A multicriteria lifespan energy efficiency approach to intelligent building assessment

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A multicriteria lifespan energy efficiency approach to intelligent building assessment

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Abstract

This paper presents a multicriteria decision-making model for lifespan energy efficiency assessment of intelligent buildings (IBs). The decision- making model called IBAssessor is developed using an analytic network process (ANP) method and a set of lifespan performance indicators for IBs selected by a new quantitative approach called energy–time consumption index (ETI). In order to improve the quality of decision-making, the authors of this paper make use of previous research achievements including a lifespan sustainable business model, the Asian IB Index, and a number of relevant publications. Practitioners can use the IBAssessor ANP model at different stages of an IB lifespan for either engineering or business oriented assessments. Finally, this paper presents an experimental case study to demonstrate how to use IBAssessor ANP model to solve real-world design tasks.

Keywords: Intelligent building; Life cycle assessment; Analytic Network process; Energy efficiency

1. Introduction

Sustainable building design, construction and operation require innovations in both engineering and management areas at all stages of a building's life. The lifespan of buildings is composed of a series of interlocking processes, starting from initial architectural and structural design, through to actual construction, and then to maintenance and control as well as to eventual demolition or renovation of buildings. Inside this lifespan, essential requirements are generated from considerations of social, environmental, and economic issues for high- efficient energy-saving building systems in compliance with building codes and regulations. In this regard, building assessment is becoming popular in order to have a standard method to evaluate new and existing building design. For example, the U.S. Green Building Council [89] developed the Leadership in Energy and Environmental Design

(LEED) Green Building Rating System asa voluntary, consensus-based national standard for developing high-performance, sustainable buildings. The Japan Sustainable Building Consortium [99] developed the comprehensive assessment system for building environmental efficiency (CASBEE) system as a new environmental assessment system to meet both the political requirements and market needs for achiving a sustainable society. The Building Research Establishment Ltd. [9] from UK developed the Building Research Establishment Environ- mental Assessment Method (BREEAM) to assess the environmental performance of both new and existing build- ings. Meanwhile, intelligent buildings (IBs) are also under assessment according to their IB related characteristics and actual circumstances. For example, the Asian Institute of Intelligent Buildings (AIIB) [5, 22] from Hong Kong devel- oped an IB Index system to specifically assess the performance of IBs; and the BRE developed a matrix tool called MATOOL for assessing the performance of intelligent buildings [12]. Although a new international benchmark of IB assessment is under developing by the Continental Automated Building Association [18] in Canada, there is not a standard sustainable IB assessment tool, and this leads to the research being presented in this paper.

Based on current practice in building assessment, the authors of this paper present a multicriteria decision-making model using the analytic network process (ANP) [70–72] to evaluate the lifespan energy efficiency of IBs. To undertake this task, this paper firstly reviews building assessment systems currently adopted in Australia, Canada, Hong Kong, Japan, Korea, mainland China, The Netherlands, the United Kingdom and the United States. A quantitative indicator selection approach to energy–time consumption during building lifespan is proposed based on a Strategic Intelligent Building Evaluation and Renovation (SIBER) model, which is a development of the *Through Life Environment Business Model* developed by the University of Reading for lifecycle assessment [24]. Under the SIBER model, the authors further developed a Tactical Intelligent Building Evaluation and Renovation (TIBER) model, and from which an ANP model named IBAssessor is then structured based on a group of key performance indicators (KPIs) [2], which are selected through a proposed quantitative approach called energy–time consumption index (ETI). In order to further exam the effectiveness of IBAssessor, an experimental case study is finally conducted with detailed calculation and evaluation procedures. The paper concludes that auditors can use the IBAssessor when it is necessary to evaluate the lifespan energy efficiency of IBs and therefore select the most appropriate building.

The significant contributions of this paper include an energy–time analysis based quantitative approach to KPI selection, a set of criteria applied to IB assessment regarding their lifespan performances of energy efficiencies, and an ANP model for lifespan energy efficiency assessment in IB design, construction and operation. Meanwhile, the evidence to be presented in this paper include the SIBER model for building lifespan performance management; the TIBER model for IB assessment; the energy–time analysis based quantitative approach to KPI selection; the ANP model for selecting the most appropriate IB alternative based on lifespan energy–time consumption analysis; and an experi- mental case study. It is the authors' expectation that practitioners including managers and auditors can use the proposed IBAssessor for energy efficiency assessment in IB design, construction and operation.

2. Assessment methods

According to the latest literature [24], an IB is one that provides a productive and cost-effective environment through optimizations based on its three basic elements—people (owners; occupants; visitors, etc.); products (materials; fabric; structure; facilities; equipments; services); and processes (automation; control; systems; maintenance; performance evaluation)—and the interrelationships between them. IBs use integrated and intelligent systems to provide a rewarding experience for the building owners, property managers, occupants and visitors to achieve their goals. These goals include the lifespan high energy efficiency, the environmental- friendly built environment with substantial safety, security, well-being and convenience, a lower life-cycle cost, and long- term flexibility and marketability, which lead to achieve a high- level of buildings that have the highest social, environmental and economic values. Meanwhile, IBs use advanced information and communication technologies to develop embedded data collection and information networks through which its services systems are automatically controlled to respond using an approach similar to the sensor system of human beings, guided by predictions based upon knowledge of the past situations of the building and usage, maintained in an integrated data base. Thus, IBs should be sustainable, healthy and technologically aware, meet the needs of occupants and business, and should be flexible and adaptable to deal with change.

Practitioners use assessment methods to evaluate the design or the performance of IBs. There are three main kinds of assessment methods including building rating, computer simulation and facilities management [24]. The rating method relies on a series of factors/indicators related to the design and the performance issues together with their defined scales to rate an IB. The simulation method uses artificially settings based on real-world data from the operation of IBs. The facilities management method use experts' knowledge to achieve goals in practical IB design, construction and operation. The applications of the first two kinds of assessment methods can be at either design or operation stage of any IB under evaluation, while the third method can be applied at all stages of the IB life cycle.

The authors are conducting an extensive literature review on conventional building assessment systems in order to extract a group of indicators for the proposed ANP model. Current building assessment systems under review include:

- Assessment Standards for Certifying Intelligent Buildings (ASCIB, by Intelligent Building Society of Korea (IBSK), Seoul, Korea) [39],
- Building Quality Assessment (BQA, by Building Economics Bureau, UK),
- Building Research Establishment Environmental Assessment Method (BREEAM, by Building Research Establishment Ltd. (BRE), UK) [9],
- Building Sustainability Assessment Tool (BSAT, by the Department of Trade and Industry, UK) [73],
- Building IQ Rating Criteria (BIQRC, by Task Force 1— Intelligent Building Ranking System, Continental Automated Building Association (CABA), Ottawa, Canada) [18],
- Comprehensive Assessment System for Building Environ- mental Efficiency

(CASBEE, by Japan Sustainable Building Consortium (JSBC), Japan) [99],
- Design Quality Indicator (DQI, by Construction Industry Council, UK),
- Environmental Performance Express of Buildings (Eco- Quantum, by IVAM, The Netherlands),
- Assessment Framework and Green Building Tool (GBTool, by the International Initiative for a Sustainable Built Environment (IISBE), Canada) [100],
- Green Mark for Buildings (GMB, by Building and Construction Authority, Singapore) [104],
- Hong Kong Building Environmental Assessment Method (HK-BEAM, by HK-BEAM Society, Hong Kong) [101],
- IB Index (by Asian Institute of Intelligent Buildings (AIIB), Hong Kong) [5,22],
- IB Rating (by Shanghai Construction Council (SCC), Shanghai, China) [74],
- Leadership in Energy and Environmental Design/Green Building Rating System (LEED, by U.S. Green Building Council, USA) [89],
- A matrix tool for assessing the performance of intelligent buildings (MATOOL, by Building Research Establishment Ltd. (BRE), UK) [12],
- National Australian Built Environment Rating System (NABERS, by Department of the Environment and Heritage, Australia) [102],
- Office Scorer (Sustainable Refurbishment/Redevelopment Decision Support Tool for office buildings, Building Research Establishment Ltd. (BRE), UK) [8],
- Sustainable Project Appraisal Routine (SPeAR, by Arup, UK) [103], and
- Sustainability Checklist (Assessment of the social, environ- mental and economic impact of a proposed development, by the South East England Development Agency (SEEDA), UK) [7].

