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TECHNOLOGY-BASED MULTI-TIERED BUILDING DIAGNOSIS FRAMEWORK

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Purpose – A building deteriorates over time due to aging, wear and tear, and inadequate maintenance. Building diagnosis requires sound knowledge of engineering, building defects, and detection tools to assess the condition of building. The physical deterioration of a building reduces its ability to perform its intended function while environmental deterioration influences the comfort and health of building occupants. This study presents multi-tiered framework for inspection of building elements and the environmental conditions of building.

Design/methodology/approach –A three-tiered building inspection framework is proposed in this study, which consists of the following: Tier-I—a preliminary inspection, Tier-II—a detailed inspection, and Tier-III—an expert investigation. Each tier of inspection assesses the severity of building defects using different technologies for different levels of inspection.

Findings – Proposed multi-tier inspection framework is tested and implemented on a case study. Results were promising with organized data management on a common platform for both physical and environmental condition inspection having potential to save time.

Originality/value –The application program developed for implementation of structured multi-tiered building inspection provides better documentation and data management for building inspection data that can save time involved in manual data operations in traditional paper-based processes.

Keywords: building defects; building inspection; building diagnosis; non-destructive evaluation

Article Type: Research paper

1. INTRODUCTION

Building deterioration has negative consequences from an economic and environmental point of view. Irrespective of building age, defects occur in buildings due to aging, wear and tear, and inadequate maintenance (Faqih et al. 2020; Wahida et al. 2012). The deterioration of a building reduces its ability to perform its intended function (James et al. 2019; Marcel et al. 2013), while environmental deterioration influences the comfort and health of building occupants (Heinzerling et al. 2013; Thomas et al. 2019). There is a growing necessity to extend the service life of existing buildings from economic and sustainability point of view (Alba-Rodríguez et al. 2017; Amaral and Henriques 2013). Building diagnosis is generally conducted to assess the current state of a building and estimate the extent of its deterioration (Silva and de Brito 2019). According to Bernat and Gil (2013), appropriate building inspection and a maintenance plan are required for safety of building during its service life. The primary purpose of building inspection is to collect information about the technical performance of the building that can be used to plan maintenance action (Bortolini and Forcada 2018).

Defect can be considered as "shortcoming in the function, performance, statutory or user requirements of a building" (Lee et al. 2018). Building defects can pose potential risks to building occupants or users and can also affect the safe functioning and use of building facilities (Faqih et al. 2020). Thus, building defects can be considered as a failure to meet an expected functional requirement including health and safety. It is also important to interpret building defects accurately and with adequate objectivity to obtain a correct building diagnosis. Through periodic structured building inspection, it is possible to intervene at the early stage of occurrence of building defects. Identifying building defects accurately through structured building inspection before they become worse will help reduce the need for maintenance and repair of building components which helps to extend the service life of existing buildings (Paulo et al. 2014). Previous studies have highlighted the importance of non-destructive inspection and evaluation methods of building elements using different tools and equipment (Kwan and Ng 2015; Kylili et al. 2014; Lai and Poon 2012) . Research related to building diagnosis is mostly focused on specific tools to detect specific building defects. It is also noted that conventional detailed building inspection is costly and tedious (Chan and Choi 2015; Grussing 2018). There is also lack of literature on comprehensive, multi-tiered, structured approach to perform building inspection (Kwan and Ng 2015). The proposed model intends to respond to the need for a structured building inspection process for existing buildings. First, a literature review was conducted to study different building defects affecting the physical and environmental condition of buildings. It is imperative to understand not just the different types of defects in the building but also the various technologies employed to detect them. A qualitative comparison of different tools and technologies used in building diagnosis is presented based on ease of use, interpretation of results, and cost. Finally, a three-tiered building inspection model is proposed as follows: Tier-I involves a preliminary inspection, Tier-II involves a detailed inspection, and Tier-III involves an expert investigation. This study can help engineers and inspection personnel conduct effective building inspections by following a structured approach for collecting data of an appropriate level of detail across different tiers based on the severity of defects detected. Multi-tiered building inspections, if conducted effectively, can potentially reduce the time and cost of periodic inspections.

2. RESEARCH BACKGROUND & EXSITING PRACTICES

Mandatory Building Inspection Scheme (MBIS) is an official policy implemented in for building maintenance 2012 in Hong Kong (CHAN and Hung 2015). The building department of Hong Kong issues notices to selected old buildings over 30 years or older to carry out mandatory building inspection (W.M. Chan et al. 2014). This building inspection is to be carried out by registered professional with focus mainly on building elements which are vital to public safety such as any projections or signboards on the building; common areas; fire safety; drainage systems; and any unauthorized work in the building (Buildings Department 2012; W.M. Chan et al. 2014).

The Dutch standard NEN 2767 in Netherland is based on the detection of defects in functional elements of buildings and their importance, extent and intensity (Kuijper and Bezemer 2017; Straub 2009). National Centre of Education Statistics (NCES) in United States uses Facility Condition Index (FCI) as a tool for building condition assessment of school facilities (Amani et al. 2012; National Forum on Education Statistics. 2012; NCES 2003). Housing Health and Safety Rating System (HHSRS) in United Kingdom assesses the potential health and safety risk from the defects identified in housing (HHSRS 2005, 2006). In Portugal building defects detected are assessed on a scale based on pre-defined criteria and the level of defect in the different elements is logged in a checklist for condition assessment of buildings Pedro et al. (2008).

