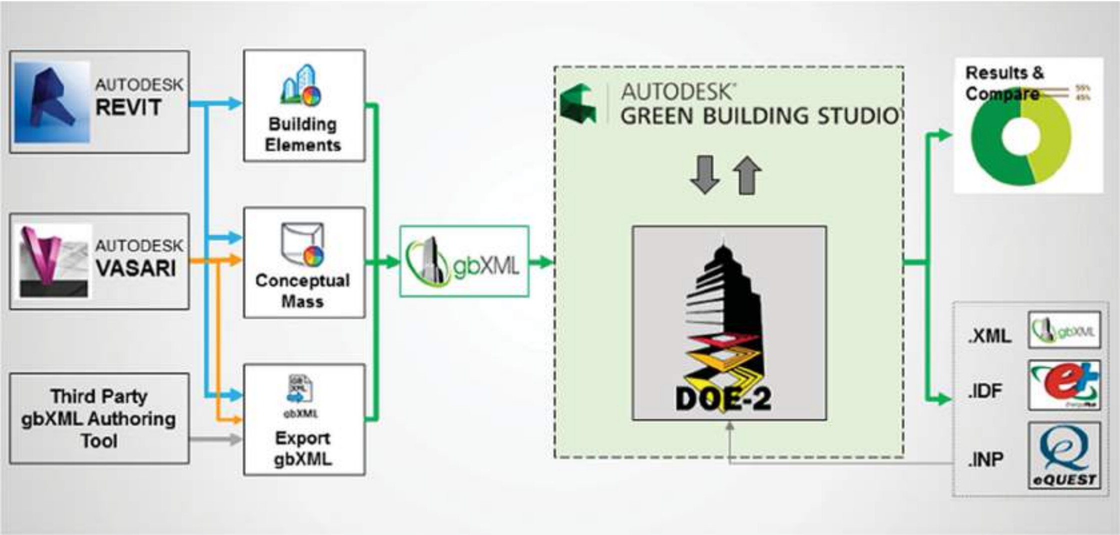


Figure 4. Software block diagram showing Green Building Studio's DOE2 engine, BIM, and BPA [30].

4. Empirical verification

This study used BPA and design optimization process for the Chiayi Harbor Hotel Project to verify the practical value of a Green BIM based decision-making cycle model.

(1) Determination of the scope of the project in the building life cycle:

The Green BIM decision-making cycle for this project—Chiayi Harbor Hotel Project—occurs during the initial design stage (PD, SD, DD stages).

(2) Setting of energy conservation target

The energy conservation target in this case study was optimized performance at least 7% better than the baseline proposal.

(3) Input external meteorological data

Taking the Chiayi Harbor area as an example (Fig. 5), we entered project settings, input the site's latitude and longitude, and selected the closest virtual weather station. (Fig. 6)

(4) Internal settings

The first step was to establish a baseline proposal model (Create Mass/Place Mass) (Fig. 6). Revit software can be used to output as CAD or the SKP format for import into Vasari, or simple modeling can be performed directly in Vasari. Area allocation was performed, and, in accordance with ordinary practice, the percentage glazing was set at 40% in the baseline proposal. The building type was set as "hotel," and the structural materials consisted of the BIM model's default values. (Fig. 7)

Figure 5. Case site location.