According to the literature review focusing on the building assessment systems, the authors noticed that there are several successful applications of rating methods for building performance assessment. For example, the LEED *Green Building Rating System*[1] is a voluntary, consensus-based national standard for developing high-performance, sustainable buildings in the United States [89]. The *Environmental Assessment Method* by the Building Research Establishment Ltd. (BREEAM) is adaptable to assess the environmental performances of both new and existing buildings in the UK [9, 30]. The *Standard Assessment Procedure* (SAP) of the National Home Energy Rating (NHER) is the UK's premier energy labelling scheme recommends by the UK Government for home energy rating [58]. On the other hand, although simulation methods can provide more reliable results than rating methods using various conditions in the building lifespan based on objective and subjective settings in computer programmes; there is not a comprehensive simulation tool for practitioners to conduct IB assessment at present. On the contrary, popular simulation approaches mainly focus on only one part of building performance such as thermal environment or acoustic environment, and it is a difficult task to develop a tool for complete performance simulations of the total environment in buildings. In this regard, rating systems have been widely adopted in building performance assessments, and the simulation method is often adopted in building design.

Among these building assessment systems, there have been several rating methods designed for for IB assessment, and there are some new rating systems under development

as well. Table 1 gives a summary of representative methods based on current practice in IB assessment. According to the literature review, the authors identified six assessment clusters of indicators centreing on Architecture, Engineering, Environment, Economics, Management, or Sociology. Among the five IB assessment systems listed in Table 1, the AIIB method, i.e. IB Index method [5, 22] is the most comprehensive one that covers all of the seven assessment clusters, and the SCC method [74] is mostly focused on the one assessment cluster, i.e. Engineering. The CABA method [18] aims to benchmark the IB assessment in a more general way but is still under construction. And the BRE method, i.e. MATOOL [12] and the IBSK method [39] have less coverage of assessment clusters than the IB Index. Therefore, the AIIB method is currently the most comprehensive method for IB assessment.

Table 1
The main categories of criteria adopted in rating methods for IB   assessment

Assessment clusters	Main modules by each assessment system					
	AIIB method [5,22] (Hong	BRE method [12] (UK)	CABA method [18]	IBSK method [39] (Korea)	SCC method [74] (Shanghai,	TIBA method
Architecture	Comfort Health and Space	Built – –	– – –	Architectural – –	– – –	Health and – –
Engineering	High-tech image Safety and Working – – – – –	Functionality Responsiveness Suitability – – – – –	Automation Comms Security Structure Systems – – –	Electrical system Info and comms Mechanical System – – – –	Conmunication Earthing Facility control Fire accident Int. integration Office automation Power supply Security Structured cabling	Info and Safety and Structured System – – – –
Environment	Green	–	–	Environment	Environment	Energy
Economics	Cost	Economic	–	–	–	–
Management	Practice and	–	Property	Facility	Property	Facilities
Sociology	Culture	–	–	–	–	–

3. Limitations of building rating methods

One problem of current building rating methods is that they actually pay less attention to functional variation in different types of buildings, which influence not only the emotional as well as the physical well-being of human beings, but also the design and the management of buildings. In other words, each assessment procedure conducted under each rating method actually uses a generic platform of indicators applied to all kinds of buildings therefore do not differentiate one building from another regarding their various features. As a consequence, assessment results of different kinds of buildings actually lack the power of comparability regarding the features of IBs. For example, AIIB method adopts 29 sub-indicators to assess the performance of lift and escalators [5, 22]; however, there is not a practical guide regarding how to compare two designs for one IB project if one uses a lift but another does not. It is not sensible to say buildings with a lift are more intelligent than buildings without them but a common generic platform will ensure all

buildings have consideration given to aesthetics, function, convenience, flexibility, adaptability, reliability and health. In addition, the IBSK method [39] uses occupation density (occupation area for one person) as one indicator to assess *Architectural Design* of IBs, and the building with larger occupation area (a low occupation density) will get a higher score; however, one cannot say easily that a supermarket is much more intelligent than an office building because occupation area in supermarket is larger than that in an office building. In fact, buildings are classed according to their patterns of use at the design stage or management stage. For example, *The Town and Country Planning* (*Use Classes*) *Order* [59] regulates building class into four main categories with 16 classes depending on the purposes of building utilization in town and country planning and has been widely adopted in building design in the UK [4]. *The NYC Building Classification Codes* [64], on the other hand, provides a complete, comprehensive list of each Building Classification Code, and has been officially used to classify all properties and parcels from private homes to amusement parks by the City of New York. The lack of flexibility in current rating methods for IB assessment and the preference of classification in building design, construction and management indicate that innovations are required to develop flexible techniques for more objective assessment results of IBs.

Another problem of current building rating methods for IB assessment is that their calculation processes are not convincing enough to provide a reasonable assessment result. For example, the AIIB method, i.e. IB Index [5,22] aims to provide a quantitative composite approach to IB assessment using 10 indicator clusters based on the Cobb–Douglas utility function[112]. However, the recommended method for the IB Index calculation (see Eqs. (1) and (2) in Equations in Appendix A) is not actually reliable due to the following four reasons:
- the criteria of the AIIB method lead to non-determinism,
- the calculation method of the AIIB method is a non-sequitur,
- the calculation results from the AIIB method are non-unique, and
- the assessment procedure is based on non-organization principle/judgement.

Brief explanations to these reasons are given below:

The non-determinism led by the criteria of the AIIB method means that the assessment scores for each IB result from the evaluation criteria has questionable validity. As assessment results from each rating method depend upon a set of criteria denoted with a group of IB indicators, it is important to select the most appropriate group of indicators that are able to stand the test, and indicators adopted in a rating method that have less relevance to the IB will reduce the accuracy in assessments. For example, Special feature(s) recommended by the auditor is adopted in the AIIB method as an IB indicator in all most every category including Green, Space, Comfort, Working efficiency, High-tech image, Safety and structure, and Practice and Security. It is clear that different auditors will give different scores to these indicators even though all auditors deal with the same building because of their knowledge and their various understanding of the fuzzy definition during assessment. Based on this consideration, evaluations of IB indicators are of necessity required.

