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Defect-based building condition assessment

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ABSTRACT: Building defects accelerates the deterioration of building condition leading to more frequent repairs with increased operating and maintenance costs up to 4% or more of total construction cost per annum. Building condition assessments are carried out in order to identify defects and evaluate health status of building. However, existing assessment models are subjective, time consuming and tedious. To address the need for more objective and expeditious condition assessment this paper proposes a novel defect-based condition assessment model for existing concrete buildings considering both building physical and environmental condition. In order to deduce weighting coefficients for building defects Analytic Network Process (ANP) was used while severity of building defects is assessed using a grading scale. To incorporate uncertainty in judgement of inspection personnel, fuzzy membership functions were used to ascertain degree of belief in assessment. Evidential reasoning algorithm was used to aggregate and integrate different types of defects and to compute the overall condition assessment of building. This model is limited to concrete buildings only. The proposed model is implemented on BIM platform for exchange of information and better documentation during inspection. Proposed model was tested on a case study building and results were promising with organized inspection data management on a common BIM platform with potential to expedite inspection process while managing large amount of inspection data on handheld tablet.

Keywords: building condition assessment; analytic network process; fuzzy set theory; evidential reasoning; building information modelling.

1.0 INTRODUCTION

Degradation of building is inevitable due to detrimental actions from improper use, external factors such as weather, wear and tear and inadequate maintenance. It is important to understand different types of defects which influences the overall condition of the building. Through periodic building condition assessment, it is possible to intervene at the early stage of building degradation. According CIB-W086 Building Pathology (2013) report, building defects accelerates the deterioration of building condition resulting in more frequent repairs with increased operating costs up to 4% or more of total construction cost per annum in addition to social and environmental costs. Identifying building defects accurately through structured condition assessment before they become worse will help reducing the need for maintenance and repair of building components which can help to extend the service life of existing buildings (Paulo, Branco, & de Brito, 2014).

Condition assessment of buildings is typically physical inspection and diagnosis of health of building. Building condition assessment is generally conducted to assess the current state of a building and estimate the extent of its deterioration (Silva & de Brito, 2019). It is important to interpret building defects accurately and with adequate objectivity to obtain an accurate building condition assessment. According to Bernat and Gil (2013), appropriate building inspection and a maintenance plan are required for safety of building during its service life. Condition assessment of building occurs at component level (Donald R. Uzarski, Grussing, & Clayton, 2007) and further each component ratings are aggregated and rolled up to arrive at building condition assessment. Building deterioration has negative consequences from an economic and environmental point of view. There is a growing necessity to extend the service life of existing buildings from economic and sustainability point of view (Alba-Rodríguez, Martínez-Rocamora, González-Vallejo, Ferreira-Sánchez, & Marrero, 2017; Amaral & Henriques, 2013).

Visual inspection complimented with non-destructive technology will help to reduce subjectivity and human errors during inspection and also reduce mistakes in overall assessment of the building (Faqih, Zayed, & Soliman, 2020). Due to complex inter dependency between building components and systems governed by intended design of the building the condition of a building may vary from one individual component to another (D.R Uzarski, Hicks, & Zahorak, 2002). The deterioration of a building reduces its ability to perform its intended function (Marcel et al., 2013), while environmental deterioration influences the comfort and health of building occupants (Heinzerling, Schiavon, Webster, & Arens, 2013). Existing building condition assessment models are time consuming and lack objectivity hence there is a need for development of better assessment models supported by objective diagnosis providing expeditious assessments (Faqih & Zayed, 2021; Ferraz, Brito, Freitas, & Silvestre, 2016). In addition, managing large amount of building inspection data using conventional tools such as spreadsheets or hard paper copies is inefficient, tedious and sometimes error prone. To address the need for a comprehensive building condition assessment, this paper presents a novel defect-based condition assessment model for existing buildings considering both building physical and environmental condition in same model.

2.0 RESEARCH OBJECTIVES

To address the gaps in existing building condition assessments this study presents a defect-based building condition assessment model for integrated physical and environment assessment of existing buildings. The primary objective of this study are as follows:

- Design a defect-based integrated building condition assessment model to assess physical and environmental building defects using different non-destructive technologies.
- Develop a software program which can be used on field in a portable windows tablet for centralized data input and management of building inspection data.

- Test and implement proposed defect-based condition assessment model on a case study

3.0 RESEARCH BACKGROUND

Building stakeholders conduct condition assessment to identify the current state of the building. Effective building condition assessment is therefore vital to ensure the safety and sustainability of existing buildings. Building condition assessment reports are often used for decision making and budget allocation for maintenance, repair and rehabilitation for existing buildings (Faqih & Zayed, 2021). After reviewing literature about existing condition assessment models (Amani, Nasly, & Samat, 2012; CHAN & Hung, 2015; HHSRS, 2005, 2006; Kuijper & Bezemer, 2017; National Forum on Education Statistics., 2012; Pedro, Paiva, & Vilhena, 2008; Straub, 2009), the authors have not found a comprehensive building condition assessment model that considers both physical as well as environment of the building together. The aim of this study is to develop a defect-based condition assessment model considering both physical and environmental defects to provide a comprehensive condition assessment of building that can help building stakeholders in decision making for repair, maintenance and rehabilitation. Existing physical building inspection are generally dependant on visual observation, which can lead to subjective results dependant on experience, training and perception of the inspection personnel (Anuar et al., 2019; Faqih & Zayed, 2021; Hegazy, Attalla, & Ahluwalia, 2010; Silva & de Brito, 2019; Straub, 2002). The limitation of existing building condition assessment models is that they do not assess the comprehensive safety of the building, which will require more in-depth inspection (Anuar et al., 2019; Ferraz et al., 2016; Vilhena, Pedro, & Brito, 2011). Building condition and its indoor environment changes over time. It is important to evaluate building by measuring substantial changes in its condition that could impact building performance as well as to assess maintenance requirements (Abbott, McDuling, Parsons, & Schoeman, 2007). The safety and health of building user is affected by malfunction of building elements and adverse indoor environment.

Building defect can be defined as “a fault, or deviation from the intended level of performance of a building or its parts” as per ISO 15686-1:2000(E). Building defects generally are inevitable and occur in different forms with various severity in different buildings irrespective of building age (Buildings Department, 2002; Yacob, Ali, & Peng, 2016). Physical condition of a space inside the building can be characterized by physical building defects, while environmental condition of a space inside the building is characterized by environmental factors that influence them.

3.1 Physical Defects of Buildings

Building user safety, comfort, convenience and health are affected by a malfunction of any element, component, or part of a building. Generally, the design of building governs the inter-relationship between individual building elements with entire building. It is important to know different defects that influence the building condition in order to assess the correct building diagnosis during building inspection (Faqih et al., 2020). Minor defects can become serious defects if they are not promptly rectified, which can lead to failure that is more difficult to remedy (Ahzahar et al. 2011). It is also possible that one type of defect can cause another type of building defect. Several studies have noted most common defects in concrete buildings are spalling of plaster finishes, seepage of rainwater, cracks in structural members, non-structural cracks in plasters and tiles, and faulty finishes (Bortolini & Forcada, 2018; Chong & Low, 2006; Haryati, Kharizam, Zainol, & Othman, 2016; Hassan, Ismail, Isa, & Takim, 2011; Kian, 2004; Marshall, Worthing, & Heath, 2013; Othman, Jaafar, Harun, & Ibrahim, 2015; Suffian, 2013).

Visually inspecting spalling of concrete, cracks in beams, columns and extensive deformation of beams, leakage and dampness in the building is still one of the easiest and most reliable methods of assessing the condition of building (D’Aloisio, 2017). Visual inspection is one of the quickest and cheapest non-destructive inspection techniques, however, it is also very subjective and highly dependent on the competency and experience of inspection personnel. The tapping hammer test is used to detect the spalled de-bonded concrete or tiles on walls. Defects can be identified by listening to the 'void' sound created when tapping the hammer (D’Aloisio, 2017). The hammer tapping test is a comparatively cheaper alternative to other NDT tests. Cracks are often the most common building defects visible which can be measured using simple crack width scale (Stawiski & Kania, 2018). The moisture meter is used to measure the water content of building elements, such as roofs, drywalls, plaster, timber, tiles. Often, walls and ceilings have water seepage, which affects the building element causing dampness and peeling off of paint or plaster. Drywalls, wood, plaster and painting are easily damaged by moisture. A standard guide for the evaluation of the moisture condition of concrete, gypsum, or other floor slabs using electronic moisture meter can be found in ASTM F2659 (2015).

3.2 Environmental Defects of Buildings

Environmental factors are not defined as defects as certain level of concentration is almost always present in the environment, only when they exceed the safe limit and affect human comfort, they can be considered as environmental defects as their concentration exceeds the desired level analogous to physical defects. Good indoor environment quality ensures the comfort, well-being and health of building users. Certain level of concentration is almost always present in the environment, only when they exceed the safe limit and affect human comfort, they can be considered as environmental defects as their concentration exceeds the desired level analogous to physical defects. Four main categories of environmental factors which influence the environmental condition of the building are indoor air quality (IAQ), thermal environment, acoustics, and lighting

(Faqih et al., 2020). People spend a large part of their lives inside buildings hence there is a large influence of indoor environments quality on health and well-being of building occupants (World Health Organization, 2010). Poor indoor air quality may also become cause of sickness, discomfort, and low productivity at workplace (Al Horr et al., 2016). Table 1 shows environmental factors namely Indoor Air Quality (IAQ), thermal environment, acoustics, and lighting that influence the environmental condition of the building and their main sources of emissions and the effects on the health of building occupants.

[Table 1 near here]

Both physical and environmental condition is considered to be important to evaluate comprehensive building condition. Although a wide variety of building defects affect building condition, however for simplicity of this study common defects were selected such as structural cracks, spalling of concrete, corrosion of steel and water seepage. These defects are very common in concrete buildings and affect the safety, function and appearance of building. Similarly, for environmental condition assessment following factors were selected temperature & humidity that affects thermal condition; light intensity; noise level that affects acoustics; carbon dioxide, carbon monoxide, nitrogen dioxide, formaldehyde and volatile organic compounds that affects the indoor air quality.

Different types of detectors and monitors are available for indoor air quality measurement. Many handheld instruments cover almost all types of gas detection for indoor air quality, such as carbon dioxide, carbon monoxide, nitrogen dioxide, particulate matter PM2.5 and ozone. A luminance meter is used to measure the intensity of light in terms of Lux. A thermometer is used to measure the temperature, while a relative humidity meter is used to measure relative humidity in percentage.