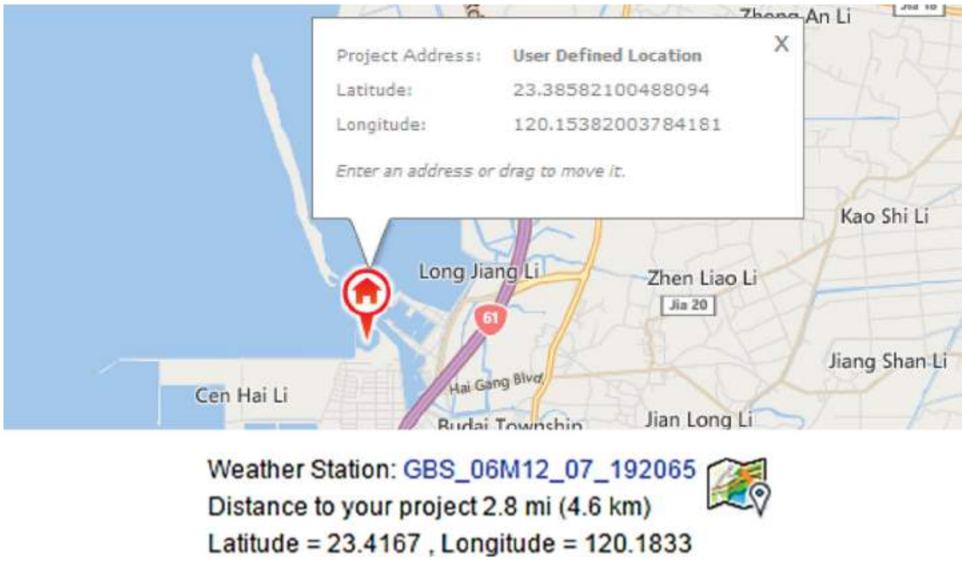


Figure 6. Site location settings and weather station selection.

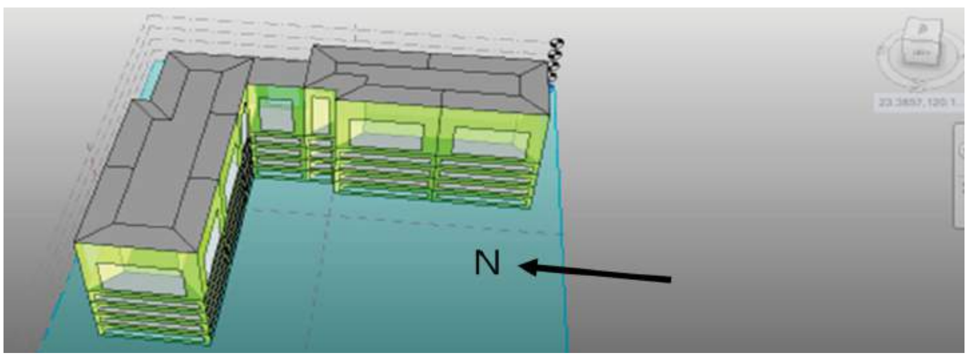


Figure 7. Model construction, including breakdown of floors and thermal zones.

(5) Energy consumption calculation module: The model, internal settings, and meteorological data are transmitted to Green Building Studio's DOE-2 engine via the cloud in gbXML format, and the results of visualized performance analysis are returned.
(6) Visualized performance analysis:

The performance analysis performed in this study included energy use performance analysis and building physical environment performance analysis. The former determined estimated energy usage, and the latter provided reference information for use in subsequent revisions of the proposal. Analysis items included energy use intensity (EUI), energy load and cost over the building life cycle (30 years), energy recovery/energy conservation potential, average carbon emissions, monthly air conditioning load, peak power demand, and other meteorological analysis items. This step consisted of the review and analysis of performance calculation results based on the content of target settings, and feedback concerning key factors was used to aid revision. Different types of buildings have different load characteristics, and "occupancy schedule" is an important concept determining load characteristics. The assessment of EUI must involve comparison with buildings of the same operating type to be meaningful. Autodesk Vasari's building occupancy schedules are based on the classification standards of the California Non-residential New Construction Baseline Study (1999), and the occupancy schedule of the hotel building in this study was taken to be as shown in Fig. 9, where a value along the ordinate axis of 1 indicates that 100 persons are active during this period, and a value of 0.1 indicates that $100 \times 0.1 = 10$ persons are active. In the case of this hotel, peak density times combining the density characteristics of weekdays and weekends are 1:00-8:00 in the morning and 19:00-24:00 in the evening. Because of this, after completing basic parameter settings, in accordance with modeling results, the building was determined to accommodate 183 persons and have a power use density of 221 kWh/ m_2*year, which