On the other hand, the AIIB method adopts, from the field of economics, the celebrated

Cobb–Douglas utility function as its calculation method in the process of assessment [5, 22]. The Cobb–Douglas utility function is a standard utility function applied to describe matching output to input in a production processes and it is used commonly in both macro- and micro-economics [108,109]. However, there is no clear information to support concerns about the application of the Cobb–Douglas utility function to the rating procedure according to personal discussions between the authors and other researchers in either the Cobb– Douglas utility function or rating procedure fields. In fact, the AIIB did not provide a reasonable explanation of reasons to adopt the Cobb–Douglas utility function in the calculation of a 10-module IB Index algorithm. Although the Cobb– Douglas utility function is one of the most widely applied utility functions in microeconomics, its major drawbacks such as the limited scope of effective regions and the harsh constraint terms to parameters definitely affect its utility in applications [10, 27, 37, 65, 97]. It is actually hard to define a physical model to describe this 10-module IB Index algorithm beyond the Cobb–Douglas utility function. Moreover, according to the second law of thermodynamics, which requires that any process that takes place at non-zero speeds must consume a minimum finite amount of exergy (the quality of energy), so production isoquants (combinations of inputs that yield the same output) [113] cannot be of the Cobb–Douglas type [40]. In these cases, the necessary and the sufficient conditions of applying the Cobb–Douglas utility function to the 10-module IB Index algorithm therefore require more study.

In addition, the AIIB method allows subjective weights of different building modules but this can lead to confusion about the interpretation of the assessment results. Table 2 recalls an example by the AIIB [5,22], in which the rate of weight comparison between two building modules are set as wx : wy ¼ 2 : 1, and the results of IB Index for each kind of building and the rank of their intelligence are in accordance with common intuition as to which kind of building is more intelligent. However, the function adopted in the IB Index calculation (refer to Eq. (3)) does not always lead to a sensible result. For example, let wx : wy ¼ 3 : 1, the IB Index values for each building are then different from the ones under wx : wy ¼ 2 : 1, and the sequence of building intelligence also changes (see Table 2). The AIIB method cannot provide a unique result, as different auditors may make different conclusions, which definitely cause complex- ity and variance in IB assessment.

Regarding the non-organization assessment procedure adopted in current building rating systems, the authors find that it is difficult to recognize Organization factors from current systems besides the Management cluster, in which only property management issues are concerned. Based on the summary in Table 1, the non-organization principle/ judgement existed in current building rating systems can definitely lead to partial assessments in which evaluators will miss their chance to study the culture, the structure and the occupants of all factors, which influence the performance of the building.

Table 2 An experimental verification of the AIIB IB Index method

Buildings	Scores		IB Index			
	Module x	Module y	$w_x : w_y = 2 : 1$	Rank of intelligence	$w_x : w_y = 3 : 1$	Rank of intelligence
	70	50	63	1	64	2
B. Balanced Building	60	60	60	2	60	3
C. Mechanical Plant	100	20	59	3	69	1
D. Tree House	20	100	34	4	30	4

Theoretically speaking, logical defects in the currently used building rating methods, such as the IB Index method, may lead to an invalid IB assessment. It is thus required to provide an alternative method to evaluate the characteristics of IB, under objective and real life conditions, in which all indicators are taken into account, not only their values but also their interrelationships. In this respect, the authors put forward an alternative measure for IB assessment by means of analytic network process (ANP) [70–72]. In a test drive using the IB Index, the authors also noticed that 43 indicators (refer to Table 5) can be extracted from an integration of its 378 elements of 10 modules by using a quantitative indicator selection approach to be introduced below in Section 4. In fact, this integrative extraction also indicates that most elements adopted in the IB Index are repeated and need simplification. As mentioned above, the IB Index has a comprehensive classification of IB indicators, from which a most appropriate group of indicators can be selected for the ANP based assessment. In terms of the selection of indicators for assessing the lifespan energy efficiency of IBs, a quantitative evaluation approach will be put forward under the criteria of energy consumptions over time in which people, processes, and products are involved. To overcome the shortcomings that exist in the current IB Index method, the proposed IBAssessor can provide an innovative IB evaluation approach, in which both the value of indicators and their interrelations are taken into account.

4. Quantitative selection of indicators

4.1. A SIBER model

Lifespans of buildings include successive process stages in design, construction and operation relevant to their structural and services systems. The life cycle analysis/assessment (LCA) method is a quantitative approach to assess load magnitude in both natural and built environments in different patterns attributable to various influential factors at each stage of building systems [42]. The LCA method was introduced to the construction industry in 1970s [14, 82] in both structural engineering and project management. In the past 30 years, it has developed another main stream of assessment theory in the building and construction industry [3,6,7,15,16,17,20,21,23,32, 34,35,36,44–46,49,50,51–57,61,62,63,66–69,77,78,83,90–96,98,105]. For implementing the concept of LCA in project management, one essential is to benchmark construction processes; significant research and development progress have been achieved already. For example, the CSI [29] in the USA made a close loop of project cycle that describes five phases for construction projects including Planning and Predesign Activ- ities, Design Activities,

Bidding Activities, Construction Activities, and Post-Construction Activities. Kagioglou et al. [48] in the UK developed a general Process protocol that describes ten phases for construction projects including Demonstrating the Need, Conception of Need, Outline Feasibility, Substantive Feasibility Study and Outline Financial Authority, Outline Conceptual Design, Full Conceptual Design, Co-ordinated Design, Procurement and Full Financial Authority, Production Information, Construction, and Operation and Maintenance. Smith [78] in the USA developed a knowledgebase support prototype for the Total Life-cycle Cost that describes ten phases for construction projects including Requirements, Plan, Program, Design, Construction, Operation, Maintenance, Evluation, Revitalization, and Disposal. The U.S. Army Corps of Engineers (USACE) conducted a series LCA research in 1990s [83–88] including the Guide for Project Partners and the Facility Composer. The Guide for Project Partners describes six basic phases of a civil works project including Reconnaissance, Feasibility, Pre-construction engineering and design, Real estate acquisition, Construction, and Operations and maintenance; and the Facility Composer is a suite of criteria/requirement-based facility modeling tools that integrate customer-specific criteria with a life-cycle facility model and commercial tools [79]. The Australian Building Codes Board [1] introduced energy efficiency performance standards into the Building Code of Australia in 2003 [76], in which Life Cycle House Energy Estimator [31] is adopted. Literature reviews indicate the process oriented LCA has been widely recognized and adopted in the building and construction industry, and become the basic view and starting point of construction management.

On the other hand, standards for quality assurance in business have been developed since late 1950s [75]. After the ISO [41–43] issued ISO 9000:1994 series of quality management standards and replaced with ISO 9000:2000, life-cycle business management has become a new development of LCA in construction management. For example, the USNIBS (1998) put forward a *Total Life-cycle Cost Model* for facilities managers to conduct the comparative evaluation of all costs, including productivity of function and impacts on the enterprise, health and the environment throughout the facilities life [78]. The FIDIC [33] introduced a *Business Integrity Management System* to set out why consultants should apply business integrity management in all of their work, and should introduce initiating the business integrity management process into their firms. Moreover, the USACE [86] developed a *Project Management Business Process* model to deliver quality projects. The model reflects the USACE corporate commitment to provide inclusive, seamless, flexible, effective, and efficient customer services, and embodies communication, leadership, systematic and coordinated management, teamwork, partnering, effective balancing of competing demands, and primary accountability for the life cycle of a project. Based on these LCA-based process benchmarks, Clements-Croome et al. [25] put forward the *Through Life Environment Business Model* (TLEBM) that concentrates upon six consistent phases for the business management of construction projects including *Client Brief*, *Design*, *Installation*/*Commission* (I/C), *Operation and Maintenance* (O&M), *Post Occupancy Evaluation* (POE), and *Reuse/Recycle/Disposal*. In order to select the most appropriate indicators for intelligent building performance assessment, the authors integrate a *Building Assessment* entity with decision processes (decision-making options) into the *TLEBM* (refer to Fig. 1). There are three decision processes involved in the proposed decision-making model including a *Design Review* between the *Design* phase and the *I/C* phase; an *I/C*

Review between the *I/C* phase and the *O&M* phase; and an *O&M Review* between the *O&M* phase and the *Disposal/Reuse/ Recycle* phase, which is integrated with the *POE* phase. The new evolving process, which is a *TLEBM* based prototype for the lifespan performance assessment of buildings, is entitled SIBER, which is a *Strategic Intelligent Building Evaluation and Renovation* model.

