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Key Performance Metrics (KPMs) for Assessing and Measuring Intelligent Building Systems

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Abstract - *Measurement and assessment of intelligent building (IB) performance is about using key performance metrics (KPMs). In this research, 24 key performance metrics are proposed for the selective categorization of intelligent buildings, with the ultimate goal of defining a conceptual model as perfomance tool for building intelligent system(IBS) in Oman. The importance and validity of the proposed metrics were evaluated through a questionnaire survey and the need of IB experts. This work is part of a major research project aimed at developing a decision support system to assist designers in assessing and measuring the performance of IB systems, thereby facilitating the sustainability of building projects.*

Key Words: **Intelligent Building, Assessment Performance, Key Performance Metrics, AHP, Conceptual Model**

1.INTRODUCTION

The concept of Intelligent building (IB) is rapidly becoming widespread and form part of design and development process of buildings, largely due to their potentials in maximizing occupants' comfort and well-being through the use of user-centred architectural design and continuing development and advances in technological innovations (Ghaffarianhoseini et al. 2016; Froufe et al. 2020). Intelligent buildings (IBs) is frequently reported as a promising solution towards achieving enhanced building performance. According to Merabet et al. (2021), the operation of building is responsible for a large percentage of primary energy consumed globally, due to the growing need for improved thermal comfort achieved through the use of Heating, Ventilation and Air-Conditioning (HVAC) system. In order to optimize the associated problem with the growing demand for energy use, the authors call for the consideration of intelligent building design.

Clements-Croome (2013) report that an IBs which is efficiently equipped with state of the art technologies, ICT, and automated systems, provides occupants with productive and cost effective building besides being optimally operational. Ghaffarianhoseini et al. (2016) in figure 1, demonstated the adoption of IBs concept overtime by looking at the factors that drive the development of IBs and the exploration of its true potential by industry stakeholders.

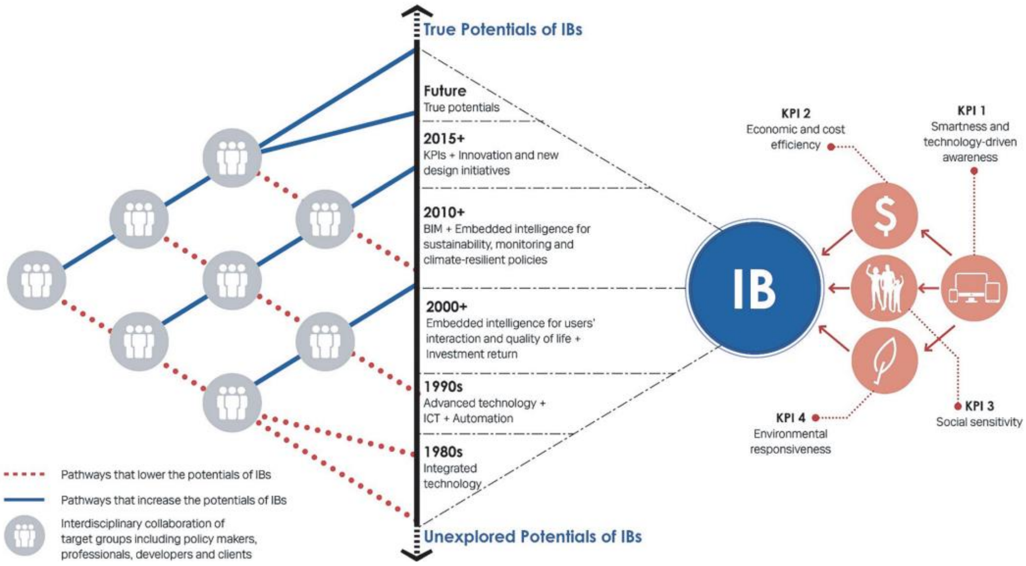

Figure 1. Evolutionary progression of IBs (Ghaffarianhoseini et al. 2016)

IBs have also proven to be capable of deploying sustainable design initiatives to enhance the overall performance of buildings and maintain an acceptable level of occupant comfort (Ghaffarianhoseini et al. 2016; Clements-Croome 2013). However, giving the inherent benefits of IBs, the concept has not been adopted as quickly and widely as expected in Oman. One of the reasons for this according to Al-Jebouri et al. (2017) is the lack of information and knowledge in the comprehensive assessment of the performance of IBs to support to all professionals involved at the design stage of a project. Ghaffarianhoseini et al.(2016) and Clements-Croome (2018) supported this assertion by reporting the complexity in the interpretation of IB system which has affected the realisation of its true potential. The authors illustrated the need for realising the true potential in IBs through research in the field and by highliting the state of the art of the system, with the current development and future direction in Fig, 2.