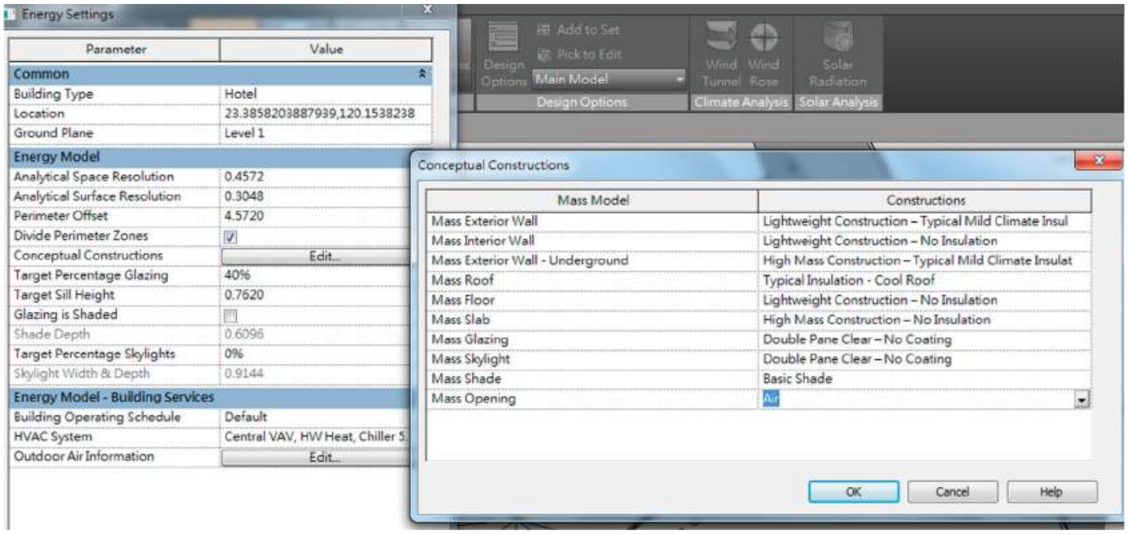


Figure 8. Building internal settings (including performance and structural materials).

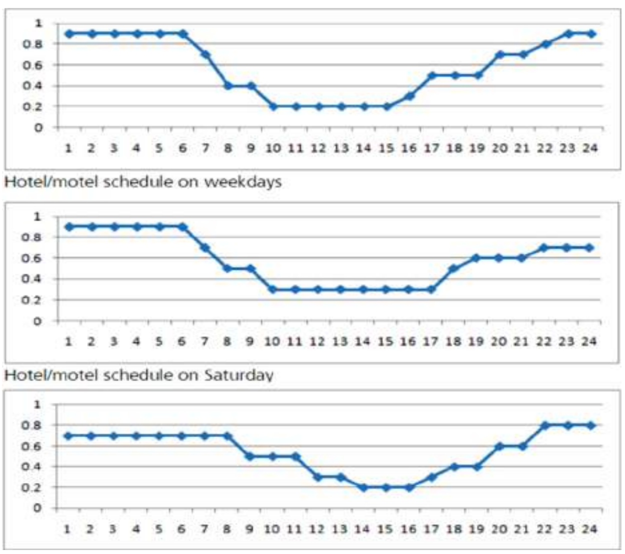


Figure 9. Hotel building occupancy schedules.

Building Performance Factors

Location:	23.3856983184814,120.15421295166
Weather Station:	545924
Outdoor Temperature:	Max: 35°C/Min: 12°C
Floor Area:	7,335 m²
Exterior Wall Area:	5,899 m²
Average Lighting Power:	10.87 W / m²
People:	183 people
Exterior Window Ratio:	0.30
Electrical Cost:	$0.06 / kWh
Fuel Cost:	$1.20 / Therm

Energy Use Intensity

Electricity EUI:	221 kWh / sm / yr
Fuel EUI:	279 MJ / sm / yr
Total EUI:	1,076 MJ / sm / yr

Life Cycle Energy Use/Cost

Life Cycle Electricity Use:	48,741,120 kWh
Life Cycle Fuel Use:	61,303,112 MJ
Life Cycle Energy Cost:	$1,621,709