Generally, handheld instruments can measure both temperature and humidity. Noise is measured using a sound level meter in decibels.

4.0 BACKGROUND OF RESEARCH METHODS

4.1 Fuzzy Set Theory

Fuzzy logic was first introduced by Lofti Zadeh (1965) and the term fuzzy refers to information that are not clear or are vague. Many real-world problems require to have results based on objective manner however, human judgement based on the information available which are often inaccurate, incomplete or have uncertainty makes decision making more complex. Hence the concept of fuzzy logic fuzzy logic provides a very valuable flexibility for reasoning similar to human reasoning in many ways while considering uncertainties and inaccuracies of the situation. Lofti Zadeh introduced the concept of membership function that characterize fuzziness i.e. all the information in a fuzzy set whether the elements in the fuzzy set are discrete or whether they are continuous and they represent the degree of truth in a fuzzy logic system (Jezewski, Czabanski, & Leski, 2017). A classical set is a collection of distinct objects with crisp values and they contain objects that satisfy exact membership properties. Hence a classical set can be defined as the set with certain defined boundaries without uncertainty while fuzzy set can be defined as a set with vague boundaries due to uncertainty in its properties. We can understand fuzzy sets in the context of set membership which allows partial membership which means that it contains elements that are varying degrees of membership in the set. The membership function symbolizes the mathematical representation of membership in a set which is represented as shown below.

$$\mu_A(x) \in [0,1] \qquad (1)$$

where $\mu_A(x)$ = degree of membership of element x in a fuzzy set A.

Consequently $\mu_A(x)$ is a value on the unit interval that measures the degree to which element x belongs to fuzzy set A i.e. $\mu_A(x)$= degree to which $x \epsilon A$ (Ross, 2010).

To deduce useful information from vague situations, the uncertain information in a universe set is transformed into fuzzy sets. All information contained in a fuzzy set is described by its membership function. Since the output is desired to be single crisp number, the fuzzy set after evaluation needs to be defuzzified. The conversion of a fuzzy quantity to a precise quantity is called defuzzification similar to the conversion of a precise quantity to a fuzzy quantity is called as fuzzification. Several methods are available for defuzzification of fuzzy output functions. The weighted average method is the most commonly used in defuzzification because it is considered to be one of the most computationally efficient methods (Ross, 2010). Fuzzy membership functions were utilized in proposed model since physical and environmental condition are two different types of assessment with fuzzy attributes.

4.2 Analytical Network Process (ANP)

Analytic Network Process (ANP) is a method for Multi criteria decision making methods (MCDM) developed by Thomas Saaty that can provide a comprehensive structure to integrate measurements for tangible criteria and derive priorities for intangible criteria for better decision making (Saaty, 2005; Saaty & Sodenkamp, 2010). ANP accounts for interdependencies and interactions between elements and alternatives with optional hierarchical structure (Saaty, 2004a, 2004b). Generally users of multiple criteria decision making methods simplify the complex problem into hierarchy structures composed of goal, criteria and alternatives however, multi-level hierarchy decisions may significantly differ from those decisions obtained from a network (Saaty, 2016).

The first step in ANP is to define set of hierarchies or network followed by pairwise comparison which can be based on questionnaire survey response from industry experts. Using pairwise comparison from the experts, unweighted pairwise matrix is formed. Next step is to calculate weighted super matrix to incorporate interdependencies among the elements. Weighted super matrix is further multiplied with itself until limiting super matrix is achieved giving final priorities are attained. The pairwise comparison matrix is composed of elements displayed on a numerical scale and decision makers give element values based on their experiences and expertise. When evaluating relative importance between different assessment criteria and degrees of severity of building defects inspection personnel often make judgement based on their experience, expertise and intuition. Multi criteria decision making methods (MCDM) can be helpful in decision making especially when information available in building condition assessment are incomplete and uncertain due to inherent human judgement.

4.3 Evidential Reasoning

During visual inspection of buildings often human judgements are characterized by varying degrees of uncertainty, inaccurate and incomplete information. To address this and yield adequate assessments evidential reasoning can be helpful. Evidential reasoning is based upon Dempster-Shafer theory of evidence (Dempster, 2008; Shafer, 1976, 2016) also called Dempster-Shafer theory or evidence theory, is prominently used to handle uncertainty in information. This theory was first proposed by Dempster and then further developed by Shafer. Building diagnosis is essential task during condition assessment to deduce explanations for a set of observation. These observations can be initial symptoms of building defects. The symptoms observed can be considered as evidence for a particular defect and thus evidence theory can be used for diagnosis. (Kohlas, 1996).

The evidential reasoning approach uses an expanded decision matrix, in which every attribute of alternative is described by a distributed assessment using a belief structure. To represent the assessment of an alternative against a criterion, belief structure is used as a distributed assessment using belief degrees. The evaluation of an alternative on a criterion can be measured by exact data or uncertain data. To represent uncertainty belief structure is utilised. If evaluation can be assessed precisely without any doubt, then decision matrix can be termed as special case of belief decision matrix (Xu, 2012).

In case these is absence of data availability for assessment, such case can be represented by belief structure that has sum of total belief degrees as zero. In case of partial data availability for assessment, the sum of total belief degrees in the distributed assessment for that attribute will be between 0% and 100%. While precise data can be termed as special cases of belief structures when all degrees of belief in each belief structure are either 1 or 0 provided that the sum of degree of belief in each belief structure is 1. Evidential reasoning algorithm for assignment of degrees of belief to different element and aggregate the outcome were referred from (Jian-Bo Yang & Dong-Ling Xu, 2002; Xu, 2012).

5.0 RESEARCH METHODOLOGY

The methodology adopted for development of proposed defect-based building condition assessment model is shown in Figure 1. Proposed model of building condition assessment is comprised of two types of assessment physical condition assessment and environmental condition assessment. Physical building defects and environmental factors that influence the condition of the building are determined. A questionnaire survey was carried out to evaluate pairwise comparison of physical and environmental defects. This pairwise comparison was further used to compute relative weights of defects using Analytic Network Process (AHP) incorporating interdependence of defects. To incorporate uncertainty in judgement of inspection personnel fuzzy set theory and evidential reasoning algorithm were used. Fuzzy membership functions were developed using defect thresholds for both physical defects and environmental thresholds derived from guidelines and codes of practices. Using condition grading scale and environmental instrument readings with their corresponding fuzzy membership functions appropriate degree of belief is calculated to assess severity of defects. Degree of belief calculated from fuzzy membership function and relative weights derived from ANP were used as input in evidential reasoning algorithm based on Dempster-Shafer (D-S) theory to compute integrated condition assessment comprised of physical and environmental condition of each room. The final condition rating is represented as a crisp value calculated by the weighted average defuzzification method. The proposed model developed was tested on a building as a case study. To implement the proposed defect-based condition assessment model on a case study building, a plugin software is developed that can run proposed condition assessment model inside Rivet software and utilize BIM model for exchange of information, for better documentation and displaying condition assessment results in graphical format. The data used in this research was obtained from questionnaire survey, previous research, building inspection data and environmental condition data. Finally, this study is concluded with suggestions and future scope of research.

[Figure 1 near here]

6.0 DEVELOPMENT OF DEFECT BASED CONDITON ASSESEMENT MODEL

The proposed model utilises three theories namely, Fuzzy sets, Analytical Network Process (ANP) and Evidential reasoning. To develop this integrated model that can combine physical and environmental condition into a single rating system, a hierarchy of assessment criteria was developed with two major branches physical condition and environmental condition. Physical condition of existing buildings is affected by four major factors i.e. Safety, Significance/Importance, Function and Appearance of element/components in the building. These four factors were chosen as assessment criteria as it is independent with type of building and applicable to all kinds of building. However, this model is primarily focussed on concrete buildings as common defects related to concrete are only considered. Environmental condition is affected by four major factors i.e. Indoor Air Quality (IAQ), Thermal, Lighting & Acoustics. A new condition scale is used to assesses the severity of defects while ANP is used to determine the relative weights between different defects. This model follows Fuzzy evaluation process composed of fuzzification, aggregation and defuzzification. Using this model every type of space in a building can be assessed for its physical and environmental condition based on the severity of their defects and then aggregated to determine overall condition assessment of the building.

Building components can be grouped according to their function within different systems such as Structural, Mechanical, Electrical and Plumbing which together forms the core physical assets of the building. A well-constructed hierarchy that incorporates upstream and downstream relationships will facilitate to focus on the tangible physical assets depending on the function of component from highest level to lowest level. Building stakeholders can use this hierarchy coupled with condition data that can be used as a framework for decision-making for higher up in the organization.

6.1 Relative Weights

In order to understand relative importance of different factors influencing the building condition, a questionnaire survey method was chosen. To determine pairwise comparison between different criteria a questionnaire survey was conducted among industry experts. Using expert judgement of industry professionals from facility management, building services and health and safety field pairwise comparison was framed. Based on pairwise comparison ANP network model is formulated with hierarchy of defects for assessment. Questionnaire survey was distributed among industry professionals to determine the relative weights between different type of defects and their criteria. Out of total survey respondents 50% were having expertise in facility management, 25% experts were from Health and Safety field, 10% were from building services and 15% were other building professionals. Seventy-five percent survey respondents were based in Hong Kong and 25% were based out of Hong Kong. The professional experience of survey respondents with 0-15 years were 30%, respondents with 15-20 years were 30%, respondents with 20-25 years were 25% and 15 % respondents were having professional experience of over 25years. Figure 2 shows questionnaire survey respondent's expertise, location and years of experience.

[Figure 2 near here]

Both online and paper-based survey was conducted to generate pairwise comparison from expert opinions using Saaty's Scale. Using pairwise comparison from questionnaire survey response from industry experts pairwise comparison matrix is developed. This pairwise matrix is evaluated using fuzzy AHP to obtain fuzzified weights. Fuzzified Saaty's scale was used for fuzzy AHP calculations. The weights are defuzzifed to get crisp values in the form of Eigen vectors which will be further used to generate super matrix for ANP calculations.