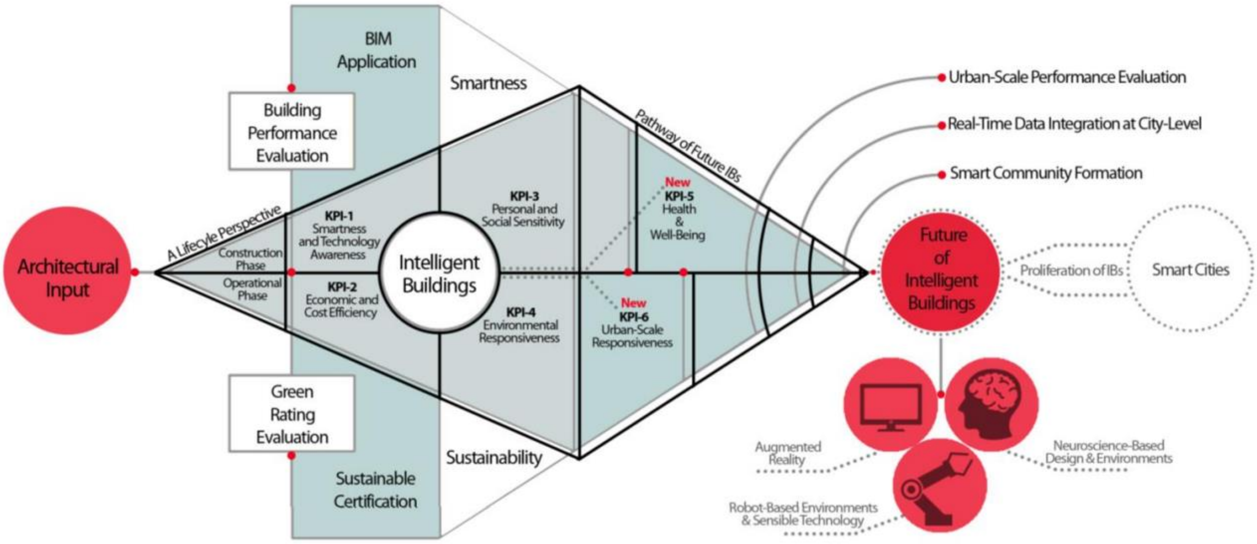

Figure 2. State of the art Overview of Pathways towards formation of IBs (Clements-Croome, 2018)

In this regard, it is necessary to assess and measure the performance of IBs in order to satisfy the clients, professionals, and occupants' growing demands. To this end, this paper proposes a conceptual model using an integrated analytic hierarchy process (AHP) and preference degree approach (PDA) under the fuzzy environment for the purpose of intelligent building assessment and measurement. Fuzzy AHP is employed to determine the local weights of performance metrics and the final weights of the intelligent building alternatives. Since, the final weights of intelligent buildings (IBs) are in the form of fuzzy numbers, fuzzy PDA is utilized to prioritize the intelligent buildings. Finally, fuzzy AHP-fuzzy PDA is proposed to assess and measure the performance of five intelligent building alternatives in Oman.

2. MULTI-ATTRIBUTE ASSESSMENT APPROACH

This article summarizes research on developing a conceptual model for assessing and measuring the performance of IBs. A set of key performance metrics are proposed and optimized by the analytical hierarchical process (AHP), which is a decision support framework appropriate for assessing and measuring the performance of IBs. The specific methods are as follows: (i)identifying the key performance metrics; (ii)optimizing the selected metrics with expert questionnaire survey.

2.1 Key Performance Metrics

In developing a set of performance metrics, two key issues were taken into consideration. What use will be made of this set of metrics? To what extent can any set of metrics encompass the performance of IBs. Since IBs are considered a complex system made up of various components, the best approach to analyze them is to divide the system to its elements. In this regard, a general survey was undertaken in order to identify the perceived critical metrics needed in assessing the performance of an IB system. For this purpose, the main metrics were collected from eight “quality environment modules” (QEMs) (from M1 to M8) including [8]: - M1; Environmental and energy - M2; Space utilization and flexibility - M3; Cost effectiveness - M4; Human comfort - M5; Working efficiency - M6; Safety and security - M7; Culture - M8; Technological factors. These are further categorized under the sub-system in Table 1.