*30-year life and 6.1% discount rate for costs

Renewable Energy Potential

Roof Mounted PV System (Low efficiency):	235,371 kWh / yr
Roof Mounted PV System (Medium efficiency):	470,743 kWh / yr
Roof Mounted PV System (High efficiency):	706,114 kWh / yr
Single 15' Wind Turbine Potential:	2,786 kWh / yr

*PV efficiencies are assumed to be 5%, 10% and 15% for low, medium and high efficiency systems

Figure 10. Breakdown of floors and thermal zones.

is approximately 13% higher than the general hotel average power use density of 195.6kWh/m$_2$*year (Fig. 10). Power consumption analysis revealed that air conditioning equipment had the highest energy load (73%), followed by lighting with 18% (Fig. 11). Inspection of monthly energy load: Use of load composition analysis indicated that heat conduction through the windows and outer walls was the largest source of air conditioning load, and was followed by lighting equipment and solar radiation entering through windows; since the latter two variables are mutually interacting, and experimental revision process was employed to determine a design proposal yielding optimal energy conservation benefits. From the perspective of monthly power use distribution, power consumption is relatively high during the

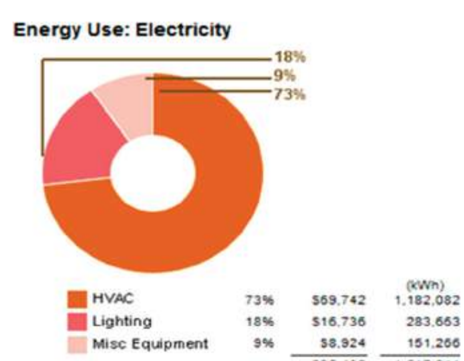


Figure 11. Analysis of relative power usage.

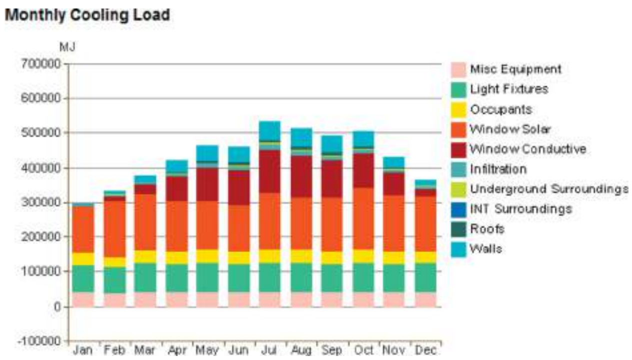


Figure 12. Monthly energy load.

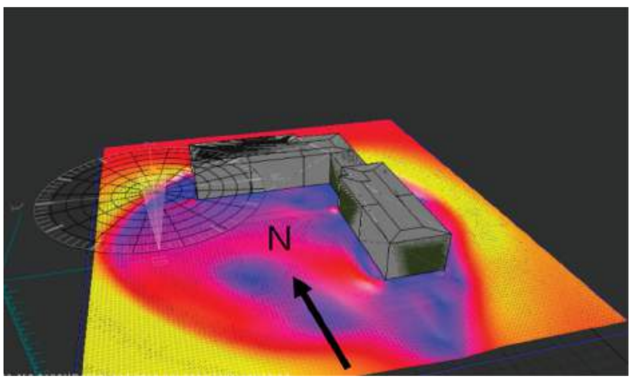


Figure 13. Dynamic simulation of building wind field.

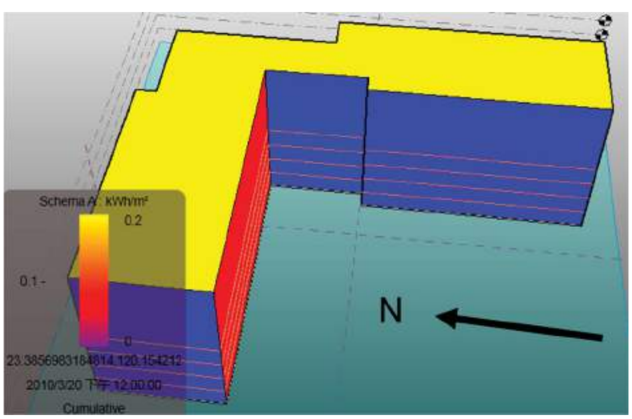


Figure 14. Distribution of solar radiation on the building's outer walls.