ANP analysis was used to determine relative weightage to be accounted for different category of defects affecting physical and environmental condition of the building. To reduce uncertainty in judgement made by experts in pairwise comparison due to inherent subjectivity and sometimes imprecise decision making in questionnaire survey fuzzy evaluation was used. A new methodology was implemented in this study to determine the weightage of individual factors using Fuzzy evaluation of Eigen vectors, which are to be used for developing super matrix for further ANP analysis. An excel sheet was used to evaluate this pairwise matrix using fuzzy theory by converting pairwise matrix in to fuzzified pairwise matrix using fuzzified Saaty Scale. Crisp relative weights were calculated by defuzzification. Relative weights of each cluster matrix of different criteria and defects were calculated. Using Eigen vector of calculated matrix, a super matrix was generated for further evaluation. Limit super matrix was reached to determine the final relative weights which would be used for further calculation.

Figure 3 shows building defects and corresponding relative weights adopted for this study.

[Figure 3 near here]

6.2 Defect Threshold

Based on literature different factors were identified which affects the condition of concrete building. Although a wide variety of defects affect building condition, however for simplicity of assessment common defects were selected such as structural cracks, delamination/spalling of concrete, corrosion of steel and water leakage/seepage. These defects affect the safety, function and appearance of building. Similarly, for environmental condition assessment following factors were selected temperature & humidity that affects thermal condition; light intensity; noise level that affects acoustics; carbon dioxide, carbon monoxide, nitrogen dioxide, formaldehyde and volatile organic compounds that affects the indoor air quality. Defect thresholds were determined from codes of practice and guidelines. These thresholds may differ and can be changed according to codes of practice and guidance updates. Physical building defects are inspected as per proposed defect-based condition assessment model using in visual observation in conjunction with handheld non-destructive instruments such as moisture meter, crack width scale and infrared thermal cameras while environmental condition measured using instruments such as, thermometer, sound meter, light meter and air quality meters.

6.3 Fuzzy Membership Function

Fuzzy membership functions were utilized to incorporate uncertainty in assessment as well as provide a common assessment platform since physical and environmental condition are two different types of assessment. Condition grading scale were defined as fuzzy sets. Severity of defects were deduced from literature to define fuzzy membership functions. Only triangular distribution was used for each linguistic grade. The severity of defect was distributed over the condition grading scale and fuzzy membership functions were created for all defects for assessment. Fuzzy membership functions adopted for this study are as shown in figure 4.

[Figure 4 near here]

6.4 Condition Grading Scale

A grading scale compares the condition of different building components. Grading scales can be represented alphabetically or as a numerical score. A new grading scale to compare the severity of defects and to assesses the condition of different building components was developed. This condition grading scale is represented linguistically with corresponding numerical score. Proposed grading scale is in terms of number ranging from 0-10 and corresponding linguistic description for easy understanding. Proposed grading scale is shown in Table 2.

[Table 2 near here]

6.5 Integrated Condition Assessment Model

ANP network model is created with hierarchy of defects for assessment. Questionnaire survey was distributed among industry professionals to determine the relative weights between different type of defects and their criteria. Both online and paper-based survey was conducted to generate pairwise comparison from expert opinions using Saaty's Scale. Using pairwise comparison from questionnaire survey response from industry experts pairwise comparison matrix is developed. An excel sheet was used to evaluate this pairwise matrix using fuzzy theory by converting pairwise matrix in to fuzzified pairwise matrix using fuzzified Saaty Scale. Crisp relative weights were calculated by defuzzification. Consistency index and the consistency ratio were calculated using to check the consistency of the pairwise comparison of each matrix respectively.

Relative weights of each cluster matrix of different criteria and defects were calculated. Using Eigen vector of calculated matrix, a super matrix was generated for further evaluation. Limit super matrix was reached to determine the final relative weights which would be used for further calculation. A rating scale to compares the severity of defects to assesses the condition of different building components was developed. This rating scale is represented linguistically with corresponding numerical score.

Evidential reasoning was used to account for the uncertainty accompanied with judgement while making decision to convert the visible symptoms of building defects to condition grading scales.

Physical building defects were observed by visual observation in conjunction with handheld non-destructive instruments such as moisture meter and infrared thermal cameras while environmental condition was observed using instruments such as, thermometer, sound meter, light meter and air quality meters.

For assignment of degrees of belief to different element and aggregate the outcome, evidential reasoning algorithm from Yang & Xu (Jian-Bo Yang & Dong-Ling Xu, 2002; Xu, 2012) were referred. The degree of belief was extracted from fuzzy membership functions to assign to each detected defect over rating scale with corresponding relative weights earlier deduced from ANP. The degrees of beliefs of each of the defects were multiplied by their corresponding weights to get the basic probability assignments as shown in equation 2 while the remaining probability mass that remained unassigned to any of the condition scales was calculated as shown in equation 3.

$$m_{n,i} = \omega_i \beta_{n,i} \qquad where\ n = 1, \ldots\ldots, N \tag{2}$$

$$m_{H,i} = 1 - \sum_{n=1}^{N} m_{n,i} = 1 - \omega_i \sum_{n=1}^{N} \beta_{n,i}\ where\ n = 1, \ldots\ldots, N \tag{3}$$

where, $m_{n,i}$= basic probability mass representing the degree to which the assessor evaluates defect from grading scale of 1-10. $m_{H,i}$= remaining probability mass unassigned to any individual grade after all the $N = 10\ grades$ have been considered. ω_i is the respective weight of defect calculated from ANP.

Leftover unassigned degrees of belief were redistributed over the condition scale after aggregating all of the defects recursively. The same above steps were applied for each defect group of each component to determine the condition of space/room. The final step was aggregate all the individual conditions to determine the overall condition.

Then probability masses $m_{n,I(i)}$ and $m_{H,I(i)}$ can be deduced by combining the basic probability masses $m_{n,j}$ and $m_{H,j}$ for all $n = 1, \ldots\ldots, N\ and\ j = 1, \ldots\ldots, i.$

Hence the recursive evidential reasoning algorithm can be summarized as follows

$$m_{n,I(i)} = K_{I(i+1)}\left(m_{n,I(i)} m_{n,i+1} + m_{n,I(i)} m_{H,i+1} + m_{H,I(i)} m_{n,i+1}\right)\ where\ n = 1, \ldots\ldots, N \tag{4}$$

$$m_{H,I(i+1)} = K_{I(i+1)} m_{H,I(i)} m_{H,(i+1)} \tag{5}$$

$$K_{I(i+1)} = \left[1 - \sum_{t=1}^{N} \sum_{\substack{j=1 \\ j \neq t}}^{N} m_{t,I(i)} m_{j,(i+1)}\right]^{-1} \quad where\ i = 1, \ldots\ldots, L-1 \tag{6}$$

where $K_{I(i+1)}$ is a normalizing factor in which $\sum_{n=1}^{N} m_{n,i+1} + m_{H,i+1} = 1$

also $m_{n,I(i)} = m_{n,1}\ (n = 1, \ldots\ldots, N)\ and\ m_{H,I(1)} = m_{H,1}$

It is important to note that attributes in E are numbered arbitrarily that means $m_{n,I(L)}$, $(n = 1, \ldots\ldots, N)\ and\ m_{H,I(L)}$ do not depend on the order in which the basic attributes are aggregated. The combined degree of belief β_N is given by equation 7.

$$\beta_N = m_{n,I(L),} \qquad where\ n = 1, \ldots\ldots, N \tag{7}$$

The remaining unassigned degree of belief β_H after all the L basic attributes are assessed is given by equation 8.

$$\beta_H = m_{H,I(L)} = 1 - \sum_{n=1}^{N} \beta_N \tag{8}$$

The incompleteness in the assessment is represented by β_H and when there is no incompleteness in basic assessment $\beta_H = 0$.

For decision making with crisp values after calculating the aggregated degree of belief in terms of percentages the output has to be defuzzified using the weighted average method of the fuzzy set theory. Aggregate of combined degree of belief for all components were defuzzified to compute the overall condition. This overall condition can be used by building stakeholders to assist them in decision making process for budget allocation for maintenance and repair.

7.0 CASE STUDY AND MODEL IMPLEMENTATION

The proposed defect-based condition assessment model was implemented as a case study. For model implementation block Z building in Hong Kong Polytechnic University campus was selected. To test the developed defect-based condition assessment model for this research, an entire floor was selected of block Z building. This building is divided into two blocks North and South. The selected floor is situated on level 7. This floor has 44 rooms in North block and 37 rooms in

South block majority of the rooms are offices and research lab on this floor. In addition, there are 5 staircases, 9 lifts blocks, 4 toilet rooms along with separate electrical rooms and maintenances rooms for building services.

7.1 BIM model development for case study

A BIM model was developed as a part of model testing and validation. Floor plan drawings were retrieved from facility management office (FMO) of the university. Using 2D AutoCAD drawings as base, 3D BIM model was generated in Rivet 2019 software. The floor plan of 7th floor of Block Z building used a case study is shown in Figure 5(a). Figure 5(b) shows 3D BIM model generated using CAD drawings of 7th floor of Block Z of Poly U. To easily identify the rooms during inspection each room was color coded and assigned room number. To assign room numbers at desired location tagging function was used in Rivet software. Figure 5(c) shows color coded room number tagging of BIM model in Rivet.

[Figure 5 near here]

7.2 Development of BIM based software program

Current practices of using conventional methods of handling data using spreadsheets or managing hard paper copies for storing inspection data is inefficient. Transferring building inspection data is time consuming, tedious and sometimes error prone. To address management of building inspection data Building Information Modeling (BIM) is used and a plugin is developed to integrate the physical & environmental condition assessment with BIM model of facility. To encourage application of BIM for condition assessment and utilize same BIM model environment to manage building inspection data for condition assessment, a Windows based GUI was developed. Autodesk Rivet was used to create BIM model of case study building floor. Rivet was chosen for BIM model development as it provides API (Application Programming Interface). API gives user ability to extract building data from BIM model to another program. Microsoft Visual Studio was used to develop a plugin program with window based Graphical user interface using C# language.

The defect based integrated condition assessment model discussed earlier was implemented into a Revit plugin software to interact with BIM models of existing buildings using Revit API. This plugin will act a tool during condition assessment process to act as input from user, extract building data from BIM models, store inspection data and pictures, analyze, store and display assessment results in graphical format. Figure 6 shows the system architecture of Revit plugin named Integrated Facility Management (iFM) developed for this study.

[Figure 6 near here]

7.3 iFM Graphical User Interface (GUI)

Entire condition assessment process can be carried out using portable windows table installed with iFM plugin in Rivet software and all the inputs can be entered on field followed by quick analysis and result on the field. Figure 7(a) shows windows 10 tablet with BIM model. To provide a user-friendly input tool a window based graphical user interface is developed similar to any window layout in PC. This window user interface can be used by user to interact with iFM software to enter their desired input. GUI interface consist of menus bar with icons for different functions. Figure 7(b) shows the graphical user interface of iFM plugin running within Rivet software. This window-based GUI allows users to input information of project, physical evaluation of defects, environmental instrument readings, attach photos of defects and add comments or remarks if any. This program helps in centralized data input and management of inspection data such as defect severity, images, comments and instrument readings. This program also helps in management of building inspection data for both physical defects and environmental condition on one single platform.