In addition to the review of current rating systems, the authors are also planning a generic platform of IB assessment under the SIBER model, which is a representation of sustainable issues over the whole lifespan performance of buildings [25]. In this paper, the SIBER model will be used to effectively control a process in which a group of assessment indicators is quantitatively selected (refer to Fig. 2).

The SIBER model regulated assessment process requires a group of indicators, this will include quality of life factors that can effectively signify the sustainable lifespan performance of buildings for peoples. In this regard, three indicator clusters [11] are adopted to cover the whole range of indicators including the cluster for *People*, the cluster for *Products*, and the cluster for *Processes*; and all possible indicators are evaluated under restraining criteria of natural and social environmental factors before they can flow into the *Indicator Cluster* (refer to Fig. 1). In order to find the most appropriate indicators for the *Building Assessment* entity of the SIBER model under the restraining criteria, the authors create a quantitative energy–time based indicator evaluation approach, and introduce it below.
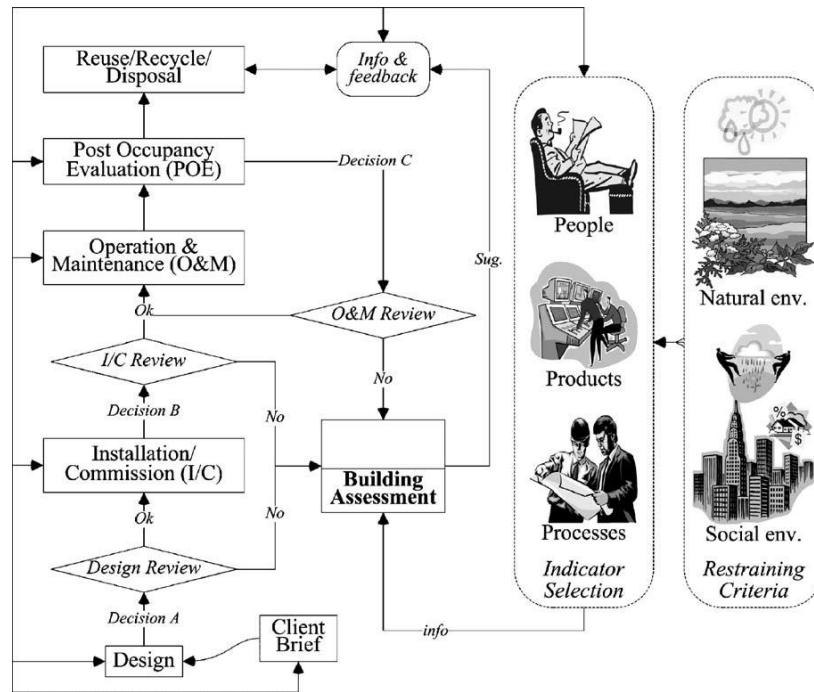

Fig. 1. The Strategic Intelligent Building Evaluation and Renovation (SIBER) model.

Fig. 2. The Tactical Intelligent Building Evaluation and Renovation (TIBER) model.

4.2. An energy–time consumption index

It is generally accepted that both energy and time consumptions exist in each process, in term of *Products* and *Processes*, for any building component or building system to fulfill all kinds of requirements for *People*. Regarding the energy consumption, embodied energy is one important measurement. Embodied energy is the energy consumed by all of the procedures associated with the production of a building, from the acquisition of natural resources to product delivery, including mining, manufacturing of materials and equipment, transport and administrative functions [26]. Previous research that focus on the LCA of cost and environmental impacts of construction projects include the embodied energy of products such as material, component, equipment and building [13,15,16,80,81,110]; and the processes such as construction, installation and maintenance [28,38,47,60]. Although the time factor features in project management, the speed of energy consumption is disregarded in previous LCA research based on the embodied energy. However, it is important to measure the velocity of energy consumptions in producing and processing in accordance with the performance of IBs as required by people. Because the environment itself has power but needs time to eliminate pollutants [107,111], and a high-energy consumption in a long lifespan may not be more adverse to the environment than a relatively low energy consumption over a short period. In this regard, a quantitative measurement for selecting indicators, called ETI is put forward by means of an embodied energy consumption rate (see Eqs. (4) and (5)). This reflects the idea of energy intensity being important.

$$F_{\text{ETI}} = f(e, t) \qquad (4)$$

$$\text{ETI}_i = \frac{\partial F_{\text{ETI}_i}}{\partial t} \qquad (5)$$

Eq. (4) gives a normal expression of ETI function (FETI)consisting of two variables including energy (e) and time (t); Eq. (5) gives a normal calculation method of the ETI for whichever indicator i, and is a partial time derivative of Eq. (4). The application of Eq. (5) depends on a specific function to describe the dependent relation with energy and time variables for the ETI. As there is not enough statistical data to mine and formulate such a function at this moment, the authors propose an alternative simplified approach to calculate the ETI (refer to Eq. (6) in Equations).

$$\text{ETI}_i = \frac{\sum_{j=1}^{2} \text{SEC}_{i,j}}{\sum_{j=1}^{2} \text{STC}_{i,j}} \qquad (6)$$

In Eq. (6), ETI_i is the ETI of indicator i; $\text{SEC}_{i,j}$ is the score of energy consumption (SEC) of indicator i relevant to *Indicator Cluster j* (j = 1 or 2, corresponding to the two *Indicator Cluster* which include *Products Cluster* (j = 1) and *Processes Cluster* (j = 2)); $\text{STC}_{i,j}$ is the score of time consumption (STC) of indicator i relevant to *Indicator Cluster j*. The set of $\text{SEC}_{i,j}$ is based on consideration that the energy embodied into a product covers a period of time during a process. To further regulate the selection of indicators, the authors subjectively define the fundamental scales as given in Table 3 in accordance with the values of $\text{SEC}_{i,j}$ and $\text{STC}_{i,j}$.

