A Decision-Making Model for the Asian Intelligent Building Index

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Abstract: The paper presents a multi-criteria decision-making model to evaluate the sustainable performances of intelligent buildings based on the Asian IB index, which is recommended by the Asian Institute of Intelligent Buildings. To undertake this task, this paper first determines current evaluation method adopted in the Asian IB index and demonstrates its unreliability in calculation. A decision-making model called AIBChoice is then introduced as an alternative approach to IB assessments. The AIBChoice model can be used by either contractors or clients when it is necessary to evaluate the sustainable designs and select the best solution for proposed IB projects based on the Asian IB index.

Key words： Analytic network process; Intelligent buildings; Asian intelligent building index; Sustainable design and construction

1. INTRODUCTION

Technological innovation and environmental sustainability for the built environment require contractors to provide advanced solutions for lifecycle benefits to their clients. Regarding innovative engineering and management at all stages of the construction lifecycle from the initial architectural design and structural design, through to the actual construction, and then the maintenance and control as well as the eventual deconstruction of buildings and civil infrastructures, environmental consciousness and performances are definitely essential. Progresses have been made to advance environmental-friendly design and construction. For example, quantitative approaches to reducing or mitigating pollution level in construction planning have been put forward and proved to be efficient in selection of the best construction plan based on distinguishing the degree of its potential adverse environmental impacts [3, 8]. Moreover, research initiatives focusing on decision-making for different solutions within building lifecycles are becoming a common concern. For example, the Asian Institute of Intelligent Building (AIIB) developed a practical approach to evaluate intelligent buildings called Asian IB index [1]. However, case studies conducted by the authors of this paper indicate that current calculation method of the Asian IB index is unreliable in providing decision support. In order to overcome this and provide an alternative method for the Asian IB index, this paper proposes a multi-criteria decision-making model using Analytic Network Process (ANP) [9] to evaluate the sustainable performance of intelligent buildings. To undertake this task, this paper firstly determines problems existed in current Asian IB index. After that, an ANP model named AIBChoice is introduced to demonstrate its effectiveness in intelligent building assessment. The set of indicators is transplanted from the Asian IB index into the AIBChoice model. Experimental study shows that the model can be used to evaluate the sustainability of buildings at either design or operation stage, and select the best solution for a proposed building project.

The contributions of this paper include a discussion about the reliability of current Asian IB index method for intelligent building assessment, a multi-criteria decision-making model for sustainability-oriented intelligent building assessment, and a practical alternative process for adopting the Asian IB index into intelligent building assessment. It is expected that practitioners can use the proposed AIBChoice model for sustainability-oriented intelligent building assessment at either design stage or operation stage in order to achieve the best performance level of their buildings.

2. LIMITATIONS

The Asian IB Index put forward by AIIB (2001) provides a quantitative method to conduct composite evaluation of intelligent buildings by using 9 series of IB indicators with 315 sub-indicators (see Table 1) based on the Cobb-Douglas utility function [1]. Within the column of Asian IB Index in Table 1, two experimental building alternatives, including Building A and Building B are given with their generic forms of scores in accordance with modules and elements based on the Asian IB Index. As there are total 315 indicators included in Table 1, this paper only provide generic forms of the modules and their elements of the Asian IB Index, as well as generic forms of scores of indicators for each building alternatives in the experimental case study.

Tab. 1 A generic form for building assessment using Asian IB Index [1]

Modules/Clusters	Elements/Nodes (IB indicators)	AIIB scores (Building A)	AIIB scores (Building B)
Green Index (GRI)	GRI_i (i=1~67)	$S_{GRI_i}^{(A)}$	$S_{GRI_i}^{(B)}$
Space Index (SPI)	SPI_i (i=1~19)	$S_{SPI_i}^{(A)}$	$S_{SPI_i}^{(B)}$
Comfort Index (CFI)	CFI_i (i=1~50)	$S_{CFI_i}^{(A)}$	$S_{CFI_i}^{(B)}$
Working Efficiency Index (WEI)	WEI_i (i=1~81)	$S_{WEI_i}^{(A)}$	$S_{WEI_i}^{(B)}$
Culture Index (CLI)	CLI_i (i=1~10)	$S_{CLI_i}^{(A)}$	$S_{CLI_i}^{(B)}$
High-tech Image Index (HTI)	HTI_i (i=1~38)	$S_{HTI_i}^{(A)}$	$S_{HTI_i}^{(B)}$
Safety and Security Index (SSI)	SSI_i (i=1~30)	$S_{SSI_i}^{(A)}$	$S_{SSI_i}^{(B)}$
Construction Process and Structure (CPS)	CPS_i (i=1~19)	$S_{CPS_i}^{(A)}$	$S_{CPS_i}^{(B)}$
Cost Effectiveness Index (CEI)	CEI_i (i=1)	$S_{CEI_i}^{(A)}$	$S_{CEI_i}^{(B)}$