[Figure 7 near here]

7.4 Physical evaluation input

After checking all the required tools and selection of desired rooms for inspection next step is to input physical evaluation into the application program. Physical defects as per our proposed model can be detected by visual inspection complimented with NDT instruments such as moisture meter, crack width scale and other handheld instruments. Figure 7(c) shows tab for physical evaluation input. In this tab after detecting the building defects, severity of defects can be used as an input. User also has the option to attach a picture of the room with or without defects for record. User can also add comments and remarks about any specific observation during the inspection in the program. This input will be saved in database for future analysis once the user clicks save button in menu bar. This input can be retrieved at any time based on date of assessment under view facility condition which can be assessed using navigation tree in the program.

7.5 Environmental measurement input

Similar to physical input tab environmental instrument readings can be used as an input for different readings of IAQ, thermal, lighting and noise level in the program. Handheld environmental instruments such as Air Quality monitoring device for IAQ, temperature and humidity meter for thermal readings, Lux meter for lighting and sound level meter to measure the noise can be used. Figure 7(d) shows tab for environmental instrument measurement readings input in the program. In this tab the instrument readings can be used as an input with their respective units as shown in the program. Along with instrument readings for a particular room user also has the option to attach a picture of the room for record. User can also add comments and remarks about any specific observation during the inspection. This input will be saved in database for further analysis once the user clicks save button in menu bar. This input can be retrieved at any time based on date of assessment under view facility condition which can be assessed using navigation tree in the program.

8.0 RESULTS AND DISCUSSION

To test and validate the proposed defect-based condition assessment model it is implemented on a case study. After entering all the required physical evaluation input and environmental instrument readings for all the desired tagged rooms next step is to analyse and compute the integrated condition rating of individual tagged rooms and aggregated whole building condition. To compute click Run under Analysis tab of iFM plugin GUI. Figure 7(e) shows graphical presentation of analysis result in the form of bubble diagram plotting the group of tagged rooms where x-axis represents physical condition and y-axis environmental condition. Each bubble represents each type of room in the building with separate colours. User can also view individual condition of a room from view facility condition located in navigation tree. Results are also available in tabular format in the iFM plugin.

The case study used in this research of entire floor with of university building was in good condition hence very few defects were detected (e.g., hairline cracks), there was no major cracks, or any spalling and no water seepage was detected. Similarly, the environmental instrument readings were all within permissible limits and in excellent condition. A sample calculation is shown for condition assessment based on ER algorithm in figure 8. Successful implementation of defect-based condition assessment model as proof of concept has shown potential to provide better documentation for building inspection process which in turn can reduce time and cost of inspection compared to traditional paper-based condition assessment.

Building information data for desired space to be assessed along with their respective physical inspection data and IAQ data are fed into the developed application program software. Entire building inspection process can be carried out using portable windows tablet installed with application software developed and all the inputs can be entered on field using NDT and environmental instruments. Proposed model is thus implemented in the form of an application software which can be run on any windows-based tablet during inspection process. After completing the condition assessment, one of four decisions can be made: no action, minor repairs, major repairs, or rehabilitation, based on the severity of the defects detected.

Defect based condition assessment framework is developed to address the need for comprehensive and structured approach to perform building inspection. Identifying building defects accurately through structured building inspection before they become worse will help reducing the need for maintenance and repair of building components which can help to extend the service life of existing buildings. Defect based condition assessment will also help to reduce subjectivity, human errors during inspection and reduce mistakes in overall assessment of the building. The integrated tool developed as an application program for input from user, store inspection data pictures, and comments during inspection process can transform the traditional field of paper-based building inspection into more efficient and interactive process.

The developed application program which runs within windows environment has potential to improve productivity of inspection personnel by digitally entering inspection data for huge number of building components within large building complex. This program also provides better documentation and data management for building inspection data that can save time involved in manual data operations and transfer in traditional paper-based processes. This program developed for implementation of defect-based condition assessment model for physical and environmental condition can be used by building stakeholders to assist them in decision making process for maintenance, repair and rehabilitation of existing buildings.

Buildings will deteriorate over time due to ageing, and wear and tear that will reduce the ability of building elements to perform their intended function (Grussing, Uzarski, & Marrano, 2009). The interest and demand of building inspection is increasing due to rapidly deteriorating conditions of building (Alba-Rodríguez et al., 2017; Amaral & Henriques, 2013). However, high cost of inspection and time consumption to inspect existing buildings are deterring factors that restricts building owners and facility managers from adopting periodic condition assessment for decision making in maintenance and repair (Ahluwalia, 2008). Literature review reveals that very few countries have implemented periodic building condition assessment system as a statutory requirement (Bortolini & Forcada, 2018; Faqih & Zayed, 2021; Vilhena et al., 2011). Hence for sustainable management of existing buildings there is a need for cost effective building condition assessment model with reduced subjectivity and expedited processes. There was also lack of comprehensive assessment model that considers both physical and environmental condition of the building together (Anuar et al., 2019; Ferraz et al., 2016; Vilhena et al., 2011). The model developed in this study fills the gap with defect based comprehensive condition assessment of building considering both physical and environmental condition. Conventional building inspection are generally dependant on visual observation, that can lead to subjective results dependant on experience, training and perception of the inspection personnel. Defect based model developed in this study along with visual inspection gives a framework to adopt non-destructive technology for condition assessment. The model also utilizes research techniques such as fuzzy membership functions and evidential reasoning to incorporate subjectivity of inspection which was not addressed in previous research. Although previous research studies have highlighted the need for regular periodic condition assessment and improved the process with use of checklist forms and computer programs (Faqih & Zayed, 2021; Vilhena et al., 2011). In this model BIM platform was used for storing and analysing inspection data during building inspection that also addresses the need for structured data management in building condition assessment process thereby reducing the time and cost of data handling. The defect-based condition assessment model develop in this study is a step forward to reduce the cost and time of building inspection by providing a framework to conduct effective building inspections that can help building stakeholders in decision making for repair, maintenance and rehabilitation.

9.0 CONCLUSION

Ageing and deterioration of buildings are inevitable and challenging tasks for facility management. Facility stakeholders with limited resources are facing increased difficulties in making decisions for budget allocation, maintenance and repair based on condition assessment of building. During building inspection decisions for evaluation of condition are often ingrained with uncertainty of human judgement based on visual inspection only. Multi-storey buildings with increased complexity and multiple assessment criteria demands a more systematic framework for building condition assessment. One of the major challenges during condition assessment of buildings by visual inspection is uncertainty in judgement of inspection personnel due to subjective and sometimes imprecise decision making on site. The proposed defect-based condition assessment model can help to incorporate the uncertainty in judgement of inspection personnel for evaluation and consequently help building stakeholders with robust aggregated building condition in decision making for maintenance, repair and rehabilitation. This paper proposed a novel defect-based condition assessment model for existing buildings incorporating both building physical and environmental condition. The proposed assessment model utilised multiple criteria decision-making methods such as analytic network process (ANP) in order to deduce weighting coefficients for building defects that determines their relative importance. The severity of building defects is assessed using a grading scale to ascertain degree of belief in assessment using fuzzy membership functions. Degree of belief and defects weighting coefficients are used in aggregation model based on Evidential Reasoning theory to integrate different types of defects and to compute the overall condition assessment of building. This study is limited to selected common building defects that influence the condition of the concrete building hence the model developed is limited to concrete buildings only. The framework developed is flexible and can be expanded to incorporate various different types of building defects in future studies. Taking appropriate remedial action based on accurate condition assessment of buildings could reduce time and cost required for major repairs due to propagation of minor defects into major defects.