Table 3 Fundamental scales of the sores and relevant descriptions of energy/time consumptions

Scales for scoring	Products (embodied energy/time pattern)	Processes (operational energy/time pattern)
Score of energy consumption ($\text{SEC}_{i,j}$)	Embodied energy of products in manufacture, construction and installation	Energy required in operation processes upon People' occupancy requirements
1 = extremely low 6 = high 2 = very strongly low 7 = moderately high 3 = strongly low 8 = strongly high 4 = moderately low 9 = very strongly high 5 = low 10 = extremely high		
Score of time consumption ($\text{STC}_{i,j}$)	Time requirements in product making in manufacture, construction and installation	Time required in operation processes upon People' occupancy requirements
1 = (0, 1 day] 4 = (1 month, 1 year] 2 = (1 day, 1 week] 5 = >1 year 3 = (1 week, 1 month]		

Based on the fundamental scale of the scores of energy and time consumptions given in Table 3, the ETI score of each indicator, i.e. *Indicator i*, can have its value regarding energy and time consumptions in a scoring form (see Table 4). Generally, the $\text{ETI}_{i,\max}$ = 1000 and the $\text{ETI}_{i,\min}$ = 20 (refer to Tables 3 and 6). As mentioned in Section 2, the IB Index has a comprehensive category of indicators for assessing IBs. In this regard, the authors chose it as a model for scoring ETI, and therefore chose a group of ETI-scored indicators for the proposed BAssessor ANP model. Because the ETI is a general approach to selecting indicators under the criteria

of building sustainability, it is suggested that a further complete evaluation of IB indicators is made for the IBAssessor ANP model based on current building rating systems as mentioned in Section 2. This paper only demonstrates the usability of ETI and the IBAssessor ANP model. Table 5 gives a result from ETI-scored indicator evaluation based on the IB Index. At Reading University and HK Polytechnic University, further development of this model is taking place.

Table 4 The scoring form of *Indicator i* regarding its energy and time consumptions

	Produ	Process	Subtotal	Total
Energy consumption score	$(SEC_{i,}$	$(SEC_{i,2})$	(SEC_i)	
Time consumption score	$(STC_{i,1})$	$(STC_{i,2})$	(STC_i)	(ETI_i)

Table 5 Selected indicators using ETI based on the IB Index

Indicator	IB Index code	$SEC_{i,1}$	$SEC_{i,2}$	SEC_i	$STC_{i,1}$	$STC_{i,2}$	STC_i	ETI_i
Electricity and electrical services	GRI25	7	5	12	1	5	6	200
Heating services	GRI27	7	9	16	3	5	8	200
Ventilation and air conditioning	GRI31	6	9	15	3	5	8	188
Building services automation	HTI25	9	7	16	4	5	9	178
Construction materials	HTI35	8	8	16	4	5	9	178
IT&C facilities and services	WEI30	8	6	14	3	5	8	175
Thermal comfort and indoor air	GRI22	5	8	13	3	5	8	163
Lifts/escalators and controls	GRI02	5	8	13	3	5	8	163
Security and safety control	SSI19	6	5	11	3	5	8	138
Reserve electric power	SSI26	7	3	10	3	5	8	125
Green materials	MPS18	5	5	10	3	5	8	125
Flushing water system	HSI07	6	4	10	3	5	8	125
External decoration	SSI05	5	6	11	4	5	9	122
Building architectural design	HTI28	4	2	6	4	1	5	120
Lavatory accommodation	GRI18	4	5	9	3	5	8	113
Refuse collection	HSI21	5	4	9	3	5	8	113
Circulation for the disabled	SSI11	5	5	10	4	5	9	111
Computer aided	MPS03	2	8	10	4	5	9	111
Waste disposal	GRI64	1	2	3	1	2	3	100
Flexibility for renovation	SPI15	4	3	7	2	5	7	100
Internal decoration	CLI03	4	4	8	3	5	8	100
Structural monitoring and control	SSI04	4	4	8	3	5	8	100
Computer aided manufacturing	MPS03	8	1	9	4	5	9	100
Potable water system	HSI01	5	3	8	3	5	8	100
Green design	MPS01	6	2	8	4	5	9	89
Lighting	GRI45	4	3	7	3	5	8	88
Fire detection and resistance	SSI13	4	3	7	4	4	8	88
Cleanliness	HSI20	4	3	7	3	5	8	88
Property management	WEI70	1	5	6	2	5	7	86
Computer aided design	MPS02	5	2	7	4	5	9	78
Carpark/transportation facilities	SPI06	2	3	5	2	5	7	71
Entertainment facilities	CFI48	1	4	5	2	5	7	71
External landscape	CLI07	2	3	5	2	5	7	71

Indicator	IB Index code	SEC$_{i,1}$	SEC$_{i,2}$	SEC$_i$	STC$_{i,1}$	STC$_{i,2}$	STC$_i$	ETI$_i$
Extensive use of artificial	HTI31	4	2	6	4	5	9	67
Electromagnetic compatibility	GRI66	3	1	4	2	5	7	57
Environmental friendliness	GRI53	1	2	3	1	5	6	50
Conference and meeting facilities	WEI77	1	3	4	3	5	8	50
Drainage	GRI65	2	1	3	2	5	7	43
Existence of green features	GRI01	1	1	2	1	5	6	33
Access sign and directory	WEI61	1	1	2	1	5	6	33
Maintainality	SSI28	1	1	2	1	5	6	33
Usable areas	SPI01	1	1	2	2	5	7	29
Means of escape	SSI14	1	1	2	3	5	8	25

Note: Green Index (GRI), Space Index (SPI), Comfort Index (CFI), Working Efficiency Index (WEI), Culture Index (CLI), High-tech Image Index (HTI), Safety and Structure Index (SSI), Management Practice and Security (MPS), Cost Effectiveness Index (CEI), Health and Sanitation Index (HSI).

1.1. Key performance indicators

There are 378 elements under 10 modules of the IB Index, including a Green Index (GRI) module, a Space Index (SPI) module, a Comfort Index (CFI) module, a Working Efficiency Index (WEI) module, a Culture Index (CLI) module, a High- tech Image Index (HTI) module, a Safety and Structure Index (SSI) module, a Management Practice and Security Index (MPS) module, a Cost Effectiveness Index (CEI), and a Health & Sanitation Index (HSI) module. As summarized in Table 5, 43 indicators emerge from these 378 indicators following the ETI based identification. To finally select a group of key performance indicators (KPIs) for the ANP model, the authors further estimate the scope of ETI, i.e. ETI$_{i,max}$ = 1000 and the ETI$_{i,min}$ = 20, based on Gann's *Square of Nine* [106] (refer to Table 6). The purpose of this study is to explain concisely but in detail simple mathematical and graphical techniques for applying Gann's *Square of Nine* to KPI selection.

Table 6 Gann's square of nine [106] for KPI identification

	1000	990	980	**970**	960	950	940	930	**920**
660	650	640	630	**620**	610	600	590	**580**	910
670	**380**	370	360	**350**	340	330	**320**	570	900
680	390	**180**	170	**160**	150	**140**	310	560	890
690	400	190	**60**	**50**	**40**	130	300	550	880
700	**410**	**200**	**70**	**20**	**30**	**120**	**290**	**540**	**870**
710	420	210	**80**	**90**	**100**	110	280	530	860
720	430	**220**	230	**240**	250	**260**	270	520	950
730	**440**	450	460	**470**	480	490	**500**	510	840
740	750	760	770	**780**	790	800	810	**820**	830

The Gann's *Square of Nine* [106] for KPI selection is constructed using a grid of numbers that begins in the centre with number 20 in accordance with the value of ETI$_{i,min}$. The

number 30 goes to the box to the right of the number 20. Moving up and round anticlockwise, 10 is added to the previous number and the resulting number goes to the box. This is repeated in a spiral around the centre. There are two crosses in the developed grid, including a Cardinal Cross and a Fixed Cross. The Cardinal Cross is composed of the vertical and horizontal rows that intersect at the middle of the square; the line extending at 45$8$ constitutes the Fixed Cross. The Cardinal Cross and Fixed Cross are used to determine likely points of ETI related to KPIs. Table 6 gives the results of the *Square of Nine* for KPI identification.