However, the recommended method of Asian IB Index is not reliable due to the following reasons:

First, the calculation method of Asian IB Index is a non sequitur. The AIIB didn't provide a reasonable explanation for adopting the celebrated Cobb-Douglas utility function into Asian IB Index calculation with a 9-dimension 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 [2, 4, 5, 6, 7, 10]. Recalling the Asian IB Index method, two equations are recommended by the AIIB [1]:

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

$$M_i = \prod_{j=1}^{n} x_j^{\frac{w_{x_j}}{\sum_{j=1}^{n} w_{x_j}}} \quad (2)$$

Where *IBI* represents the Asian IB Index, M_i is the score of the i^{th} modules, w_i is the weight to the i^{th} module relevant to other modules ($w_i \in [1, 9]$), x_j is the score of the j^{th} element of the i^{th} module ($x_j \in [1, 100]$), w_{x_j} is the weight to the j^{th} element relevant to other elements of the i^{th} module ($w_{x_j} \in [1, 9]$), and n is the number of elements in the i^{th} module. It is noticed that it is difficult to define a physical model to describe this 9-dimension IB Index algorithm beyond the Cobb-Douglas utility function. Moreover, according to the second law of thermodynamics which requires that any process which takes place at non-zero speed must consume a minimum finite amount of energy, production isoquants cannot be of the Cobb-Douglas type [5]. In these cases, the necessary and sufficient conditions of applying the Cobb-Douglas utility function to the 9-dimension IB Index algorithm should be thoroughly examined.

Second, the calculation results from the Asian IB Index method are non-unique. Table 2 below recalls an example quoted by the AIIB (2001), i.e. when w_x:w_y=2:1, the Asian IB Index method can provide an acceptable sequence of buildings in accordance with intuition. However, the function adopted in IB Index calculation (see Equation 3 below) cannot always lead to an appropriate result. For example, let w_x:w_y=3:1, the Asian IB Index values to each building are then different from ones under w_x:w_y=2:1, and the sequence of the IB also changed (see Table 2). When the Asian IB Index method cannot provide a unique result, different auditors may give different conclusions, which definitely cause complexity and variance in IB evaluation.

$$IBI = x^{\frac{w_x}{w_x+w_y}} y^{\frac{w_y}{w_x+w_y}} \quad (3)$$

Where x and y represent different modules, w_x and w_y represents the weight of module x and module y.

Tab. 2 A generic form for building assessment using Asian IB Index [1]

Buildings	Modules		IB Index	
	x	y	w_x:w_y=2:1	w_x:w_y=3:1
A. Smart Tower	70	50	63	64
B. Balanced Building	60	60	60	60
C. Mechanical Plant	100	20	59	69
D. Tree House	20	100	34	30

Theoretically speaking, logical defects in the Asian IB Index method may lead to confusions in IB evaluations. It is thus required to provide an alternative method to evaluate the characters of IB under objective or more reality conditions, in which all indicators will be taken into account with both their values and interrelations considered. For this purpose, this paper presents an alternative measure of intelligent building assessment under a multi-criteria decision-making circumstance using ANP [9]. As the AIIB has provided a comprehensive classification of IB indicators, they are then directly used in this study to develop the multi-criteria decision-making model named AIBChoice. To overcome the shortcomings of current Asian IB Index method, the AIBChoice will evaluate intelligent buildings by considering both the values and the interrelations of all indicators.

3. AIBCHOICE APPROACH

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 [9]. An ANP model consists of two parts: one is a control network of criteria and sub-criteria that control the interactions including interdependencies and feedback; another is a network of influences among the nodes and clusters. Moreover, the control hierarchy is a hierarchy of criteria and sub-criteria for which priorities are derived in the usual way with respect to the goal of the system being considered. The criteria are used to compare the components of a system, and the sub-criteria are used to compare the elements of a component. A four-step procedure using AIBChoice for intelligent building assessment is described below.