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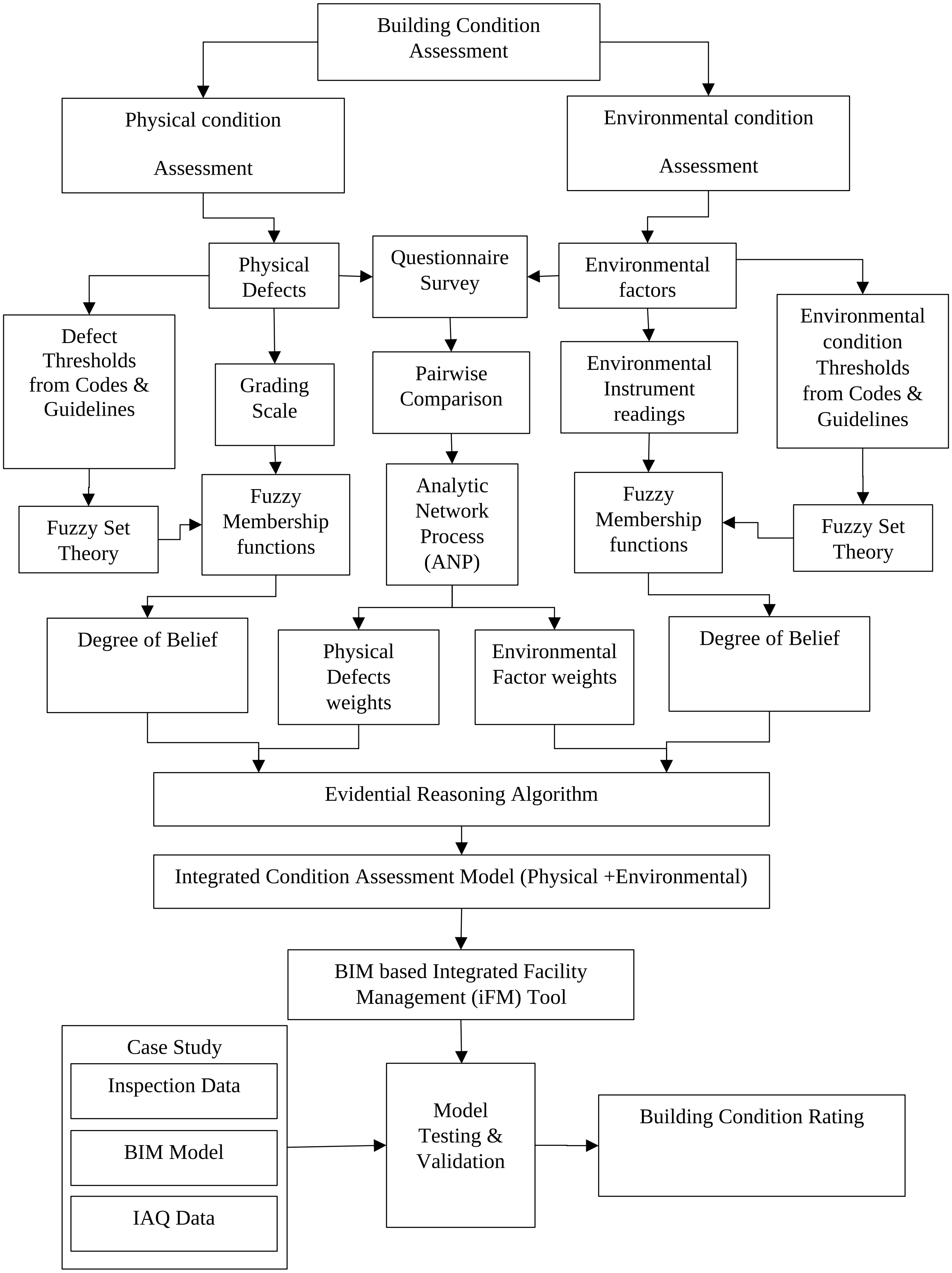
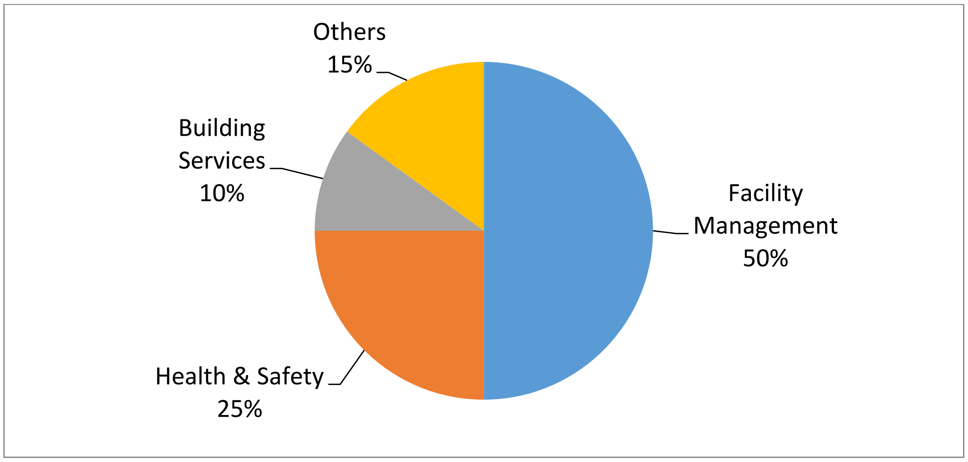
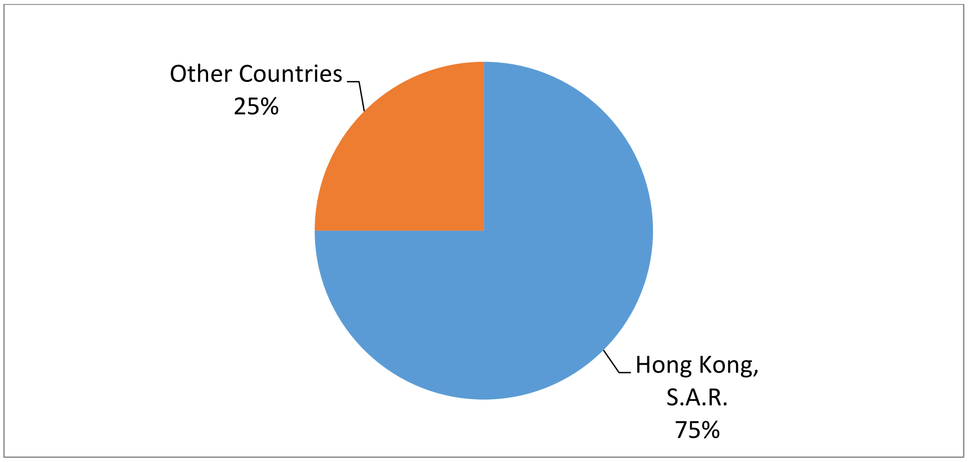


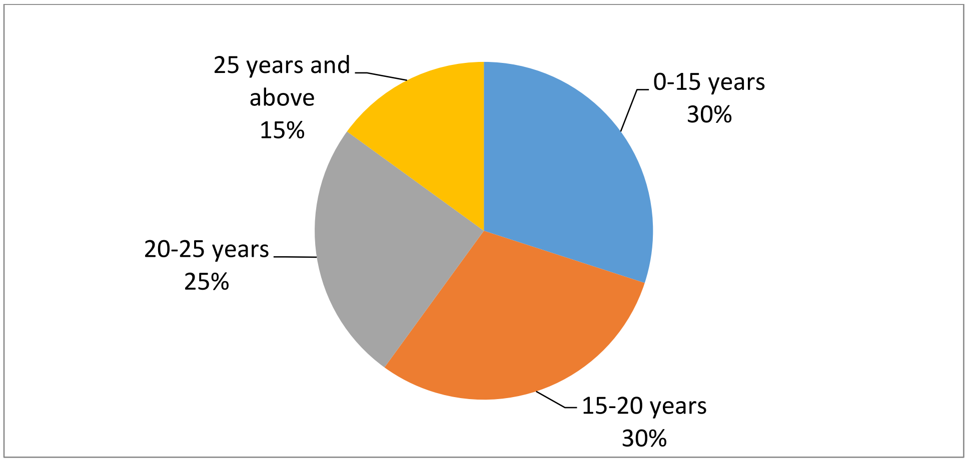
Fig. 1. Methodology adopted for proposed model



(a) Respondent’s expertise



(b) Respondent’s location of work



(c) Respondent’s years of experience

Figure 2. Survey respondent’s expertise, location and years of experience.