Table 1: Identified Key Performance Metrics (KPMs)

	Quality environment modules (QEMs)	Subsystem	Key Performance Indicators (KPIs)
1	Environmental and energy (M1)	Environmental metrics group (En-KPMs	Greenhouse Gas Emissions (GHG) [EN 1] Energy and Natural Resources [EN2] Water conservation [EN3] Materials used, durability and waste [EN4] Land use and site selection [EN5] Transport and accessibility [EN6]
2	Space utilization and flexibility (M2) Human comfort (M4) Culture (M7)	Socio-Cultural metrics group (SC-KPMs)	Functionality and Usability [SC1] Use of local materials and labour [SC2] Space utilization and usage [SC3] Architectural Considerations-cultural heriage integration and the compatibility with local heritage value [SC4] Aesthetic aspects [SC5] Indoor Environmental Quality(IEQ)- Health and Well being [SC6] Psychological and physical comfort[SC7] Innovation and design process[SC8]
3	Cost effectiveness (M3)	Economic metrics groups (Ec-KPMs)	Economic performance and affordability [EC 1] Building Manageability [EC2] Whole life cycle cost [EC3]
4	Working efficiency (M5) Safety and security (M6) Technological factors (M8)	Engineering and Technological metrics group (ETc-KPMs)	Communications and mobility [ET1] Automatics and remote control and monitoring [ET2] Fire detection and fighting [ET3] Emergency escape capability [ET4] Automatic fault detention [ET5] Possibility of further system upgrade [ET6] Compliance with regulations [ET7]

The identified performance metrics relates primarily to the ability of buildings and its component system to sustain and enhance the performance of the functions for which it is designed. For any decision process, the selected metrics must be broadly applicable to performance assessment and measurement of IBs.

2.2 Data Collection and Sample

Based on the derived metrics in table 1, an industry questionnaire survey was designed at investigating the perspective of building designers in Oman on the importance of the metrics for IBs performance assessment. The survey first sought the background information of respondents and their organizations. Thereafter respondents were thus asked to rate the level of importance of the derived metrics based on a scale of 1–5, where 1 is 'least important', 2 'fairly important', 3 'important', 4 'very important', and 5 'extremely important'. The sample used in the survey was drawn from a database of architects and engineers listed in the Oman Society of Engineers (OSE) and top engineering consultants in Oman. A total of 120 questionnaires were mailed out to participants for completion, out of which 32 effective responses were received giving a response rate of 26.7%.

2.3 Criteria importance rating

To ensure that the rating scale [1–5] for measuring the criteria yields the same result over time, a reliability analysis using the internal consistency method was first examined. Cronbach's alpha was calculated to test the internal consistency reliability of the generated scale. The alpha reliability coefficient normally ranges between 0 and 1. The closer alpha is to 1 the greater the internal consistency reliability of the metrics in the scale. All alpha values for the sub-systems are greater than 0.7, indicating that all reliability coefficients are acceptable and the internal consistency of the criteria included in the scale is excellent.

In order to identify the relative importance of SACs based on the survey data, ranking analysis was performed. Relative index analysis was used to rank the criteria according to their relative importance. The following formula is used to determine the relative index (Akadiri, 2015):

$$RI = \sum w/A \times N \qquad (1)$$

where w, is the weighting as assigned by each respondent on a scale of one to five with one implying the least and five the highest. A is the highest weight (i.e 5 in our case) and N is the total number of the sample. Based on the ranking (R) of relative indices (RI), the weighted average for the groups was determined. Five important levels are transformed from Relative Index values: High (H) ($0.8 \le RI \le 1$), High–Medium (H–M) ($0.6 \le RI < 0.8$), Medium (M) ($0.4 \le RI < 0.6$), Medium–Low (M–L) ($0.2 \le RI < 0.4$), and Low (L) ($0 \le RI < 0.2$). A cut-off value of 0.4 is used and identified the metrics as relevant for which the values are greater than or equal to 0.4. In all these, the Statistical Package for the Social Sciences (SPSS) and Microsoft Excel for Windows application software package were employed for data analysis.

3. DATA ANALYSIS AND DISCUSSION

Data shows respondents where mostly working in the private sector. Experience of respondents was highly impressive as 72.5% have over 20 years experience working in the building industry. Virtually all the respondents have reasonable experience in intelligent building design and construction. As for the size of organisation, 82.4% work in small to medium size organizations, with the remaining working in large organizations with over 250 staff. The result also shows that 91 % of the survey participants have completed at least undergraduate degrees and 52% have additional postgraduate qualifications.