Building condition assessment is being used for repair and maintenance decision making (Abbott et al. 2007; NCES 2003; Salim and Zahari 2011; Straub 2009). Condition assessment of building is also used to decide rent and levy taxes according to the state of building (Pedro et al. 2008) and for asset management (Dejaco et al. 2017; Eweda 2012; Ho et al. 2008). It can be concluded that building condition assessment has broad range of uses for decision making from assessing state of health of building, safety of building elements, prioritizing repair and maintenance.

However, every building inspection system has limitations that should be understood before using them. There are also barriers for successful implementation of building inspection system. According to Chan and Choi (2015), heavy financial burden due to inspection cost is among one of the difficulties in implementing the Mandatory Building Inspection Scheme (MBIS) for buildings in Hong Kong. It is imperative to understand that building inspection is a means and not the end. Condition assessment of building occurs at component level (Uzarski et al. 2007) and further each component assessment is aggregated and rolled up to arrive at whole building condition assessment. Existing inspection methods are generally based on only visual observation, which can lead to highly subjective results dependant on experience, training and perception of the inspection personnel (Anuar et al. 2019; Hegazy et al. 2010; Silva and de Brito 2019; Straub 2002). Existing inspection systems also lack protocols for correction of human inspection errors. The limitation of building diagnosis systems 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 et al. 2011). Detailed inspection is expensive and time consuming hence there is a need for new economical building inspection method with reduced subjectivity (Faqih and Zayed 2021). The proposed multi-tier building inspection will ensure detailed inspection is carried out only when major or severe defect is encountered in Tier-I inspection with potential to reduce the cost and time of overall building inspection. Hence technology based multi-tier inspection will help to reduce subjectivity and human errors during inspection and also reduce mistakes in overall assessment of the building.

3. RESEARCH OBJECTIVES

Building inspections are conducted to evaluate the current state of the building to help make the appropriate decision for repair and maintenance. However, traditional building inspections are time consuming and costly for large number of building elements which could be one of the reasons which discourages periodic inspection of buildings. In addition, inspection of large number of building components is a huge task while current practices of using traditional methods of managing and storing building inspection data using spreadsheets or hard paper copies is inefficient. Managing huge amount of building inspection data is time consuming, tedious and sometimes error prone. There is a need to develop a cost effective and reliable building inspection system. The primary objective of this study are as follows:

- Develop a multi-tiered building inspection model to detect physical and environmental building defects using different technologies for different levels of detailed inspection.
- Develop a windows-based software program which can be used on field in a portable windows tablet for centralized data input and management of building inspection data such as defect severity, images, comments and instrument readings.
- Test and implement proposed multi-tier inspection framework on a case study

4. RESEARCH METHODOLOGY

The methodology adopted for this study follows the steps shown in Figure 1. To conduct this study, a review of current literature was carried out using research databases, such as Web of Science, Scopus and Google Scholar. Different building inspection practices were reviewed. After reviewing the literature on building diagnosis, it was noted that several studies have been carried out with different inspection tools and equipment (Ferraz et al. 2016). These building inspection tools and equipment are used primarily for detecting various building defects (Kwan and Ng 2015). However, there is lack of literature on comprehensive building diagnosis approach to perform building inspection (Bortolini and Forcada 2018; Vásquez-Hernández and Restrepo Álvarez 2017). Inspection personnel must know different types of building defects that influence building conditions in order to conduct effective building inspection. Based on literature, the building defects that affect building condition are categorized as physical defects and environmental defects (Faqih et al. 2020). To identify those building defects, it is essential to recognize the different technologies available to detect them. Hence a brief overview of building defects that influence the condition of the building is presented followed by common non-destructive technologies to detect them. This study is thus limited to the inspection of the concrete building elements for common defects and the environmental condition of the building. The primary aim of this research is to develop a multi-tiered building inspection system using different tools and technologies to detect common building defects. A three-tiered building inspection model is proposed. Tier-I is a preliminary inspection with minimum tools and equipment to avoid huge inspection cost. Tier-II is a detailed inspection of major defects discovered during the Tier-I inspection to avoid wastage of time and resources. Tier-III is an expert investigation on the severe defects encountered during Tier-I or Tier-II inspection to investigate in depth cause of the problem. A software program is developed for building inspection data management and storage and implementation of proposed multi-tier inspection model. To test the proposed model, it was implemented on a university building as a case study.

[Figure 1 near here]

5. BUILDING DEFECTS AND INSPECTION TECHNOLOGIES

The first step in literature review is searching for all the relevant research and academic work related to building diagnosis or inspection to detect building defects affecting building condition. Bibliometric analysis was carried out to understand the status of research in building diagnosis.

Building defects that affect building condition are reviewed and categorized as physical defects and environmental defects followed by a review of different common non-destructive technologies to detect them.

5.1 Bibliometric Analysis

This bibliometric analysis was carried out assess the current state of research in building inspection and diagnosis. Web of Science and Scopus are the most important and reliable databases of scientific articles (Aghaei Chadegani et al. 2013; Guz and Rushchitsky 2009), while Google Scholar offers more varied and wider coverage of scientific articles across disciplines (Harzing and Alakangas 2016). The following keywords were interchangeably used in conjunction with each other for the search: building inspection, building diagnosis, building defects, building, and non-destructive evaluation. Peer reviewed research articles from academic journals, conferences, theses and dissertations, codes of practice, standard guidelines and technical reports were considered in this study. The literature used for this study was limited for 25 years from year 1994 to year 2019 within the subject fields of building engineering, building survey, condition assessment, maintenance, and management. Figure 2 shows the number of published research papers containing the words “building inspection” or “building diagnosis” in their title, abstract or keywords. As shown in figure 2, it is evident from increasing number of publications that building diagnostic research has been rising steadily in recent years.