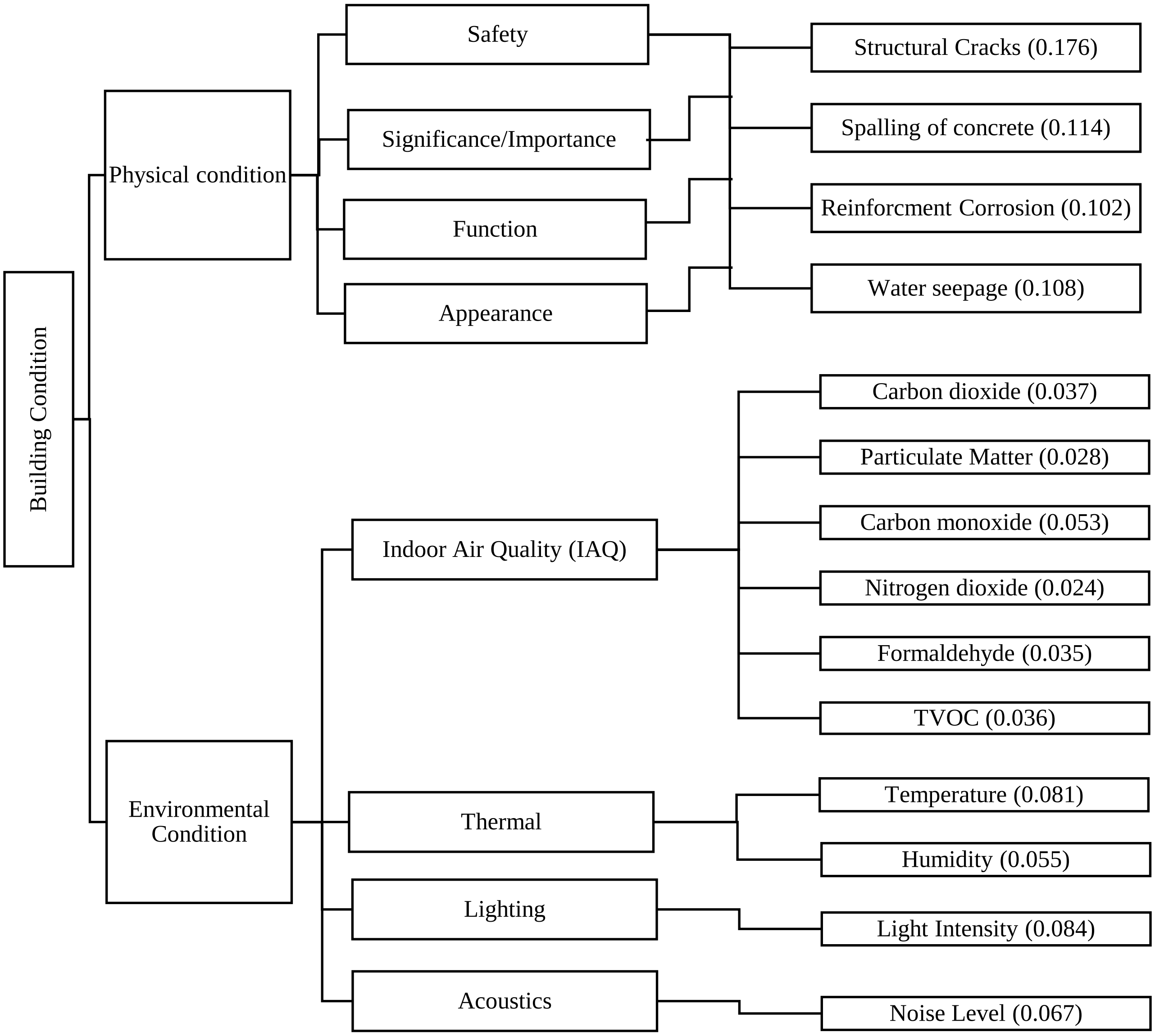


Figure 3. Building defects and their relative weights shown in brackets

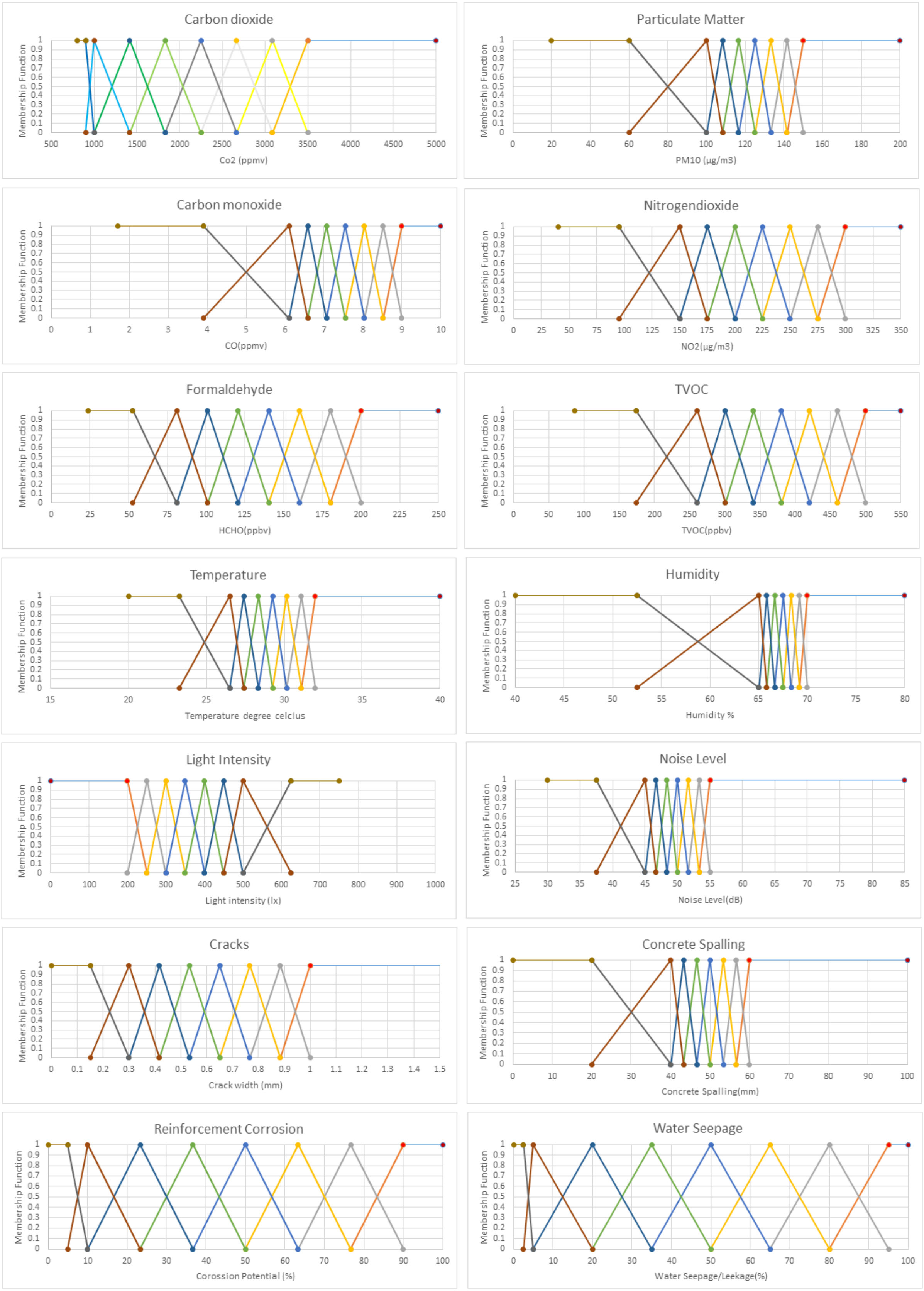
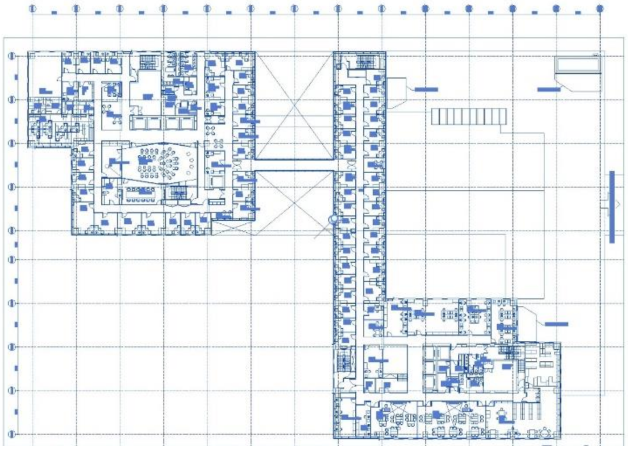
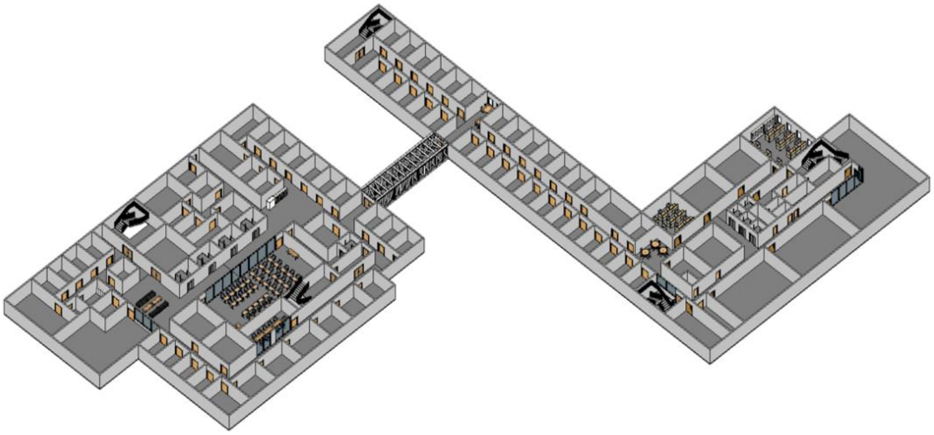


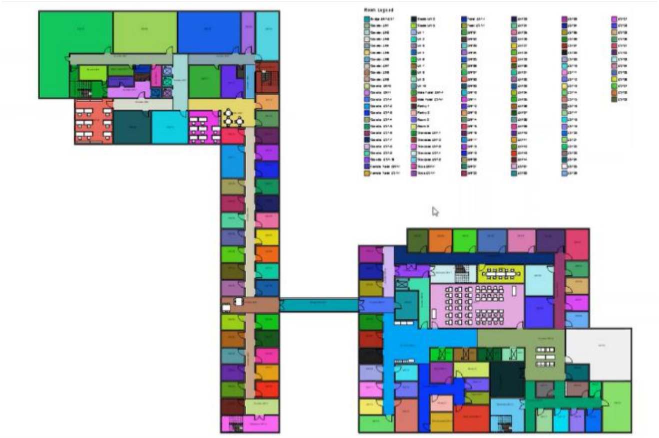
Fig. 4. Fuzzy Membership functions



(a) 2D CAD floor plan of 7th floor of Block Z of case study building



(b) 3D BIM model of 7th floor of Block Z building of Poly U.



(c) Colour coded room number assignment in BIM model

Fig. 5. Conversion of CAD drawing into BIM model for case study

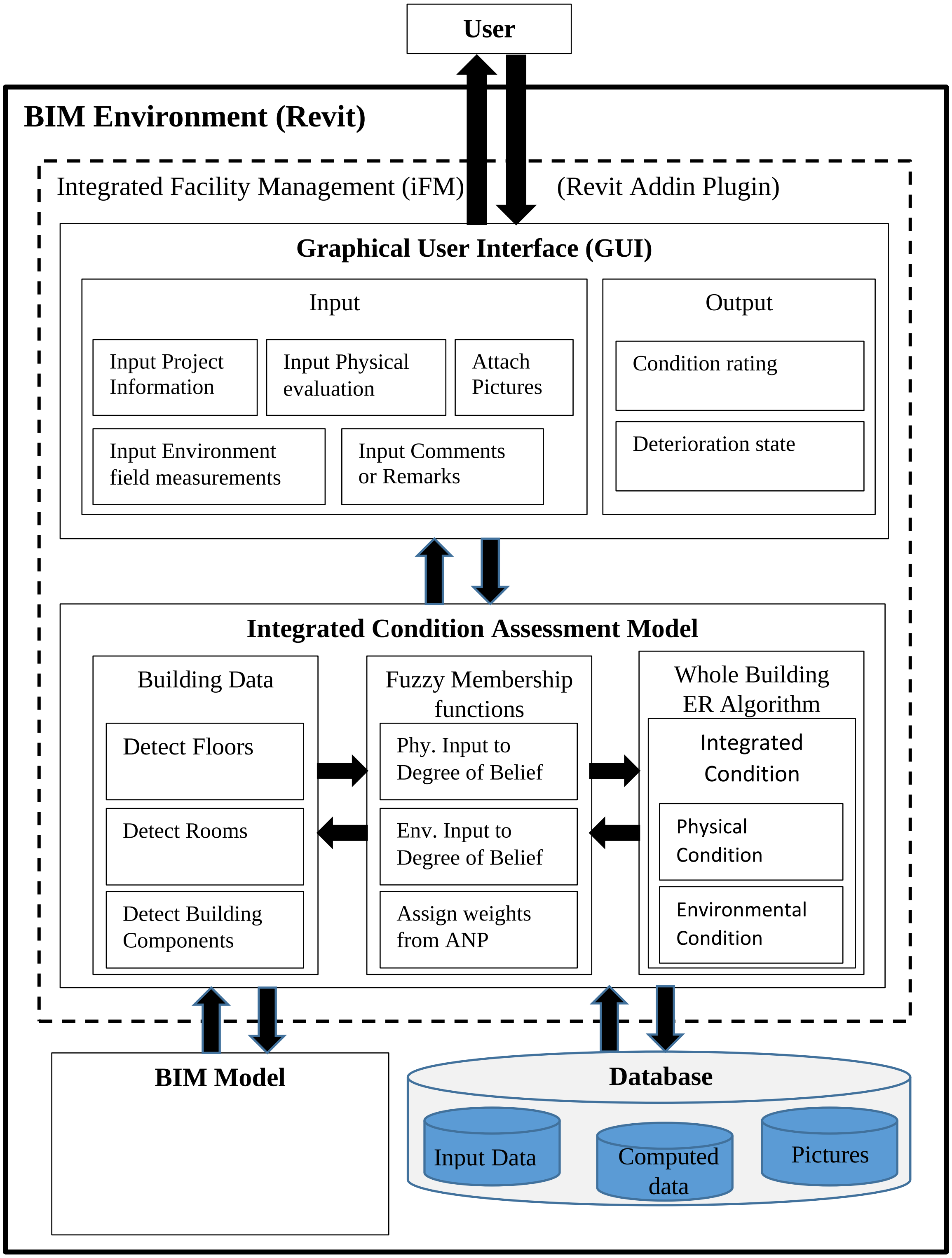
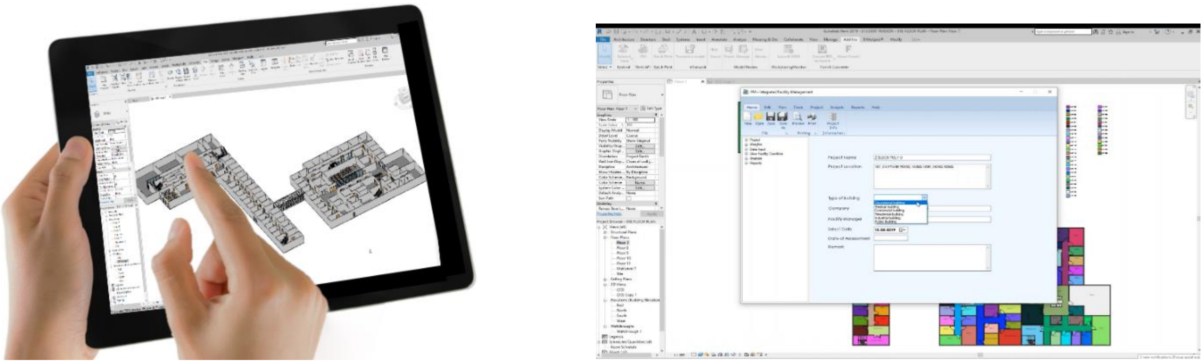
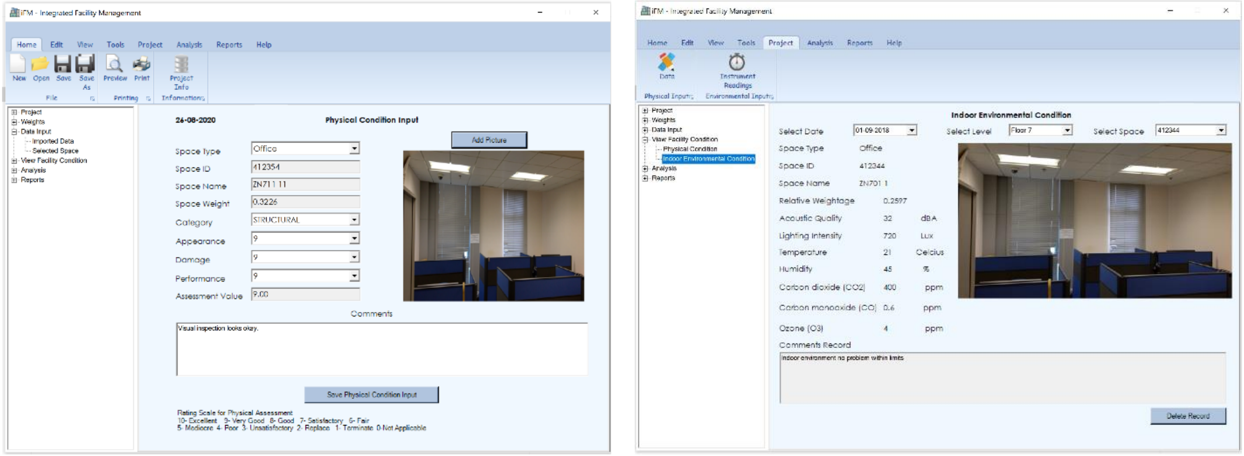