Table 2 show the ranking results for each sub-system. Twelve performance metrics were highlighted to have "High" importance levels in assessing IBs, with an RI value between 0.808 and 0.898. A total of 12 performance metrics were recorded to have "High– Medium" importance levels. An interesting observation is that none of the performance metrics fall under the medium and other lower importance level. This clearly shows how important the metrics are to building designers in assessing the performance of IBs. All metrics were rated with "High" or "High–Medium" importance levels.

Table 2: Rank of metrics for assessing performance of Intelligent builidng systems

Sub-system	Key Performance Metrics (KPMs)	Valid percentage of score (%)					Relative index	Ranking by Group	Overall Ranking	Importance level
		1	2	3	4	5				
Environmental metrics Group (En-KPMs	EN1: Greenhouse Gas Emissions (GHG)	0.0	0.0	13.2	44.0	42.9	0.859	1	5	H
	EN2: Energy and Natural Resources	4.4	1.1	13.2	29.7	51.6	0.846	2	7	H
	EN3: Water conservation	1.1	7.7	29.7	38.5	23.1	0.749	4	17	M-H
	EN4: Materials used, durability and waste	1.1	3.4	15.9	40.9	38.6	0.825	3	9	H
	EN5: Land use and site selection	4.4	15.4	31.9	37.4	11.0	0.670	6	22	M-H
	EN6: Transport and accessibility	4.4	8.8	35.2	39.6	12.1	0.692	5	21	M-H
Socio-Cultural metrics Group (SC-KPMs)	SC1: Functionality and Usability	1.1	0.0	22.0	47.3	29.7	0.808	4	12	H
	SC2: Use of local materials and labour	5.5	19.8	45.1	20.9	8.8	0.615	8	24	M-H
	SC3: Space utilization and usage	1.1	10.1	36.0	34.8	18.0	0.717	6	20	M-H
	SC4: Architectural Considerations- cultural heriage integration and the	5.	16.	39.	29.	8.8	0.639	7	23	M-H

	compatibility with local heritage value	5	5	6	7					
	SC5: Aesthetic aspects	0.0	0.0	10.1	30.3	59.6	0.898	1	1	H
	SC6: Indoor Environmental Quality(IEQ)- Health and Well being	0.0	0.0	9.9	53.8	36.3	0.853	2	6	H
	SC7: Psychological and physical comfort	0.0	5.5	14.3	49.5	30.8	0.810	3	11	H
	SC8: Innovation and design process	3.3	5.5	23.1	48.4	19.8	0.752	5	16	M-H
Economic metrics Group (Ec-KPMs)	EC1: Economic performance and affordability	3.3	8.8	19.8	39.6	28.6	0.763	2	15	M-H
	EC2: Building Manageability	3.3	2.2	22.2	38.9	33.3	0.793	1	13	M-H
	EC3: Whole life cycle cost	3.3	7.7	29.7	39.6	19.8	0.729	3	18	M-H
Engineering and Technological metrics Group (ETc-KPMs)	ET1: Communications and mobility	0.0	0.0	3.3	47.3	49.5	0.892	1	2	H
	ET2: Automatics and remote control and monitoring	0.0	0.0	12.1	56.0	31.9	0.839	4	8	H
	ET3: Fire detection and fighting	0.0	0.0	3.2	50.4	46.2	0.886	2	3	H
	ET4: Emergency escape capability	0.0	0.0	4.4	50.5	45.1	0.881	3	4	H
	ET5: Automatic fault detention	1.1	1.1	28.6	48.4	20.9	0.774	6	14	M-H
	ET6: Possibility of further system upgrade	1.1	9.9	28.6	47.3	13.2	0.723	7	19	M-H
	ET7: Compliance with regulations	1.1	1.1	18.0	46.1	33.7	0.820	5	10	H

3.1 Multi-attribute assessment model

The weight reflects relative important degree of each metric, directly influences their contribution related to the totality. "Structure entropy weight method" is given to identify the weights in this paper. Through analyzing system metrics and their relations, several independent hierarchies are decomposed. Combining Delphi experts' investigation with fuzzy analysis method, the "typical sort" for the importance of metrics is formed. Through data process, relative importance sort of the same hierarchy is obtained. The important degree is identified for similar metrics of each level, which is metric weight.