[Figure 2 near here]

In order to filter relevant articles and limit broad scope of building inspection and building diagnosis field, two major selection criteria were adopted. The first criterion of selection was that the research must have been exclusively focussed on buildings and the second criterion was that the study must be about building inspection, building diagnosis, or non-destructive evaluation of buildings. With these selection criteria, different articles were identified and selected primarily studies mentioning different tools and equipment used to detect building defects. In order to understand status of building diagnosis related research, the contribution of researchers from different institutions, universities and countries were collated. Figure 3 shows academic publications between 1994 and 2019 related to building diagnosis.

[Figure 3 near here]

Table 1 shows institutions and universities contribution with at least three papers related to building diagnosis during the years 1994 up to 2019.

[Table 1 near here]

Further citations from literature search results have been analysed using VOS viewer, a software tool that can be used to create and visualize bibliometric networks based on citations and text mining functionalities (VanEck and Waltman 2016). In VOS viewer, a distance-based approach is used to plot a bibliometric network map of nodes indicating a close relationship between two nodes (VanEck and Waltman 2014). The distance between two nodes shows the relatedness of nodes approximately. Smaller the distance between nodes indicate stronger relatedness while larger distance shows weaker relations. If the distance between two nodes is smaller indicates they are highly related to each other. Keywords are important indicators of research trends and area of the research published. A keyword co-occurrence map was produced using VOS viewer as shown in Figure 4. Prominent keywords include building inspection, non-destructive evaluation, building survey, building diagnosis, defects, cost, housing, moisture, thermography, building maintenance, monitoring, diagnosis.

[Figure 4 near here]

5.2 Building Defects

According to ISO 15686-1:2000(E) defect is defined as "a fault, or deviation from the intended level of performance of a building or its parts". Defects occur in different forms and to various extents in all types of buildings irrespective of building age (Buildings Department 2002; Yacob et al. 2016). Building defects can pose risks that can lead to serious or fatal injuries. It is useful to classify building defects into categories for easier identification of defect type (Haryati et al. 2016). Poor maintenance and external weather plays a huge role in the deterioration of the building (Wahida et al. 2012). Hence, an understanding of building defects which affect the condition of the building will greatly help in devising building inspection strategies. Building defects if identified at an early stage could reduce the burden of excessive repair and rehabilitation costs.

Building defects were then categorized as either physical or environmental defects that affect building condition. It was imperative to determine which defects affected the building conditions and to categorize them. The literature review resulted in different categories of defects, however, this study is limited to defects of concrete building elements and building environment. Physical condition of a space inside the concrete building is characterized by building defects such as cracks, spalling of concrete, corrosion and water seepage in building components such as beams, columns, slab and other structural elements within the space chosen for assessment. While environmental condition of a space inside the building is characterized by environmental factors.

Four main categories of environmental factors that affect environmental condition of building are Indoor air quality (IAQ), thermal environment, acoustics, and lighting (Faqih et al. 2020).

Environmental factors are not defined as defects as certain levels of concentration is almost always present in the environment. When the concentration level exceeds 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. For this study two categories of defects are considered for building inspection namely physical defects and environmental factors/defects as shown in figure 5.

[Figure 5 near here]

5.2.1 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 possible that a part of the building effects the performance of the whole building. To evaluate any building, its current state is assessed by building inspection. 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). Studies related to defects in building often find some common building defects irrespective of the type of building. Hassan et al. (2011) tracked defects in hospital buildings and found that a majority of the defects were in doors and fittings, followed by defects in walls, floors, and finishes. Hassan et al. (2011) noted most frequently occurring defects were damaged door frames, peeling of paint, cracks in walls, discoloured paint, fungus and staining on walls. A similar study by Haryati et al. (2016) on university buildings found that the majority of all defects were related to floor tile cracks, detached skirting, corroded windows, damaged doors, fungi and stain marks. According to the Marshall et al. (2013) most common defects in concrete buildings were, spalling of plaster finishes, seepage of rainwater, cracks in structural members, non-structural cracks in plasters and tiles, and faulty finishes.

Bortolini and Forcada (2018) found that cracking and water leakage were most common building defects, while leakage and corrosion were more prevalent in the plumbing system. It is also possible that one type of defect can cause another type of building defects. Othman et al. (2015) found that moisture problems in a hospital building had a cascading effect and led to several other building defects, such as peeling paint, blistering wallpaper, staining, discoloration, watermarks, mould growth, and corrosion of different building elements, such as the roof, wall, ceiling, and floors. Several studies have noted similarly common building defects, such as cracks, water leakage, and corrosion indicating these defects frequently affects building condition (Chong and Low 2006; Kian 2004; Othman et al. 2015; Suffian 2013).

5.2.2 Environmental Defects of Buildings

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 2 shows all four environmental factors namely indoor air quality (IAQ), thermal environment, acoustics, and lighting that influence the environmental condition of the building.

[Table 2 near here]

The indoor air pollutants that impact air quality, their main sources of emissions and the effects on the health of building occupants are given in Table 3.(IAQMG HKSAR 2019; World Health Organization 2009, 2010).