summer months of July and August (Fig. 12), and air temperature and solar radiation follows similar trends. We therefore concluded that if the power rate was used to assess power costs throughout the year, improved summer power conservation could reduce operating costs. Analysis of the site's physical environment: In accordance with the results of visualized performance charts, including the wind rose and wind field simulation results in Fig. 13 and solar radiation simulation results in Fig. 14, the directions of prevailing winds were found to chiefly include north and north north-east, and the L-shaped building received intense thermal radiation on the south side.

(7) Analysis and revision

According to the foregoing visualized performance analysis of the baseline proposal, because the site is located in a tropical, maritime climate, thermal radiation is intense near the water, and there is no vegetation to provide shade. Analysis of the thermal environment revealed that heating would be most intense on the southern and western sides of the building. In order to reduce thermal load, the following revisions and adjustments were made:

- Target percentage glazing: reduced from 40% to 25%
- Target sill height: increased from 0.76 to 0.85
- Eaves shading: eaves shading was increased by 3 m on the southern and western sides
- Construction of mass exterior wall: changed from lightweight construction–typical mild climate insulation (R-value of 10) to high mass construction-high insulation (R-Value of 17) (Fig. 15, Fig. 16):

(8) Candidate of optimized proposal

In accordance with the foregoing optimization recommendations, the proposal's EUI was adjusted from 221 kwh/m_2-year to 203 kwh/m_2-year, which was an approximate reduction of 8.1% $\geq$ 7%; [(221–203)/221] = 8.1% $\geq$ 7% (Fig. 17). This reduction ratio was greater than the preset energy conservation target, and the revised proposal could therefore serve as a candidate optimized proposal.

5. Conclusions

Green BIM emphasizes the use of building information modeling as a basic tool from the initial design stage. In addition, use of a "design" and "analysis" decision-making cycle when performing BPA in response to local climate conditions can yield optimized design proposals with good environmental effectiveness, and ultimately achieve the goal of environmental sustainability. This study proposed a Green BIM decision-making cycle model. Taking energy consumption throughout the building life cycle as an example, the study verified the practical effectiveness of Green BIM in the case of the "Chiayi Harbor Hotel Project." The study input a project drafted using BIM software into Vasari for BPA calculations, and used the gbXML format to transmit the resulting data to the DOE-2 engine via the cloud for