Phase 1: acquisition of experts' opinion, typical order Experts independently give the importance sort of the assessment metrics based on their knowledge and experience. Through consultation and feedback, finally experts' opinion sort is formed, called "typical sort".

Phase 2: blind degree analysis for typical sort. The opinions of typical sort often produce potential deviation and uncertainty of the source data. Therefore qualitative judgments of metrics need statistical analysis and processing, means entropy value calculation.

A set of metrics of k expert questionnaires are: $U = \{u_1, u_2, \ , u_n\}$. metric collection corresponding typical sort array are: $(a_{i1}, a_{i2}, \quad , a_{in})$. metric order matrix (typical sort) are:

A ($A = (a_{ij})_{k\times n}$, $i = 1,2, \ , k$, $j = 1,2, \ ,n$). a_{ij} is the assessment u_j of expert i to indicator j.

Quantitative transformation for typical sort, membership function definition:

$$\mu(I) = -\frac{\ln(m-I)}{\ln(m-1)} \qquad (2)$$

I is qualitative sequence number for the evaluation of each metric according to the form of typical sort by experts. $\mu(I)$ is the membership function value corresponding I.

I $= 1,2, \ , j, j+1, j$ is the actual maximum sequence number, that is serial number of metric. m is transformation parameter number, $m = j + 2$.

$I = a_{ij}$ is substituted into formula(1), quantitative transformation value of a_{ij} is b_{ij} ($\mu(a_{ij}) = b_{ij}$), b_{ij} is the membership of sequence number. Matrix $B = (b_{ij})_{k\times n}$ is membership matrix. It is the consistent view of u_j by k experts. Mark it as b_j,

$$b_j = (b_{1j} + b_{2j} + \ + b_{kj}) / k \qquad (3)$$

Uncertainty caused by acknowledges of expert z_i on u_j is defined, called blind degree Q_j,

$$Q_j = |\{[\max(b_{1j}, b_{2j}, \ , b_{kj}) - b_j] + [\min(b_{1j}, b_{2j}, \ , b_{kj}) - b_j]\} / 2| \qquad (4)$$

General understanding degree of k experts about u_j is defined, marked as x_j ,

$$x_j = b_j(1 - Q_j),\ x_j > 0. \qquad (5)$$

The evaluation vector of the entire metrics u_j : $X = (x_1, x_2, \ , x_n)$.

Phase 3: normalized processing

In order to obtain the weight of the metric u_j, $x_j = b_j(1 - Q_j)$ is normalized, set:

$$\alpha_j = x_j / \sum_{i=1}^{m} x_j. \qquad (6)$$

$(\alpha_1, \alpha_2, , \alpha_n)$ is the consistency judgment for importance of factor sets $U = \{u_1, u_2, , u_n\}$ by k experts. $W = \{\alpha_1, \alpha_2, , \alpha_n\}$ is the weight vector of factor set $U = \{u_1, u_2, , u_n\}$.

Fuzzy comprehensive evaluation use fuzzy transform principle and maximum membership degree to make a comprehensive evaluation, considering the various factors related to evaluate things. Fuzzy mathematical make fuzzy things enter into mathematical model without cutting, and finally make segmentation on a proper threshold value by making full use of intermediary information. It can also reduce influence of subjective factors and make the result of the evaluation more objective and reliable.

The influence factors of intelligent buildings are $U = \{u_1, u_2, , u_n\}$, $u_1, u_2, , u_n$ are assessment metrics. Valuation level are $V = \{v_1, v_2, v_3\}$. Metric weight vectors are: $W = \{\alpha_1, \alpha_2, , \alpha_n\}$. The fuzzy set (r_{i1}, r_{i2}, r_{im}) are fuzzy mapping from U to $V f: U \to V$, which identify a judgment matrix: $R = (r_{ij})_{n\times m}$. The single factor evaluation result is $B = W \cdot R$. Comprehensive evaluation model: $C = W \cdot B = W \cdot (b_{ij})_{n\times m}$. Vector C determines evaluation results by max membership degree principle.

4. CONCLUSION

Performance assesment metrics for intelligent building systems are researched and identified based on comprehensive review of relevant literatures, combined with the characteristics of intelligent buildings. A questionnaire survey was employed to obtain the perceived importance of the metrics. Following the results of the survey, the twenty four performance metrics identified as being important components of intelligent building system. Theoretical basis is provided for design scheme and assessment work of intelligent buildings from eight "quality environment modules" (QEMs). Assessment model is proposed by using analytic hierarchy process and multi-level fuzzy analysis technique.

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