Fig. 6. System Architecture for iFM Revit plugin



(a) Windows 10 tablet with BIM software (b) Graphical User Interface (GUI) iFM Revit plugin



26-08-2020 Physical Condition Input

Space Type: Office
Space ID: 412354
Space Name: ZN711 11
Space Weight: 0.3226
Category: STRUCTURAL
Appearance: 9
Damage: 9
Performance: 9
Assessment Value: 9.00

Comments: Visual inspection looks okay.

Rating Scale for Physical Assessment
10- Excellent 9- Very Good 8- Good 7- Satisfactory 6- Fair
5- Mediocre 4- Poor 3- Unsatisfactory 2- Replace 1- Terminate 0-Not Applicable

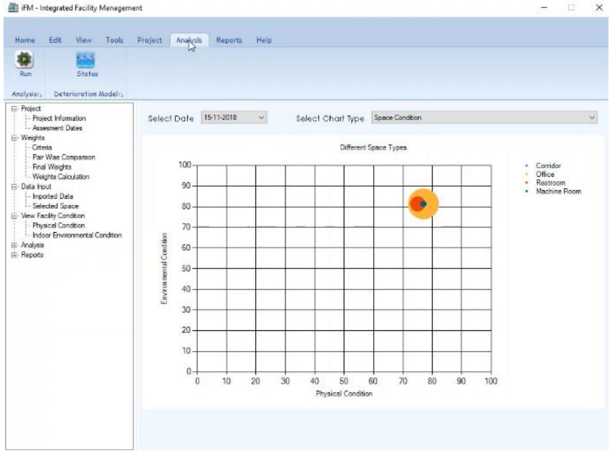
Indoor Environmental Condition

Select Date: 01-09-2018 Select Level: Floor 7 Select Space: 412344

Space Type	Office	
Space ID	412344	
Space Name	ZN701 1	
Relative Weightage	0.2597	
Acoustic Quality	32	dBA
Lighting Intensity	720	Lux
Temperature	21	Celcius
Humidity	45	%
Carbon dioxide (CO2)	400	ppm
Carbon monooxide (CO)	0.6	ppm
Ozone (O3)	4	ppm

Comments Record: Indoor environment no problem within limits

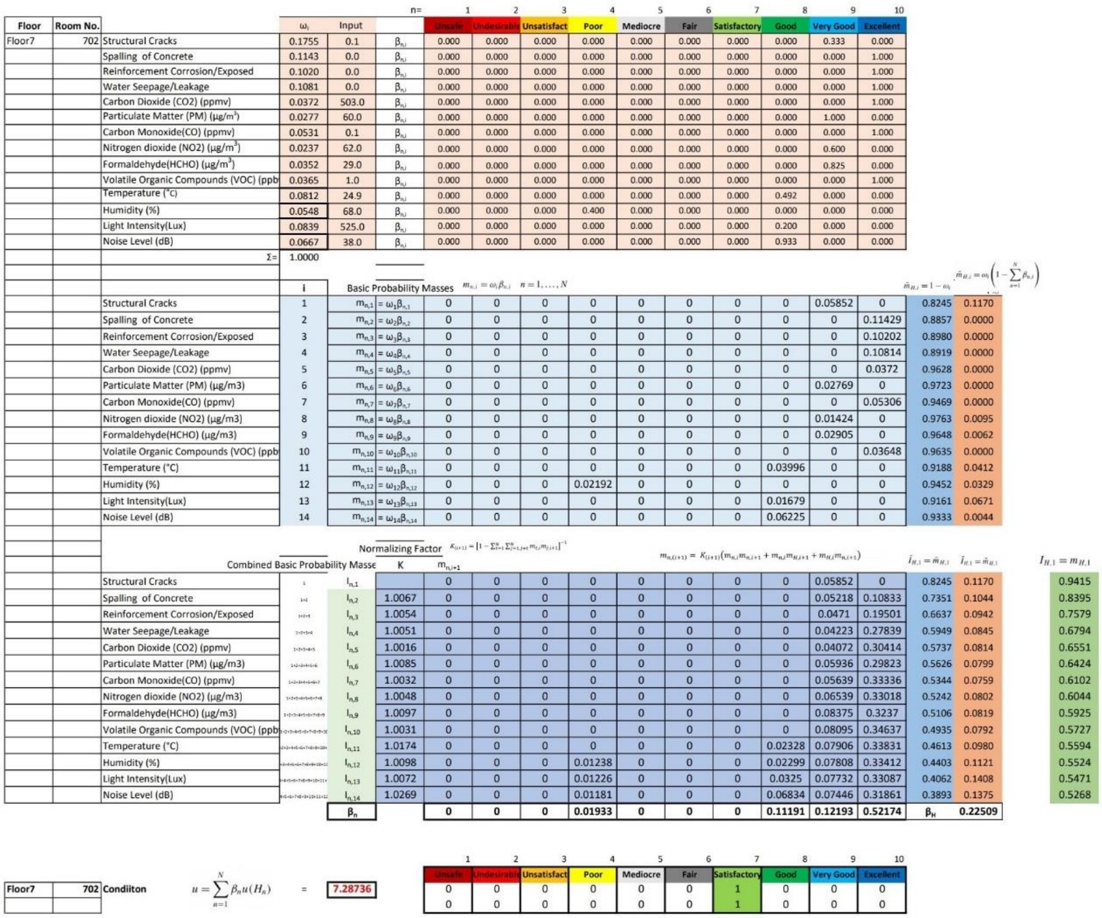
(c) Input window for physical (d) Input window for environmental conditions



Select Date: 15-11-2018 Select Chart Type: Space Condition

(e) Integrated building condition assessment result represented by bubble chart

Fig. 7. Screenshot showing different windows of developed software application program for implementation of defect-based condition assessment model



						n=	1	2	3	4	5	6	7	8	9	10
Floor	Room No.		ω_i	Input		Unsafe	Undesirable	Unsatisfact	Poor	Mediocre	Fair	Satisfactory	Good	Very Good	Excellent
Floor7	702	Structural Cracks	0.1755	0.1	$\beta_{n,i}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.333	0.000
		Spalling of Concrete	0.1143	0.0	$\beta_{n,i}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000
		Reinforcement Corrosion/Exposed	0.1020	0.0	$\beta_{n,i}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000
		Water Seepage/Leakage	0.1081	0.0	$\beta_{n,i}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000
		Carbon Dioxide (CO2) (ppmv)	0.0372	503.0	$\beta_{n,i}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000
		Particulate Matter (PM) (μg/m^3)	0.0277	60.0	$\beta_{n,i}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000
		Carbon Monoxide(CO) (ppmv)	0.0531	0.1	$\beta_{n,i}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000
		Nitrogen dioxide (NO2) (μg/m^3)	0.0237	62.0	$\beta_{n,i}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.600	0.000
		Formaldehyde(HCHO) (μg/m^3)	0.0352	29.0	$\beta_{n,i}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.825	0.000
		Volatile Organic Compounds (VOC) (ppb	0.0365	1.0	$\beta_{n,i}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000
		Temperature (°C)	0.0812	24.9	$\beta_{n,i}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.492	0.000	0.000
		Humidity (%)	0.0548	68.0	$\beta_{n,i}$	0.000	0.000	0.000	0.400	0.000	0.000	0.000	0.000	0.000	0.000
		Light Intensity(Lux)	0.0839	525.0	$\beta_{n,i}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.200	0.000	0.000
		Noise Level (dB)	0.0667	38.0	$\beta_{n,i}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.933	0.000	0.000
		Σ=	1.0000												