[Table 3 near here]

Thermal comfort according to ASHRAE 55 (2017) can be defined as “that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation”. Temperature, humidity and air circulation are also important factors because they can affect the perception of IAQ by people however, thermal comfort may vary from person to person based on their gender, age, and personal preferences (Al horr et al. 2016; Kim et al. 2013; Maykot et al. 2018)

Humidity affects human body's ability to lose heat by perspiration, which in turn affects people's thermal comfort. High humidity promotes growth of funguses in buildings, furnishings and fabrics while low humidity can lead to a dryness of eyes , nose and throat creating discomfort and irritation (IAQMG HKSAR 2019). Low humidity may cause discomfort among the occupants of the room and may also cause static electricity generation affecting electronic components. Low relative humidity may also cause some viruses to survive, thereby increasing the risk of transmission of viral infections (Wolkoff 2018).

Noise is an undesirable sound and its perception differs from person to person, however building acoustic can impact comfort level of occupants. Sound characteristics in a room is affected by magnitude, duration, time of occurrence and room surfaces absorbing, reflecting, or transmitting sound (Al horr et al. 2016). Good lighting is essential for safely and comfortably carry out a visual task while poor lighting can affect visual comfort productivity of people in work places (Huang et al. 2012; Ricciardi and Buratti 2018).

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 and 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.

5.3 Building Inspection Technologies

Non-destructive methods play an important role in the inspection and detection of defects in buildings. Many researchers worldwide have presented their studies on non-destructive evaluation techniques for aged and deteriorated structures. There are various non-destructive and destructive techniques to assess the condition of building. A few common techniques and methods are summarised below.

5.3.1 Physical defect inspection tools

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 and 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 moisture meter has two electrodes that, when touching to the surface and held for few seconds, will give moisture content values in percentage. 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).

Infrared thermography is a non-destructive method for the examination of buildings. Infrared thermal cameras provide a means for temperature measurement of buildings surfaces. Temperature variations can be detected using infrared thermal cameras. The high variations of temperature in the thermal images often indicate defects, such as structural changes, structural abnormalities, cracks, air leakage sources, heat losses, moisture (Plesu et al. 2012). The infrared camera gives a thermal image with temperature variations of the building surface which can help to identify the problematic zones with potential defects hidden from naked eyes during visual inspection. (Bauer et al. 2016; Lo and Choi 2004). The analysis of infrared thermal camera images may not always reveal a correct diagnosis and depends on thermal changes in the point of observation (Fox et al. 2016). Only a trained and experienced personnel can identify the defects accurately using thermal images.

5.3.2 Environmental instruments

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. Almost all of the environmental measurement devices come as handheld instruments, as well as sensors that can be installed on the wall or ceiling for monitoring.

Table 4 summarizes the different methods, tests, and technologies that can be used to detect different building defects. A qualitative comparison is also presented in Table 4 based on ease of use for a particular technology, interpretation of results, and cost of conducting an inspection using that technology.

[Table 4 near here]

6. MULTI-TIERED BUILDING INSPECTION MODELING AND FRAMEWORK

Building inspections are a resource intensive task because of the large number of building elements. Hence, to optimize the available resources, an appropriate level of detail is collected during building inspection based on its scope. Usually, detailed inspections are more expensive than preliminary inspections due to the significant cost and time involved (Ahluwalia 2008).

In this study, a three-tiered inspection model is proposed, which is composed of Tier-I, Tier-II and Tier-III as shown in Figure 6. Tier-I is a preliminary inspection mainly based on visual inspection. However, it may be supplemented by a minimum level of tools and equipment to avoid huge costs.

Tier-II is a detailed inspection of major defects detected during Tier-I inspection. Tier-III is an expert investigation on severe defects which may be encountered during a Tier-I or Tier-II inspection. The scope of Tier-III encompasses the scope of Tier-II and Tier-I inspections, while Tier-II encompasses the scope of a Tier-I inspection. A Tier-I preliminary inspection may involve observing signs of visible defects or potential distress and estimate the extent and severity of the building defects. A Tier-II detailed inspection will include the use of tools and equipment for an in-depth inspection. Tier-III requires expertise that may include detailed in-situ or laboratory testing to ascertain the safety and strength of a building element.

[Figure 6 near here]

Different tools, equipment, or methods are available for the detection of various building defects. Table 5 gives a brief guide on different tools that may be used in conjunction with one or more pieces of equipment in different tiers of inspection, as required by the scope of inspection. Figure 7 shows the proposed multi-tiered building inspection model. The severity of defects is categorized into three types, namely, minor defects, major defects, and severe defects. Minor defects can be defects that are apparent but do not pose immediate danger to the safety and serviceability of the building and can be rectified with minor repair work (e.g., non-structural cracks). Major defects can be defects that affect the building's serviceability and have the potential to develop into severe defects, posing a significant threat to the safety of the building. Major defects can be fixed with major repairs (e.g., structural cracks, delamination). Severe defects are those that pose imminent danger to the safety of a building and require major rehabilitation work (e.g., concrete spalling, exposed steel reinforcement, corrosion of reinforcement). After completing the appropriate inspection tier, one of four decisions can be made: no action, minor repairs, major repairs, or rehabilitation, based on the severity of the defects detected.

[Figure 7 near here]

[Table 5 near here]

6.1 Tier-I Preliminary Inspection

The preliminary inspection is a visual inspection intended to look out for visible building defects, based on the experience of inspection personnel. It aims to evaluate the preliminary structural safety, integrity, and stability of the building element. Visual inspection can be supplemented with adequate handheld instruments or equipment to facilitate the effective detection of defects. These handheld instruments include, but are not limited to, a measure tape, camera, tapping hammer, moisture meter, crack gauge, and infrared camera. The use of these additional tools and equipment for Tier-I preliminary inspection will depend on several factors, namely requirement, availability, cost, scope of inspection, and importance of structure or building element.