Step A: ANP model construction

The objective of Step A is to build an ANP model for evaluation based on determining the control hierarchies, as well as the corresponding criteria for comparing the clusters and the sub-clusters of the model and sub-criteria for comparing the nodes inside each cluster and each sub-cluster, together with a determination of clusters and sub-clusters with their nodes for each control criteria or sub-criteria. Before finalize 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 intelligent building assessment based on the Asian IB Index, the group of indicators currently adopted in the Asian IB index is therefore wholly transplanted into the proposed ANP model, i.e. AIBChoice, and the model is outlined in Figure 1.

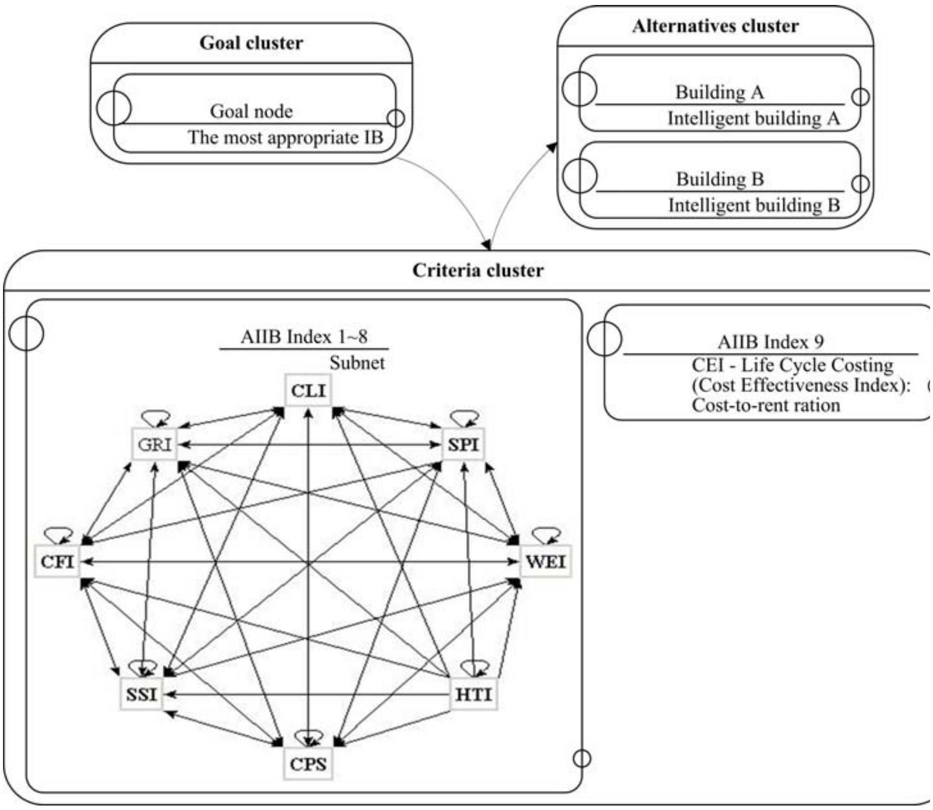

Fig.1 The AIBChoice model

There are three clusters inside the AIBChoice model, including one Goal cluster, one Criteria cluster and one Alternatives cluster. The Goal cluster has one node, i.e. Goal node, and is to select the most appropriate building alternative under evaluation. In accordance with the Goal cluster, the cluster of Alternatives supposably consists of two nodes in this paper including Building A and Building B which are two building alternatives to be evaluated by the AIBChoice. The Criteria cluster, on the other hand, contains one Subnet and one node, which constantly adopts the 9 series of IB Indexes recommended by the AIIB (2001). The Subnet inside the Criteria cluster comprises eight sub-clusters in accordance with the Asian IB Index 1 to 8, including Green Index, Space Index, Comfort Index, Working Efficiency Index, Culture Index, High-tech Image Index, Safety and Security Index, and Construction Process and Structure Index. As the 9th Index, i.e. the Cost Effectiveness Index is a relatively objective item that is obtained by statistic calculation; it is thus a separated node coming off the Subnet. According to the Asian IB Index, there are 315 nodes inside the Criteria cluster as shown below:

- 67 nodes in the sub-cluster of Green Index (GRI) (denoted as C_{GRI}),
- 19 nodes in the sub-cluster of Space Index (SPI) (denoted as C_{SPI}),
- 50 nodes in the sub-cluster of Comfort Index (CFI) (denoted as C_{CFI}),
- 81 nodes in the sub-cluster of Working Efficiency Index (WEI) (denoted as C_{WEI}),
- 10 nodes in the sub-cluster of Culture Index (CLI) (denoted as C_{CLI}),
- 38 nodes in the sub-cluster of High-tech Image Index (HTI) (denoted as C_{HTI}),
- 30 nodes in the sub-cluster of Safety and Security Index (SSI) (denoted as C_{SSI}),
- 19 nodes in the sub-cluster of Construction Process and Structure (CPS) (denoted as C_{CPS}), and
- 1 node in the cluster of Cost Effectiveness Index (CEI) (denoted as C_{CEI}).