Basic Probability Masses $m_{n,i}=\omega_i\beta_{n,i}\quad n=1,\ldots,N$

	i												$\bar{m}_{H,i}=1-\omega_i$	$\tilde{m}_{H,i}=\omega_i\left(1-\sum_{n=1}^{N}\beta_{n,i}\right)$
Structural Cracks	1	$m_{n,1}$ = $\omega_1\beta_{n,1}$	0	0	0	0	0	0	0	0	0.05852	0	0.8245	0.1170
Spalling of Concrete	2	$m_{n,2}$ = $\omega_2\beta_{n,2}$	0	0	0	0	0	0	0	0	0	0.11429	0.8857	0.0000
Reinforcement Corrosion/Exposed	3	$m_{n,3}$ = $\omega_3\beta_{n,3}$	0	0	0	0	0	0	0	0	0	0.10202	0.8980	0.0000
Water Seepage/Leakage	4	$m_{n,4}$ = $\omega_4\beta_{n,4}$	0	0	0	0	0	0	0	0	0	0.10814	0.8919	0.0000
Carbon Dioxide (CO2) (ppmv)	5	$m_{n,5}$ = $\omega_5\beta_{n,5}$	0	0	0	0	0	0	0	0	0	0.0372	0.9628	0.0000
Particulate Matter (PM) (μg/m3)	6	$m_{n,6}$ = $\omega_6\beta_{n,6}$	0	0	0	0	0	0	0	0	0.02769	0	0.9723	0.0000
Carbon Monoxide(CO) (ppmv)	7	$m_{n,7}$ = $\omega_7\beta_{n,7}$	0	0	0	0	0	0	0	0	0	0.05306	0.9469	0.0000
Nitrogen dioxide (NO2) (μg/m3)	8	$m_{n,8}$ = $\omega_8\beta_{n,8}$	0	0	0	0	0	0	0	0	0.01424	0	0.9763	0.0095
Formaldehyde(HCHO) (μg/m3)	9	$m_{n,9}$ = $\omega_9\beta_{n,9}$	0	0	0	0	0	0	0	0	0.02905	0	0.9648	0.0062
Volatile Organic Compounds (VOC) (ppb	10	$m_{n,10}$ = $\omega_{10}\beta_{n,10}$	0	0	0	0	0	0	0	0	0	0.03648	0.9635	0.0000
Temperature (°C)	11	$m_{n,11}$ = $\omega_{11}\beta_{n,11}$	0	0	0	0	0	0	0	0.03996	0	0	0.9188	0.0412
Humidity (%)	12	$m_{n,12}$ = $\omega_{12}\beta_{n,12}$	0	0	0	0.02192	0	0	0	0	0	0	0.9452	0.0329
Light Intensity(Lux)	13	$m_{n,13}$ = $\omega_{13}\beta_{n,13}$	0	0	0	0	0	0	0	0.01679	0	0	0.9161	0.0671
Noise Level (dB)	14	$m_{n,14}$ = $\omega_{14}\beta_{n,14}$	0	0	0	0	0	0	0	0.06225	0	0	0.9333	0.0044

Normalizing Factor $K_{(i+1)}=\left[1-\sum_{t=1}^{N}\sum_{j=1,j\neq t}^{N}m_{t,i}m_{j,i+1}\right]^{-1}$

$m_{n,(i+1)}=K_{(i+1)}(m_{n,i}m_{n,i+1}+m_{n,i}m_{H,i+1}+m_{H,i}m_{n,i+1})$

Combined Basic Probability Masse		K	$m_{n,i+1}$										$\bar{I}_{H,1}=\bar{m}_{H,1}$	$\tilde{I}_{H,1}=\tilde{m}_{H,1}$	$I_{H,1}=m_{H,1}$
Structural Cracks	$I_{n,1}$		0	0	0	0	0	0	0	0	0.05852	0	0.8245	0.1170	0.9415
Spalling of Concrete	$I_{n,2}$	1.0067	0	0	0	0	0	0	0	0	0.05218	0.10833	0.7351	0.1044	0.8395
Reinforcement Corrosion/Exposed	$I_{n,3}$	1.0054	0	0	0	0	0	0	0	0	0.0471	0.19501	0.6637	0.0942	0.7579
Water Seepage/Leakage	$I_{n,4}$	1.0051	0	0	0	0	0	0	0	0	0.04223	0.27839	0.5949	0.0845	0.6794
Carbon Dioxide (CO2) (ppmv)	$I_{n,5}$	1.0016	0	0	0	0	0	0	0	0	0.04072	0.30414	0.5737	0.0814	0.6551
Particulate Matter (PM) (μg/m3)	$I_{n,6}$	1.0085	0	0	0	0	0	0	0	0	0.05936	0.29823	0.5626	0.0799	0.6424
Carbon Monoxide(CO) (ppmv)	$I_{n,7}$	1.0032	0	0	0	0	0	0	0	0	0.05639	0.33336	0.5344	0.0759	0.6102
Nitrogen dioxide (NO2) (μg/m3)	$I_{n,8}$	1.0048	0	0	0	0	0	0	0	0	0.06539	0.33018	0.5242	0.0802	0.6044
Formaldehyde(HCHO) (μg/m3)	$I_{n,9}$	1.0097	0	0	0	0	0	0	0	0	0.08375	0.3237	0.5106	0.0819	0.5925
Volatile Organic Compounds (VOC) (ppb	$I_{n,10}$	1.0031	0	0	0	0	0	0	0	0	0.08095	0.34637	0.4935	0.0792	0.5727
Temperature (°C)	$I_{n,11}$	1.0174	0	0	0	0	0	0	0	0.02328	0.07906	0.33831	0.4613	0.0980	0.5594
Humidity (%)	$I_{n,12}$	1.0098	0	0	0	0.01238	0	0	0	0.02299	0.07808	0.33412	0.4403	0.1121	0.5524
Light Intensity(Lux)	$I_{n,13}$	1.0072	0	0	0	0.01226	0	0	0	0.0325	0.07732	0.33087	0.4062	0.1408	0.5471
Noise Level (dB)	$I_{n,14}$	1.0269	0	0	0	0.01181	0	0	0	0.06834	0.07446	0.31861	0.3893	0.1375	0.5268
	β_n		**0**	**0**	**0**	**0.01933**	**0**	**0**	**0**	**0.11191**	**0.12193**	**0.52174**	**β_H**	**0.22509**	

Floor7	702	**Condiiton**

$$u=\sum_{n=1}^{N}\beta_n u(H_n)\quad = \quad \boxed{7.28736}$$

1	2	3	4	5	6	7	8	9	10
Unsafe	Undesirable	Unsatisfact	Poor	Mediocre	Fair	Satisfactory	Good	Very Good	Excellent
0	0	0	0	0	0	1	0	0	0
0	0	0	0	0	0	1	0	0	0

Fig. 8. Sample calculation shown for condition assessment based on ER algorithm

Table 1. Factors affecting environmental condition of buildings and environmental defects

Categories	**Factors Affecting Environmental condition**	**Source**	**Environmental defects affecting Human comfort**	**Detection Instruments or Equipment**	**Health effect on building occupants**	**References**
Indoor Air Quality (IAQ)	Carbon dioxide (CO_2)	By-product of human exhalation	High Concentration	Carbon dioxide meter	Difficulty in breathing, sweating, tiredness, increased heart rate	IAQMG HKSAR (2019), ASHRAE 62.1 (2016), World Health Organization (2010), World Health Organization (2009), (Al horr et al., 2016; Altomonte, Schiavon, Kent, & Brager, 2019; Faqih et al., 2020; MacNaughton et al., 2017; Mujan, Anđelković, Munćan, Kljajić, & Ružić, 2019; Tham, 2016; Wolkoff, 2018)
	Respirable Suspended Particulates Matter (RSPM)	Dust, copiers, printers, cigarette smoking	High Concentration	Particulate monitor	Affects respiratory system, Coughing, Allergic effects	
	Carbon monoxide (CO)	Flue gas of burning stove, diesel car exhaust, cigarette smoking	High Concentration	Carbon monoxide meter	Impaired vision and coordination; Headaches; Dizziness; Nausea at high concentration	
	Nitrogen dioxide (NO_2)	Flue gas of burning stove, diesel car exhaust, cigarette smoking	High Concentration	Nitrogen dioxide meter	Eye, nose, and throat irritation. Respiratory infections, affects lungs	
	Ozone (O_3)	Refrigerators, Air conditioners, Copiers, Laser printers	High Concentration	Ozone monitor	Affects respiratory system, Chronic respiratory disease	
	Formaldehyde (HCHO)	Pressed wood products, Paint and Glues	High Concentration	Formaldehyde detector	Affects respiratory system, watery eyes	
	Total volatile organic compounds (TVOC)	Paint, Solvents and aerosol products	High Concentration	VOC monitor	Sensitive and irritation symptom, Nuisance odour, Carcinogenic	

Lighting	Artificial Lighting	Room lighting	High/Low light intensity	Luminance Meter	Visual Discomfort	BS EN 12464-1 (2011), (Huang, Zhu, Ouyang, & Cao, 2012; Ricciardi & Buratti, 2018)
Thermal	Temperature	Weather conditions / Ventilation / HVAC	High/Low temperature	Thermometer	Thermal Discomfort	ASHRAE 55 (2017), ASHRAE 62.1 (2016), IAQMG HKSAR (2019) (Al horr et al., 2016; Kim, de Dear, Cândido, Zhang, & Arens, 2013; Maykot, Rupp, & Ghisi, 2018; Wolkoff, 2018)
	Humidity		High/Low humidity	Relative Humidity Meter		
Acoustics	Noise	Internal or external unwanted sound	High Noise	Sound Level Meter	Acoustic Discomfort	ASHRAE Handbook (2017) (Al horr et al., 2016)

Table 2. Proposed condition grading scale for assessment

Condition Scale	**Linguistic Description**
1	Unsafe
2	Undesirable
3	Unsatisfactory
4	Poor
5	Mediocre
6	Fair
7	Satisfactory
8	Good
9	Very Good
10	Excellent/ No Problem