Based on these results, KPIs for IB assessment are finally divided into five ETI aggregations, i.e. [20,100], (100,   260],
(260, 500], (500, 820], and (820, 1000]. In accordance with these aggregations, five groups of KPIs, i.e. KPI Group t (t = 1–5) can be defined. Among the 43 indicators as summarized in Table 5, 18 indicators are recognized as KPI Group 1 with their ETI scores above 100 but below 260, i.e. 260 2: ETI_i > 100; 25 indicators are allocated to KPI Group 2 with their ETI scores below 100 but including 100, i.e. 100 2: ETI_i > 0. The ETI scores presented in Table 5 are calculated using Eq. (6) and the score of energy–time consumption (SEC/STC), which can be compared with experts' opinions. As a result, two groups of KPIs for IBAssessor model are identified based on the IB Index (refer to Table 8).

5. IBAssessor approach

Developed by Saaty [70–72], the ANP is a general theory of relative measurement used to derive composite priority ratio scales from individual ratio scales that represent relative measurements of the influence of elements that interact with respect to control criteria. An ANP model consists of two parts including a network of interrelationships among each two nodes or clusters, and a control network of criteria/subcriteria that control interactions based on interdependencies and feedback. In order to conduct decision-making process, a control hierarchy is generally employed to build an ANP model. The control hierarchy is a hierarchy of criteria and subcriteria for which priorities are derived in the usual way with respect to the goal of a system being considered. The criteria are used to compare the clusters of an ANP model, and the subcriteria are used to compare the nodes of a cluster. Regarding how to conduct IB assessment by using ANP, Fig. 2 illustrates a four-step ANP procedure, in which the SIBER model (refer to Fig. 1) based ETI supported indicator selection process is integrated, and the ANP based IB assessment model presented in Fig. 2 is called TIBER model.

There are four general steps in ANP based multicriteria decision-making process: model construction; paired comparisons between each two clusters or nodes; supermatrix calculation based on results from paired comparisons; and result analysis for the assessment. As a frame of reference, Fig. 2 also summaries a four-step procedure for AIIB method, which is regarded as one important source of indicators for IB assessment to support building an ANP model. For users who want to conduct IB assessment, Fig. 2 provides two options to either use ANP method or other rating methods. Based on their evaluation theory, the rating methods such as the AIIB method can only be used to evaluate one IB each time, whilst the ANP method can be used to evaluate either one IB or several IBs. To evaluate several IBs together each time, information of a reference IB such as a standard IB in a

particular building class or alternative building plans for a same IB has to be added to the ANP model. To achieve this, Fig. 2 also illustrates how the ANP method retrieves information from other rating methods and rating systems to collect information for IB assessment. As all other rating methods such as AIIB method [5, 22] and IBSK method [39] have their own developed IB indicators, it is therefore useful and important for ANP model construction. In addition to the parallel assessment procedures between the rating method and the ANP method, Fig. 2 proposes an assessment database, which is essential for an ANP model development loop including processes of model construction, model evaluation, model revision and model reuse. The proposed IB database can also provide information of a standard IB when the ANP model is used to assess a building comparing with a standard building in the same building class; otherwise, an alternative of the building has to be presented to support the assessment. However, this paper will not discuss how to develop such an IB database to support ANP-based assessment, and will focus on the procedure of IB assessment using ANP method and the group of indicators collected from the ETI based selection.

5.1. Step A: ANP model construction
5.2.

The objective of Step A is to build an ANP model for IB assessment. The ANP model is built based on determining the control hierarchies, as well as the corresponding criteria for comparing the clusters, including subclusters, of the model and sub-criteria for comparing the nodes inside each cluster and each subcluster, together with a determination of clusters and subclusters with their nodes for each control criteria or subcriteria. Before finalising an ANP model, a set of indicators for the model construction has to be defined. As the purpose of this paper is to provide an alternative approach for IB assessment based on the IB Index [5, 22], the group of KPIs identified in Section 4 is therefore selected for the proposed ANP model. Fig. 3 gives an outline of the proposed IBAssessor ANP model.
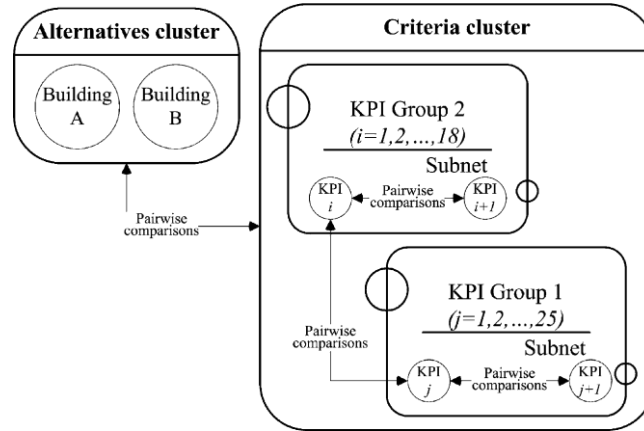

Fig. 3. The IBAssessor ANP model.

There are two clusters inside the IBAssessor model, including one Criteria cluster and one Alternatives cluster. The goal of the IBAssessor model is to select the most appropriate IB from several alternatives in the process of evaluation or to make a comparison between a

proposed IB and a standard IB in a same catalogue in the process of assessment. In correspondence with this goal, the cluster of Alternatives (denoted as $C_{selection}$) consists of two nodes in this paper including Building A and Building B, which are two IB candidates to be evaluated by the IBAssessor. On the other hand, the Criteria cluster contains two Subnets including the subcluster of KPI Group t ($t = 1, 2$) (denoted as C_{KPIGt}). Inside these two subclusters, the KPI Group 2 subcluster consists of 18 nodes (i.e. KPI i ($i = 1,2,.. .,18$)) in accordance with the 18 indicators of KPI Group 2, and the KPI Group 1 subcluster consists of 25 nodes (i.e. KPI j ($j = 1,2,.. .,25$)) in accordance with the 25 indicators of KPI Group 1. All these KPIs involved in the Criteria cluster are collected based on the ETI evaluation of the IB Index [5, 22] (refer to Tables 5 and 8).

In accordance with these two clusters and their total 45 nodes, the IBAssessor ANP model is thus set up with interrelation connectivity between each two clusters and their nodes. Connections inside the two clusters finally generate a network with interrelations among clusters, subclusters and nodes (refer to Table 9) including the Alternatives cluster (with two nodes), the KPI Group 2 subcluster (with 18 nodes), and the KPI Group 1 subcluster (with 25 nodes). The network connections are modelled by using one- or two-way arrows and looped arrows to describe the interdependences that exist between each two clusters or subclusters and each two nodes (refer to Fig. 3).

5.3. Step B: paired comparisons

The objective of step B is to carry out pairwise comparisons among clusters and subclusters, as well as pairwise comparisons between each two nodes, because they are interdependent on each other during the lifespan of IBs. The pairwise comparison is a quantitative description approach to interrelation connections illustrated in the IBAssessor ANP model (refer to Fig. 3). In order to complete pairwise comparisons, the relative importance weight, denoted as a_{ij}, of interdependence is determined by using a scale of pairwise judgements, where the relative importance weight is valued from 1 to 9 [70]. Table 7 reproduces the fundamental scale of pairwise judgements generally applied in pairwise comparisons.