In accordance with the 9 series of IB Indexes and total 315 indicators listed in Table 1, the AIBChoice model is thus set up with connections to represent interrelations between each two clusters or each two nodes (indicators). Connections among the Alternatives cluster and the Criteria cluster finally generate a network among 10 sub-clusters (see Table 5) including the Alternatives cluster and the 9 series of IB Indexes, and 318 nodes belonging to the 10 sub-clusters. The network connections are modeled by one-way or two-way and looped arrows to describe the interdependences existed between each two clusters, each two sub-clusters and each two nodes (see Figure 1).

Step B: Paired comparisons

The objective of step B is to carry out pairwise comparisons among the 10 sub-clusters, as well as pairwise comparisons between each two from the 318 nodes, because they are more or less interdependent on each other. In order to complete the pairwise comparisons, the relative importance weight, denoted as a_{ij}, of interdependence is determined by using a scale of pairwise judgment, where the relative importance weight is valued from 1 to 9 [9]. The fundamental scale of pairwise judgment is given in Table 3.

Tab. 3 The Scale of pairwise judgment

Nine Scales [9]
1 = Equal
2 = Equally to Moderately dominant
3 = Moderately dominant
4 = Moderately to Strongly dominant
5 = Strongly dominant
6 = Strongly to Very Strongly dominant
7 = Very strongly dominant
8 = Very Strongly to Extremely dominant
9 = Extremely dominant

In fact, the weight of interdependence is generally determined by decision makers who are abreast with professional experience and knowledge. In this study, it is determined by the authors as the objective of this study is mainly to demonstrate the usefulness of the AIBChoice model for intelligent building assessment.

Table 4 gives a general form adopted in this study for pairwise judgment among indicators and building alternatives. As an example, for the node GRI_{60}, i.e. Environmental friendliness- Use of natural ventilation, in the sub-cluster Green Index (*GRI*) (denoted as C_{GRI}), the paired judgments are given in Table 4, because the use of natural ventilation in Building A is less than Building B (see Table 1). In this regard, quantitative pairwise judgments are thus conducted in order to define priorities of each indicator for each building alternative, and the judgments are based on the quantitative attribute of each indicator from each building alternative. Besides the pairwise judgment between an indicator and a building alternative, the AIBChoice model contains all other pairwise judgments between each two indicators (Indicator I_i and Indicator I_j as shown in Table 4) and this essential initialization is set up based on the quantitative attribute (as described in Table 1) of indicators from each building alternative.

Tab. 4 Pairwise judgment of indicator I_i and I_j (GRI_{60})

Pairwise judgment		1	2	3	4	5	6	7	8	9
Indicator I_i	Building A	×	×	×	✓	×	×	×	×	×
	Building B	×	×	×	×	×	×	×	✓	×
Indicator I_i	Indicator I_j	×	×	×	×	✓	×	×	×	×

Note: 1. The fundamental scale of pairwise judgment is given in Table 3. 2. The symbol × denotes item under selection for pairwise judgment, and the symbol ✓ denotes selected pairwise judgment.

Step C: Super-matrix calculation

This step aims to form a synthesized super-matrix to allow for the resolution of the effects of the interdependences that exists between the elements (including nodes, sub-clusters and clusters) of the AIBChoice model. The super-matrix is a two-dimensional partitioned matrix consisted of one hundred sub-matrices (see Table 5).

It is necessary to note that pairwise comparisons are necessary to all connections among each node, sub-cluster and cluster in the AIBChoice model to identify the level of interdependences which are fundamental in the ANP procedure. After finishing the pairwise judgment, from indicator *1* to *n*, the series of sub-matrices are then aggregated into a super-matrix which is denoted to super-matrix *A* in this study (see Table 5), and it is then used to derive the initial super-matrix in the later calculation in Step C, and the calculation of the AIBChoice model can thus be conducted following Step *C* to *D*.