The main objective of Tier-I building inspection is to evaluate a building and classify it into one of four categories:

1. The building has no visible signs of building defects or any other distress. Thus, no further action is required, and next periodic inspection is scheduled.
2. The building has visible minor building defects that can be fixed without resorting to any major repairs.
3. The building has visible signs of major defects that need to be investigated in detail in order to determine the extent and severity of defects before repairs can be prescribed.
4. The building has visible signs of severe defects that need expert detailed investigation to ascertain the cause, extent, and severity of defect. The building may require huge repairs, rehabilitation, or replacement.

6.2 Tier-II Detailed Inspection

Tier-II detailed inspection is proposed if visible major defects or combination of significant minor defects are encountered during a Tier-I inspection. Since major defects or combination of significant minor defects need to be investigated in detail, different non-destructive evaluation techniques can be used to assess the extent and severity of the defects. Based on the defect identified and sound engineering principles, one or more appropriate technologies may be used as per Table 4 to conduct the detailed inspection. It is also possible that the supposed major defect, after the completion of Tier-II inspection, turns out to be a severe defect. If a severe defect is detected during a Tier-II inspection, a more comprehensive expert investigation is to be commenced. After the inspection of a major defect, appropriate major repairs may be planned followed by a building inspection once the repair work is finished.

6.3 Tier-III Expert Investigation

When severe defects are detected, professionals with expertise and experience should be consulted for expert investigation. A Tier-III expert investigation may include detailed in-situ testing using appropriate tools and equipment. The primary objective of a Tier-III investigation is to find the probable cause of the severe defect and assess the extent and severity of the defect. In this tier, investigation estimating the residual strength of the building element may also be involved. Laboratory testing in accredited laboratories may be required to ascertain the safety and strength of the building element. Further planning for rehabilitation and retrofitting may be required to solve severe defects in a building. Continuous monitoring may also be required in case of displacement, settlement, or water leakage, even after repairs.

The main purpose of the proposed multi-tiered inspection model is to describe the steps on how to carry out a building inspection effectively. The selection of tools and equipment for different tiers of inspection relies on requirement and preference of the inspection personnel.

7. CASE STUDY AND MODEL IMPLEMENTATION

The proposed multi-tier building inspection was implemented as a case study as shown in figure 8. For model implementation block Z building in Hong Kong Polytechnic University campus was selected. To test the developed multi-tiered building inspection 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. The floor plan of 7th floor of Block Z building used a case study is shown in Figure 9.

[Figure 8 near here]

[Figure 9 near here]

Physical condition of a space inside the building is characterized by building defects such as cracks, spalling of concrete, corrosion and water seepage in building components such as beams, columns, slab and other structural elements within the space chosen for assessment. While environmental condition of a space inside the building is characterized by environmental factors such as IAQ, thermal, lighting and noise level within the space chosen for assessment. 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. To inspect the selected floor and assess the severity of building defects technology based multi-tier diagnosis model is adopted. Details of multi-tier inspection model is as explained earlier in figure 7. The methodology adopted for technology based multi-tier model implementation is shown in Figure 8.

7.1 Development of the software program

Inspection of large number of building components is a huge task. 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. Therefore, to manage building inspection data a windows application software was developed using C# language in Microsoft Visual Studio. Figure 10(a) shows screenshot of the application program running on windows operating system. 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 10 near here]

7.2 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 10(b) shows the tab for physical evaluation input. In this tab after detecting the building defects, severity of defects can be used as an input. Figure 11(a) shows portable handheld NDT instruments that can be used during inspection process for Tier-I inspection. The user also has the option to attach a picture of the room with or without defects for record. The 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 the 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.

[Figure 11 near here]

7.3 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 11(b) shows portable environmental measurement devices. Figure 10(c) shows the 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, the user also has the option to attach a picture of the room for record. The 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.

7.4 Assessment

The severity of defects is categorized into three types, namely, minor defects, major defects, and severe defects. Minor physical defects can be defects that are apparent but do not pose immediate danger to the safety and serviceability of the building and can be rectified with minor repair work (e.g., non-structural cracks). Major physical defects can be defects that affect the building's serviceability and have the potential to develop into severe defects, posing a significant threat to the safety of the building. Major physical defects can be fixed with major repairs (e.g., structural cracks, delamination). Severe physical defects are those that pose imminent danger to the safety of a building and require major rehabilitation work (e.g., concrete spalling, exposed steel reinforcement, corrosion of reinforcement).

Minor environmental defects are such instrument readings which are within limits but not the excellent condition and do not pose immediate danger to the health of building occupants and can be improved (e.g., carbon dioxide within limits but not excellent condition can be improved with better ventilation). Major environmental defects can be such instrument readings which have exceeded or close lower end of permissible limits and pose a significant threat to health of building occupants over longer period of exposure. Major environmental defects can be fixed with major changes in environmental condition (e.g., consistent loud noise which can permanently damage hearing over longer period of exposure). Severe environmental defects can be such instrument readings which have far exceeded safe permissible limits that can be fatal or pose imminent danger to the health of building occupants and require immediate intervention (e.g., excess formaldehyde in the environment).