Table 7 Scale of pairwise judgement [70]

Pairwise judgement	Scale
Equal	1
Equally to moderately dominant	2
Moderately dominant	3
Moderately to strongly dominant	4
Strongly dominant	5
Strongly to very strongly dominant	6
Very strongly dominant	7
Very strongly to extremely dominant	8
Extremely dominant	9

Decision makers with professional experience and knowl- edge can use these scales for pairwise comparisons to determine the weight of interdependence. In this study, the authors determine this because the objective of this study is mainly to demonstrate the process and usefulness of the ANP model for IB assessment; in practice, the building design team will make these comparisons. Table 8 gives some details for the case study.

Table 8 A case details about KPI and their values for the IB Assessor   model

Classification	Refence number	Indicators	Score of design [5,19,22]	
			Design A	Design B
KPI Group 2	KPIG201	Electricity and electrical services	90	90
	KPIG202	Heating services	90	90
	KPIG203	Ventilation and air conditioning	80	90
	KPIG204	Building services automation system	90	100
	KPIG205	Construction materials	100	70
	KPIG206	IT&C facilities and services	90	90
	KPIG207	Thermal comfort and indoor air quality	80	100
	KPIG208	Lifts/escalators and controls	90	80
	KPIG209	Security and safety control	90	90
	KPIG210	Reserve electric power	80	90
	KPIG211	Green materials	100	80
	KPIG212	Flushing water system	80	90
	KPIG213	External decoration	80	80
	KPIG214	Building architectural design	90	80
	KPIG215	Lavatory accommodation	60	90
	KPIG216	Refuse collection	70	80
	KPIG217	Circulation for the disabled	90	90
	KPIG218	Computer aided construction/installation	90	70
KPI Group 1	KPIG101	Waste disposal	80	80
	KPIG102	Flexibility for renovation	50	70
	KPIG103	Internal decoration	80	70
	KPIG104	Structural monitoring and control	50	70
	KPIG105	Computer aided manufacturing	90	70
	KPIG106	Potable water system	70	90
	KPIG107	Green design	90	80
	KPIG108	Lighting	70	90
	KPIG109	Fire detection and resistance	80	80
	KPIG110	Cleanliness	70	80
	KPIG111	Property management	80	80
	KPIG112	Computer aided design	90	80
	KPIG113	Carpark/transportation facilities	70	80
	KPIG114	Entertainment facilities	70	80
	KPIG115	External landscape	90	70
	KPIG116	Extensive use of artificial intelligence	50	70
	KPIG117	Electromagnetic compatibility	70	80
	KPIG118	Environmental friendliness	90	90
	KPIG119	Conference and meeting facilities	70	90
	KPIG120	Drainage	70	80
	KPIG121	Existence of green features	70	70
	KPIG122	Access sign and directory	80	90
	KPIG123	Maintainality	70	90
	KPIG124	Usable areas	90	70
	KPIG125	Means of escape	80	100

Table 9 gives a general form for pairwise judgement between each two nodes inside the IBAssessor ANP model. There are two types of pairwise judgements, one is the pairwise comparison between a KPI and a building alternative, and another is the pairwise

comparison between two KPIs. As an example, for the node KPIG203, i.e. ventilation and air- conditioning (refer to Table 8), the pairwised judgements are given in Table 9, in which the scale for Building B is 8, whilst it is 4 for Building A, because the use of natural ventilation in Building A is less than in Building B (refer to Table 9). In this regard, quantitative pairwise judgements can thus be conducted in order to define priorities of each indicator for each IB Candidate, and the judgements are based on the quantitative attribute of each indicator from each IB Candidate (refer to Table 8). Besides the pairwise judgement between an indicator and an IB Candidate, the IBAssessor model also contains all other pairwise judgements between each indicator. For example, Indicator I_i (KPIG203 as a representative) is *very strongly dominant* to Indicator I_j (KPIG111 as a representative); therefore the judgement value equals seven (as shown in Table 9). In summary, the essential initialization for ANP modelling is set up based on the quantitative attribute (as described in Table 8) of indicators for each IB Candidate and inherent characteristics of each indicators.

Table 9 Pairwise judgement of indicator I_i (KPIG203) and I_j (KPIG111)

Pairwise		1	2	3	4	5	6	7	8	9
Indicator I_i	Building A	X	X	X	√	X	X	X	X	X
	Building B	X	X	X	X	X	X	X	√	X
Indicator I_i	Indicator I_j	X	X	X	X	X	X	√	X	X

Note: The fundamental scale of pairwise judgement is given in Table 7. The symbol (X) denotes item under selection for pairwise judgement, and the symbol (√) denotes selected pairwise judgement.

5.4. Step C: supermatrix calculation

This step aims to form a synthesized supermatrix to allow for a resolution based on the effects of the interdependences that exist between the elements (including nodes, subclusters and clusters) of the IBAssessor ANP model. The supermatrix is a two-dimensional partitioned matrix consisted of one nine submatrices (refer to Table 10).

Weights defined from pairwise judgements for all inter- dependences for each individual IB Candidate are then aggregated into a series of submatrices. For example, if the *Alternative* cluster and its nodes are connected to nodes in the subcluster KPI Group 1 (denoted as C_{KPIG1}), pairwise judgements of the cluster thus result in relative weights of importance between each IB Candidate and each indicator inside the KPI Group 1 subcluster. The aggregation of the determined weights thus forms a 2 x 25 submatrix located at ''W_{13}'' and ''W_{31}'' in Table 10. It is necessary to note that pairwise comparisons are necessary to all connections among each node, subcluster and cluster in the IBAssessor ANP model to identify the level of interdependences, which are fundamental in the ANP procedure. Upon the completion of pairwise judgements, the nine submatrices are then aggregated into a supermatrix, which is denoted to supermatrix A in this study (refer to Table 10). And it is then used to derive the initial supermatrix in the later calculation in Step C, and the calculation of the IBAssessor ANP model can thus be conducted following Step C to D.

Table 10 Formulation of supermatrix and its submatrix for IBAssessor ANP model

General format of supermatrix A	General format of submatrix

$$W = \begin{bmatrix} W_{1,1} & W_{1,2} & W_{1,3} \\ W_{2,1} & W_{2,2} & W_{2,3} \\ W_{3,1} & W_{3,2} & W_{3,3} \end{bmatrix}$$

$$C_i = (C_{sel.} \quad C_{KPIG2} \quad C_{KPIG1})$$

$$N_i = (N^2_{sel.} \quad N^{18}_{KPIG2} \quad N^{25}_{KPIG1})$$

$$W_{IJ} = \begin{bmatrix} w_1|_{I,J} & \cdots & w_1|_{I,J} \\ w_2|_{I,J} & \cdots & w_2|_{I,J} \\ \cdots & \cdots & \cdots \\ w_i|_{I,J} & \cdots & w_i|_{I,J} \\ \cdots & \cdots & \cdots \\ w_{N_{I_1}}|_{I,J} & \cdots & w_{N_{I_n}}|_{I,J} \end{bmatrix}$$

Note: I is the index number of rows; and J is the index number of columns; both I and J correspond to the number of cluster and their nodes (I, J 2 (1, 2, . . ., 45)), NI is the total number of nodes in cluster I, n is the total number of columns in cluster I. Thus, a 45 *45 supermatrix is formed.

In order to obtain useful information for IB assessment, the calculation of supermatrix is to be conducted following three substeps, which transform an initial supermatrix to a weighted supermatrix, and then to a synthesized supermatrix.