Weights defined from pairwise judgment for all interdependences for each individual building alternative are then aggregated into a series of sub-matrices. For example, if the Alternative cluster and its nodes are connected to nodes in the sub-cluster Green Index (GRI) (denoted as C_{GRI}), pairwise judgments of the cluster thus result in relative weights of importance between each building alternative and each indicator of the GRI sub-cluster. The aggregation of the determined weights thus forms a 2×67 sub-matrix located at "W_{12}" and "W_{21}" in Table 5.

In order to obtain useful information for intelligent building assessment, the calculation of super-matrix is to be conducted following three sub-steps which transform an initial super-matrix to a weighted super-matrix, and then to a synthesized super-matrix.

At first, an initial super-matrix of the AIBChoice model is created. The initial super-matrix consists of local priority vectors obtained from the pairwise comparisons among clusters and nodes. A local priority vector is an array of weight priorities containing a single column (denoted as $w^T = (w_1, ..., w_i, ..., w_n)$), whose components (denoted as w_i) are derived from a judgment comparison matrix *A* and deduced by Equation 4 [9].

$$w_i\Big|_{I,J} = \sum_{i=1}^{I}\left(a_{ij}\Big/\sum_{j=1}^{J}a_{ij}\right)\Big/J \qquad (4)$$

Where $w_i\big|_{I,J}$ 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 super-matrix is constructed by substituting the sub-matrices into the super-matrix as indicated in Table 5. A detailed initial super-matrix is omitted in this paper.

After the formation of the initial super-matrix, a weighted super-matrix is transformed. This process is to multiply all nodes in a cluster of the initial super-matrix by the weight of the cluster, which has been established by pairwise comparison among the four clusters. In the weighted super-matrix, each column is stochastic, i.e., sum of the column amounts to 1 [9].

Tab. 5 The Formulation of super-matrix and its sub-matrix for AIBChoice model

General format of super-matrix A

$$W = \begin{bmatrix} W_{1,1} & W_{1,2} & W_{1,3} & W_{1,4} & W_{1,5} & W_{1,6} & W_{1,7} & W_{1,8} & W_{1,9} & W_{1,10} \\ W_{2,1} & W_{2,2} & W_{2,3} & W_{2,4} & W_{2,5} & W_{2,6} & W_{2,7} & W_{2,8} & W_{2,9} & W_{2,10} \\ W_{3,1} & W_{3,2} & W_{3,3} & W_{3,4} & W_{3,5} & W_{3,6} & W_{3,7} & W_{3,8} & W_{3,9} & W_{3,10} \\ W_{4,1} & W_{4,2} & W_{4,3} & W_{4,4} & W_{4,5} & W_{4,6} & W_{4,7} & W_{4,8} & W_{4,9} & W_{4,10} \\ W_{5,1} & W_{5,2} & W_{5,3} & W_{5,4} & W_{5,5} & W_{5,6} & W_{5,7} & W_{5,8} & W_{5,9} & W_{5,10} \\ W_{6,1} & W_{6,2} & W_{6,3} & W_{6,4} & W_{6,5} & W_{6,6} & W_{6,7} & W_{6,8} & W_{6,9} & W_{6,10} \\ W_{7,1} & W_{7,2} & W_{7,3} & W_{7,4} & W_{7,5} & W_{7,6} & W_{7,7} & W_{7,8} & W_{7,9} & W_{7,10} \\ W_{8,1} & W_{8,2} & W_{8,3} & W_{8,4} & W_{8,5} & W_{8,6} & W_{8,7} & W_{8,8} & W_{8,9} & W_{8,10} \\ W_{9,1} & W_{9,2} & W_{9,3} & W_{9,4} & W_{9,5} & W_{9,6} & W_{9,7} & W_{9,8} & W_{9,9} & W_{9,10} \\ W_{10,1} & W_{10,2} & W_{10,3} & W_{10,4} & W_{10,5} & W_{10,6} & W_{10,7} & W_{10,8} & W_{10,9} & W_{10,10} \end{bmatrix}$$

$$C_i = (C_{selection}\ C_{GRI}\ C_{SPI}\ C_{CFI}\ C_{WEI}\ C_{CLI}\ C_{HTI}\ C_{SSI}\ C_{CPS}\ C_{CEI})$$

$$N_i = (N_s^2\ N_{GRI}^{67}\ N_{SPI}^{19}\ N_{CFI}^{50}\ N_{WEI}^{81}\ N_{CLI}^{10}\ N_{HTI}^{38}\ N_{SSI}^{30}\ N_{CPS}^{19}\ N_{CEI}^{1})$$