7.5 Defect Threshold

Based on literature different factors were identified which affects the condition of a 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 the building. Similarly, for environmental condition assessment, the following factors were selected, temperature and humidity affecting thermal condition, light intensity, noise level affecting acoustics, and chemicals affecting indoor air quality including carbon dioxide, carbon monoxide, nitrogen dioxide, formaldehyde and volatile organic compounds. Defect thresholds were determined from codes of practice and guidelines as shown in Table 6. These thresholds may differ and can be changed according to codes of practice and guidance updates. Physical building defects are inspected as per the proposed multi-tier inspection 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 thermometers, sound meters, light meters and air quality meters.

[Table 6 near here]

7.6 Results and Analysis

To test and validate the proposed multi-tier inspection model it is implemented on a case study. Proposed model is thus implemented in the form of an application software which can be run on any windows-based tablet during inspection process. 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. 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.

After entering all the required physical evaluation input and environmental instrument readings for all the desired spaces, the next step is to analyze and decide for further detailed inspection or expert investigation based on the severity of defects encountered. After completing the appropriate inspection tier, one of four decisions can be made: no action, minor repairs, major repairs, or rehabilitation, based on the severity of the defects detected.

The case study used in this research was an entire floor of a building in the university which was in good condition hence only few hairline cracks and peeling of plasters were detected as shown in figure 12. Similarly, the environmental instrument readings were all within permissible limits and in excellent condition. However, successful implementation of technology based multi-tier inspection model has shown potential to provide better documentation for building inspection process which in turn can reduce time and cost of inspection.

A technology based multi-tier building inspection framework is developed to address the need for comprehensive and structured approach to perform building inspection. Multi-tier building inspection will ensure detailed inspection is carried out only when major or severe defects are encountered in Tier-I inspection with potential to reduce the cost and time of overall building inspection. Identifying building defects accurately through structured building inspection before they become worse will help reduce the need for maintenance and repair of building components which helps to extend the service life of existing buildings. Technology based multi-tier inspection will also help to reduce subjectivity and 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 transforms the traditional field of paper-based building inspection into more efficient and interactive process. The developed application program which runs within Microsoft Windows environment has potential to improve productivity of inspection personnel by potentially saving time to digitally enter inspection data for huge number of building components within large building complex. This program also offers improved documentation and data management than conventional paper-based building inspection. This program developed for implementation of multi-tier building inspection 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. The interest and demand of building inspection is increasing due to rapidly deteriorating conditions of building. This research is a step forward in building inspection by providing a framework to conduct multi-tiered building inspections with an application program that can be operated on hand held portable Windows tablet and has potential to replace existing paper-based data collection and data transfer from field to office eventually saving time and cost.

8. DISCUSSION

Defects of building elements can be a fault or deviation from their expected level of performance that can hinder their serviceability or safety. A precise detection of building defects is essential to ensure an accurate diagnosis of a building’s condition. Building diagnosis is a complex task due to a number of factors that affect many building elements having complex interrelationships between them. Research related to building diagnosis is focused on specific equipment and tools used to detect specific building defects. Previous studies highlighted the importance of non-destructive evaluation using methods such as visual inspection, acoustics methods, electromagnetic methods, thermal imaging, digital imaging. There was a lack of research on structured approaches to performing building inspection. To fill this gap, this study proposed a multi-tiered building inspection system.

In this study, an overview of defects affecting the building elements and environment of a building are discussed followed by the different technologies used to detect them. These defects, individually or in combination with the others, may lead to the deterioration of a building. The cascading effects of multiple building defects may lead to an accelerated deterioration of the whole building’s condition. In order to carry out successful building inspections, inspection personnel must know the different types of building defects that affect the building condition. Recognizing the different technologies available is important to detect building defects. Building inspection is carried out to determine the current state of the building and to make the appropriate repair and maintenance decisions. Periodic building inspection is vital for the upkeep and sustainable maintenance of a building. However, the considerable resources, cost, and time involved in building inspection is one of the limiting factors governing the frequency of building inspections (Ahluwalia 2008). Hence, it is important to diagnose building defects more accurately to avoid wasting resources and time. Building inspections are generally divided into preliminary inspections and detailed inspections. In this study, detailed inspections are further divided into a third category of expert investigation, thus forming a three-tiered inspection model. The expensive costs of inspections are often a hindrance to periodic inspections. Following the proposed three-tiered building inspection can help to optimize resources and time. An application program was developed which can run on Windows-based tablet for management of building inspection data and instrument readings. This program was tested on a case study and the results were appreciable with management of inspection data on a single platform for both physical defects and environmental instrument readings and having potential to save time compared to conventional paper-based building inspection.

The main purpose of this multi-tiered inspection model is to define the steps to effectively conduct building inspection. A guide is given in Table 5 to help personnel choose from a list of tools and equipment with reference standard codes of practice which can be employed in different tiers of inspection. Most building defects will be apparently visible; however, the absence of signs of distress or visible defects does not rule out the possibility of hidden defects. As a result, there is a possibility of incorrectly diagnosing building defects during building inspection. The incorrect diagnosis of hidden building defects can lead to the occurrence of severe defects. Therefore, a well trained and experienced professional is essential for correct building diagnosis, as an experienced professional will be able to interpret the test results more accurately. Every inspection technique has limitations that should also be understood by inspection personnel (D'Aloisio 2017). Estimation of the extent and severity of defects based on test results of instruments and equipment will have an impact on the overall building assessment. Subjectivity of inspection can be reduced by complementing visual inspection with the use of non-destructive tools and equipment. The building inspections should be transparent at every level for future examination to make it easier to detect mistakes if any are committed during inspection. Hence, for any building inspection, trained inspection personnel are of vital importance. As different inspection personnel may adopt different methods or practices due to lack of structured building inspection guidelines, it is essential to recognize building diagnosis as a separate discipline to help professionals gain in-depth expertise of tools and technologies. This study can help provide early steps towards a structured approach to the building inspection process.