At first, an initial supermatrix of the IBAssessor model is created. The initial supermatrix consists of local priority vectors obtained from the pairwise comparisons among clusters and nodes. A local priority vector is an array of weight priori- ties containing a single column (denoted as wT=[w1,…, wi, …, wn]), whose components (denoted as wi) are derived from a judgment comparison matrix A and deduced by Eq. (7) [70–72].

$$w_i|_{I,J} = \frac{\sum_{i=1}^{I} \left(\alpha_{ij} / \sum_{j=1}^{J} \alpha_{ij} \right)}{J} \tag{7}$$

Where $w|_{I,J}$ is the weighted/derived priority of node i at row I and column J; a_{ij} is a matrix value assigned to the interdependence relationship of node i to node j. The initial supermatrix is constructed by substituting the submatrices into the supermatrix as indicated in Table 10. A detailed initial supermatrix is not given in this paper.

After formating the initial supermatrix, a weighted supermatrix is then transformed. This process is to multiply all nodesin a cluster of the initial supermatrix by the weight of the cluster, which has been established by pairwise comparison among clusters. In the weighted supermatrix, each column is stochastic, i.e. sum of the column amounts to 1 [70–72].

The last substep of supermatrix calculation is to compose alimiting supermatrix, which is to raise the weighted supermatrix to powers until it converges/stabilizes when all the columns in the supermatrix have the same values. Saaty [70] indicated that as long as the weighted supermatrix is stochastic, a meaningful limiting result could be obtained for prediction.

The approach to arrive at a limiting supermatrix is by taking repeatedly the power of the matrix, i.e. the original weighted supermatrix, its square, and its cube, etc., until the limit is attained (converges), in which case the numbers in each row will all become identical. A calculus type algorithm is employed in the software environment of Super Decisions by Bill Adams and the Creative Decision Foundation to facilitate the formation of the limiting supermatrix and the calculation result is omitted in this paper. As the limiting supermatrix is

set up, the following step is to select a proper plan alternative using results from the limiting supermatrix.

Table 11 Selection of the most appropriate IB

Model	Number of nodes	Synthesized priority weight W_i		Selection
		Building A	Building B	
IBAssessor	45	0.44	0.56	Building B

5.5. Step D: selection

This step aims to select the most appropriate IB Candidate based on the computation results from the limiting supermatrix of the IBAssessor model. Main results of the ANP model computations are the overall priorities of IB Candidates obtained by synthesizing the priorities of individual IB Candidate against different KPIs. The selection of the most appropriate IB Candidate that has the highest priority of lifespan energy efficiency is conducted by a limiting priority weight, which is defined in Eq. (8).

$$W_i = \frac{w_{\mathrm{CIB},i}}{w_{\mathrm{CIB}}} = \frac{w_{\mathrm{CIB},i}}{\sum_i w_{\mathrm{CIB},i}} \tag{8}$$

where Wi is the synthesized priority weight of IB Candidate i (i = 1,. . ., n) (n is the total number of IB Candidates, n = 2 in this study), and $w_{\mathrm{CIB},i}$ is the limited weight of IB Candidate i in the limiting supermatrix. Because the $w_{\mathrm{CIB},i}$ is transformed from pairwise judgements conducted in Step B, it is reasonable to be treated as the priority of IB Candidate i and thus to be used in Eq. (8). According to the computation results in the limiting supermatrix, $w_{\mathrm{CIB},i}$ =(0.433; 0.561), so the Wi = (0.44, 0.56), as a result, the most appropriate IB is Candidate B (refer to Table 11).

According to the attributes of each IB Candidate listed in Table 8, the comparison results using Wi also implies that the most preferable building is the candidate that regulates the building performance of lifespan energy efficiency with best solutions for building services systems, least energy consumption, lowest ratio of wastage, and lower adverse environmental impacts. This indicates that the IBAssessor ANP model provides a quite logical comparison result for the aim of a sense of emotional and physical well-being of people and lifespan energy efficiency of IBs and thus can be applied in practice.

6. Conclusions and recommendations

This paper presents an ANP model, named as IBAssessor, for IB assessments emphasizing the lifespan energy efficiency of buildings. The IBAssessor ANP model is developed based on the ANP containing feedback and self-loops among clusters and subclusters (refer to Fig. 3), but without the control model to simplify the ANP model. KPIs for the IBAssessor model are selected by a quantitative approach called energy–time consumption index (ETI) based on a Strategic Intelligent Building Evaluation and Renovation (SIBER) model (refer

to Fig. 1) and a Tactical Intelligent Building Evaluation and Renovation (TIBER) model (refer to Fig. 2). However, there are implicit control criteria with respect to which all pairwise judgments are made in this model, i.e. lifespan energy efficiency of buildings focusing on products and processes with respect to the well-being of people. The supermatrix computations are conducted for the overall priorities of IB Candidates, and the priorities are obtained by synthesizing the priorities of the Candidates from all the subnetworks of the IBAssessor ANP model. Finally, the synthesized priority weight Wi is used to distinguish the degree of lifespan energy efficiency due to the deployment of design and construction plans from each IB Candidate. The authors believe that the IBAssessor approach has advantages over the current building rating methods such as the Asian IB index because it can tackle both values and interrelationships among KPIs, which the current building rating systems do not achieve.

In summary, in order to apply the IBAssessor ANP model into practice, this paper recommends the following steps:

1. assess IB Candidates on all KPIs using Table 8 and the scoring criteria of IB Index by the AIIB [5,22];
2. make pairwise comparisons among all indicators usingTables 7 and 9;
3. calculate supermatrix calculation to transform an initial supermatrix to a limiting supermatrix;
4. calculate each limiting priority weight of IB Candidates using limiting supermatrix;
5. select IB Candidate using Table 11.
6. If none of the candidates meets lifespan energy efficiency and well-being requirements, adjust the plans and reevaluate by repeating the above procedure.

Although the IBAssessor ANP model has been built based on a group of KPIs extracted from IB Index, the authors admit that the KPIs adopted in current IBAssessor model are not perfect to provide a complete coverage to lifespan energy efficiency of products and processes as well as well-being of people. Further research needs to go through all current building rating systems and conduct more surveys with practitioners to collect a conclusive group of KPIs to develop a revised IBAssessor model.

Acknowledgements

Appendix A. Equations

The following equations are used in this paper:

$$\text{IBI} = \prod_{i=1}^{9} M_i^{w_i} / \sum_{i=1}^{9} w_i \tag{1}$$

$$M_i = \prod_{j=1}^{m} x_j^{w_{x_j}} / \sum_{j=1}^{m} w_{x_j} \tag{2}$$

$$\text{IBI} = x^{w_x/(w_x+w_y)} y^{w_y/(w_x+w_y)} \tag{3}$$

$$F_{\text{ETI}} = f(e,t) \tag{4}$$

$$\text{ETI}_i = \frac{\partial F_{\text{ETI}_i}}{\partial t} \tag{5}$$

$$\text{ETI}_i = \frac{\sum_{j=1}^{2} \text{SEC}_{i,j}}{\sum_{j=1}^{2} \text{STC}_{i,j}} \tag{6}$$

$$w_i|_{I,J} = \frac{\sum_{i=1}^{I} \left(\alpha_{ij} / \sum_{j=1}^{J} \alpha_{ij} \right)}{J} \tag{7}$$

$$W_i = \frac{w_{\text{CIB},i}}{w_{\text{CIB}}} = \frac{w_{\text{CIB},i}}{\sum_i w_{\text{CIB},i}} \tag{8}$$

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