General format of sub-matrix

$$W_{IJ} = \begin{bmatrix} w_1\big|_{I,J} & \cdots & w_1\big|_{I,J} \\ w_2\big|_{I,J} & \cdots & w_2\big|_{I,J} \\ \cdots & \cdots & \cdots \\ w_i\big|_{I,J} & \cdots & w_i\big|_{I,J} \\ \cdots & \cdots & \cdots \\ w_{N_{I1}}\big|_{I,J} & \cdots & w_{N_{In}}\big|_{I,J} \end{bmatrix}$$

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 ($I, J \in (1, 2, \dots, 318)$), N_I is the total number of nodes in cluster *I*, *n* is the total number of columns in cluster *I*. Thus a 318×318 super-matrix is formed.

The last sub-step is to compose a limiting super-matrix, which is to raise the weighted super-matrix to powers until it converges/stabilizes when all the columns in the super-matrix have the same values. Saaty [9] indicated that as long as the weighted super-matrix is stochastic, a meaningful limiting result can be obtained for prediction. The approach to arrive at a limiting super-matrix is by taking repeatedly the power of the matrix, i.e., the original weighted super-matrix, its square, its cube etc, until the limit is attained (converges), in which case the numbers in each row will all become identical. 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 super-matrix and the calculation result is omitted in this paper. As the limiting super-matrix is set up, the following step is to select a proper plan alternative using results from the limiting super-matrix.

Step D: Selection

This step aims to select the most suitable building alternative based on the computation results the limiting super-matrix of the AIBChoice model. Main results of the ANP model computations are the overall priorities of building alternatives obtained by synthesizing the priorities of individual building alternative against different indicators. The selection of the most suitable building alternative that has the highest sustainability priority is conducted by a limiting priority weight, which is defined in Equation 5.

$$W_i = w_{C_{Plan},i} \big/ (w_{C_{Plan},1} + \cdots + w_{C_{Plan},n}) \qquad (5)$$

Where W_i is the synthesized priority weight of building alternative i (i=1, …, n) (n is the total number of building alternatives, n=2 in this study), and $w_{C_{Plan},i}$ is the limited weight of building alternative i in the limiting super-matrix. Because the $w_{C_{Plan},i}$ is transformed from pairwise judgments conducted in Step B, it is reasonable to be regarded as priority of the building alternative i and thus to be used in Equation 2. According to the computation results in the limiting super-matrix, $w_{C_{Plan},i}$ = (0.403, 0.581), so the Wi= (0.41, 0.59), as a result, the best IB is Candidate B.

According to the attributes of each building alternative listed in Table 1, the comparison results using W_i also implies that the most preferable building is the candidate that regulates the building performance with best solutions in building service systems, least energy consumption, lowest ratio of wastage, and lower adverse environmental impacts, etc. This indicates the AIBChoice model provides a quite logical comparison result for the aim of sustainability in IB and thus can be applied into practice.

4. CONCLUSIONS

This paper presents a multi-criteria decision-making model named as AIBChoice for evaluating sustainability in the assessment of intelligent buildings. The AIBChoice model is developed based on the analytic network process containing feedback and self-loops among clusters and sub-clusters (see Figure 1), but without the control model. However, there is an implicit control criterion with respect to which all judgments are made inside this model, i.e. the sustainability of buildings. The super-matrix computations are conducted for the overall priorities of building alternatives, and the priorities are obtained by synthesizing the priorities of building alternatives from all sub-networks of the AIBChoice model. Finally, the synthesized priority weight W_i is used to distinguish the degree of sustainability due to the deployment of design and construction plans from each alternative. The AIBChoice outperforms current calculation model adopted by the Asian IB index because it can tackle both values and interrelationships among each two indicators.

In summary, in order to apply the AIBChoice model into practice, it is recommended to follow the following steps:

1. *Original assessment of building alternatives with all indicators using Table 1 and the scoring criteria of the AIIB (2001);*

2. *Pairwise comparisons among all indicators using Table 3 and Table 4;*
3. *Super-matrix calculation to transform an initial super-matrix to a limiting super-matrix;*
4. *Calculation of each limiting priority weight of building alternatives using limiting super-matrix and decision-making on building selection.*

If none of the building alternatives meets sustainability requirements, adjustments to each building are requested for the re-evaluation of building alternatives by repeating the above procedure starting from the first step.

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