9. CONCLUSIONS

Building defects that remain undetected due to incorrect diagnosis may worsen the condition of the building. It is important to understand defects that influence building conditions to accurately identify them during inspection. The building inspection personnel must be cognizant of the various defects and the appropriate technologies to detect them. Frequent periodic building inspection can be helpful, allowing building managers to intervene earlier when minor defects are detected. However, buildings are composed of many building elements that make building inspection resource intensive, time consuming, and costly which limit the frequency of periodic building inspections. There is not enough guidance available on how to conduct a comprehensive and structured building inspection. This study gave an overview of physical and environmental defects and the technologies to detect those building defects. This study proposed a multi-tiered building inspection based on different technologies used to detect various defects. An application software program was developed to implement the proposed multi-tier inspection framework effectively on a case study building. Results were promising especially in organized data management on a common platform for both physical and environmental condition inspection. This study can be further expanded with integration of condition rating with proposed multi tie-r inspection model. This study is limited to the inspection of the concrete building elements and environment of the building. It is recommended to conduct multi-tiered inspections in order to potentially reduce the cost and time of building inspection. The inspection should be, as far as possible, based on consistent techniques so that it can be reproducible by others using the same standard procedure. The findings of this study will help in understanding the different technologies used to detect building defects. Taking appropriate remedial action as preventative maintenance based on regular building inspection could reduce the time and cost required for major repair caused by the conversion of minor defects into major defects. Further research may focus more on a cost comparison between different tools and equipment to optimize the selection process and clarify their impact on the overall building inspection cost. A similar multi-tiered inspection model can also be applied to other categories of building defects such as mechanical defects, plumbing defects, and electrical defects. The proposed multi-tiered building inspection is intended to serve as a framework to complement existing building inspection techniques practiced and is not a substitute for professional engineering judgement. This study will contribute to existing knowledge and understanding of different techniques used for building diagnosis and provide a new multi-tiered building inspection model. Tools and equipment are only as good as their user; hence, sound engineering judgement is critical during building inspection to perform effective building condition assessment.