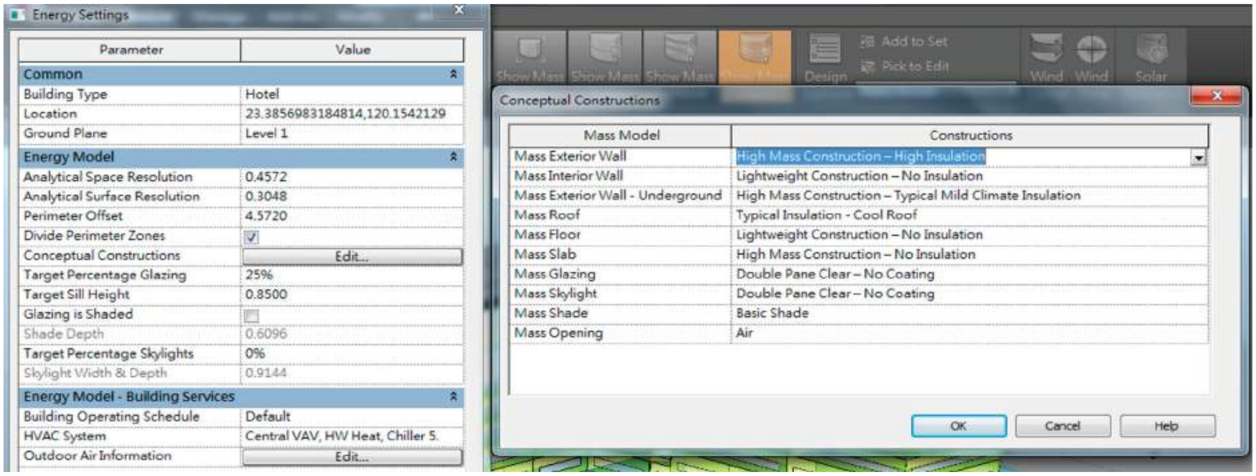


Figure 15. Revisions to the building structure (target percentage glazing, target sill height, and construction of mass exterior wall).

building energy performance analysis. Energy use intensity (EUI, annual power consumption per building unit area) was taken as an overall indicator of building energy load, and percentage performance optimization served as the approach to target value settings in the optimized proposal.

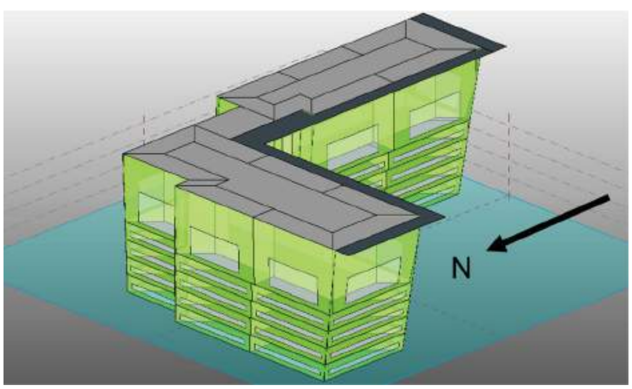


Figure 16. Optimized proposal (modification of percentage glazing, increased eaves shading).

Nevertheless, energy conservation benchmarks are not necessarily essential. In view of the fact that it would be difficult to find alternatives to the Taiwan Power Co.'s role as the predominant power supplier and its pricing model on the main island of Taiwan, this study consequently took EUI as a green energy indicator that people could understand intuitively. Depending on the ideals and goals of a design project, there are also many other possible energy target benchmarks, and the feasibility of their use will depend on the direction in which the government wishes to lead the industry and the mutually of relevant temperature. Other feasible energy conservation benchmarks [2] include:

(1) Energy cost budget

This building energy conservation benchmark is used in LEED certification. Variable parameters specified in ASHRAE 90.1 can be input into a baseline proposal, Energy Plus Software used to output an ECB (energy cost budget), and percentage performance optimization employed as the LEED rating threshold.

(2) Net zero energy

The power density achieved by a design proposal's renewable energy equipment should comply with the building's energy load density.

(3) Passivhaus standards

It takes EUI as an indicator, concerning the maximum energy load of passive household air conditioning equipment.

(4) Peak heating or cooling

Energy Use Intensity

Electricity EUI:	221 kWh / sm / yr
Fuel EUI:	279 MJ / sm / yr
Total EUI:	1,076 MJ / sm / yr

Energy Use Intensity

Electricity EUI:	203 kWh / sm / yr
Fuel EUI:	227 MJ / sm / yr
Total EUI:	957 MJ / sm / yr

Figure 17. Comparison of energy load of baseline proposal (left) and optimized proposal (right), "sm" means square meter and equals "m_2".

The energy load of mechanical systems may not exceed the peak load value.

(5) Carbon footprint target

Although the carbon emission coefficient of power use can be used to convert energy load to carbon emissions during the building use stage, total carbon emissions throughout a building's life cycle, including the stages of building materials production and transport, construction, use, and abandonment, involves many systems and great complexity, and will therefore require further research.

Apart from this, because buildings must satisfy varied functional requirements, a final optimized proposal will be the result of numerous decisions and trade-offs [6]. Energy conservation is only one of a building's important performance indicators. As a consequence and optimized proposal derived employing energy conservation targets can only be seen as a candidate proposal. Because of this, how to handle the decisions and trade-offs involved in dealing with various performance indicators and choosing among different candidate proposals will be an important research topic in further studies of Green BIM.

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