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FIGURES

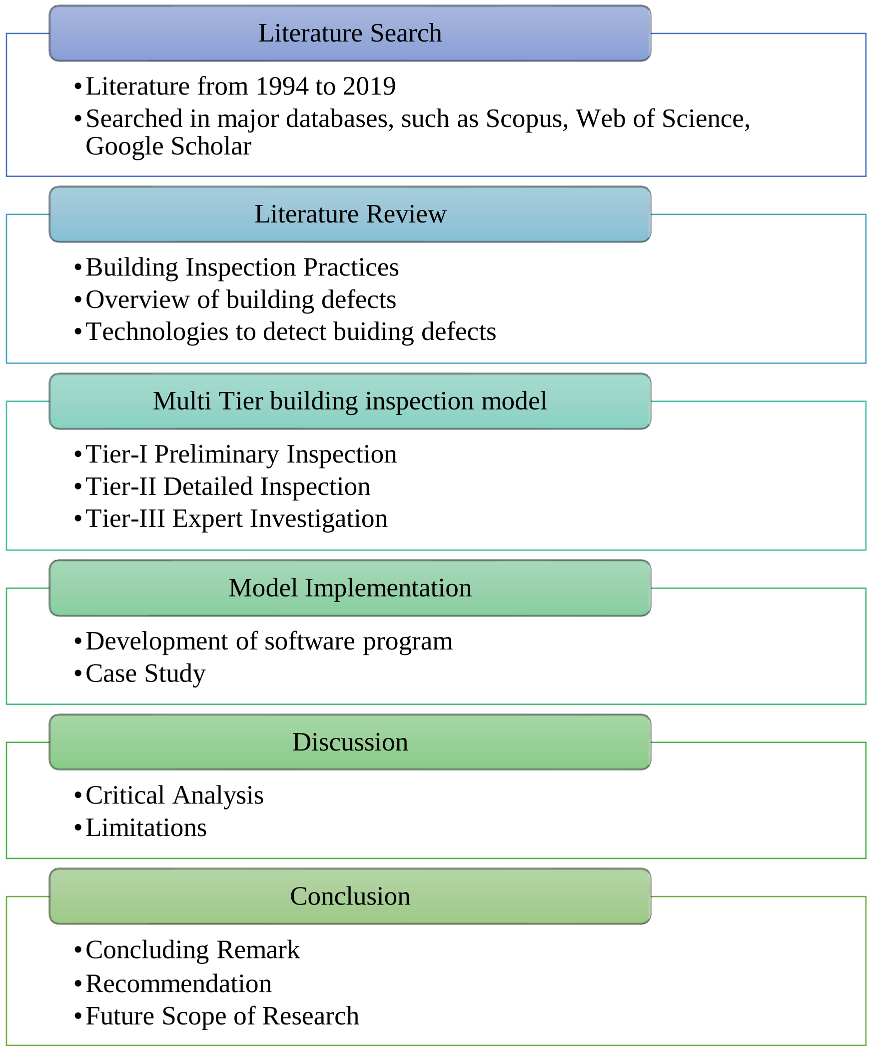


Fig. 1. Research methodology adopted in this study

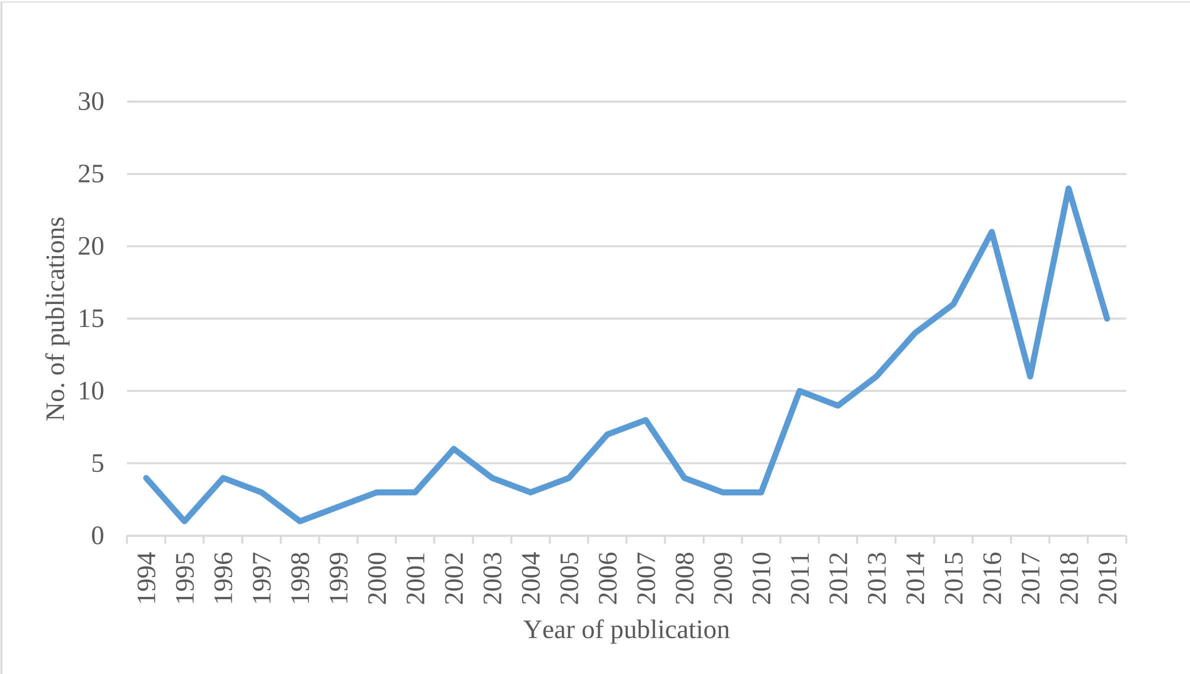


Fig. 2. Research publications related to building diagnosis from 1994 to 2019.

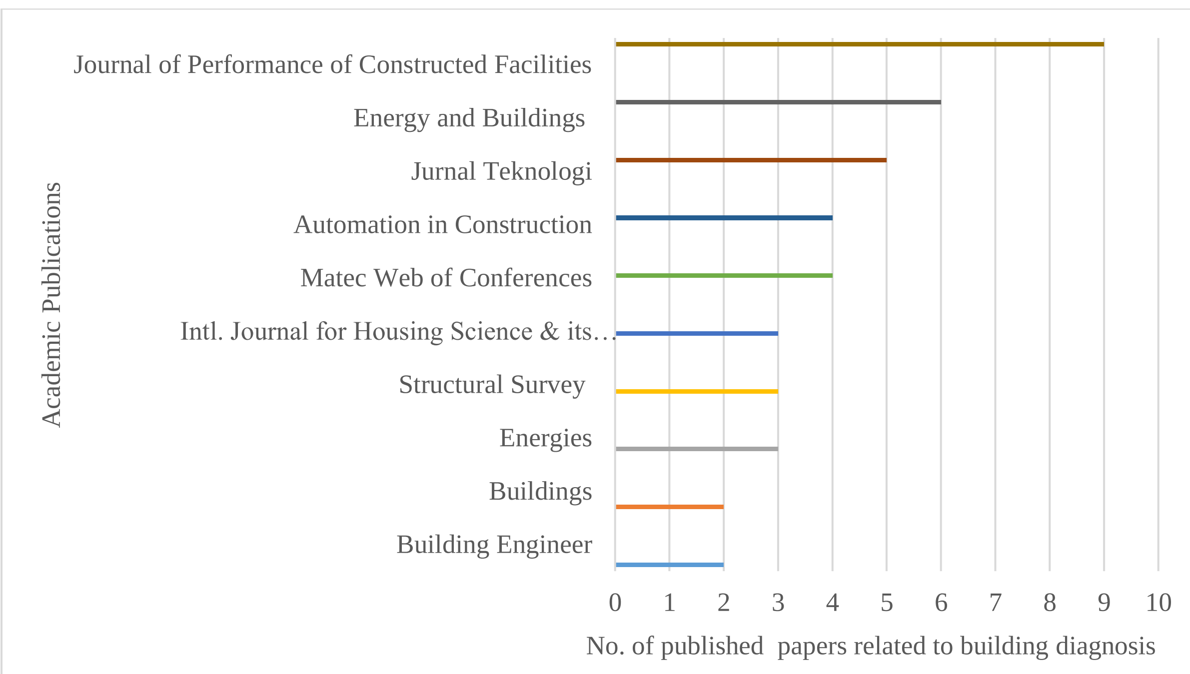


Fig. 3. Academic publications related to building diagnosis from 1994 to 2019.

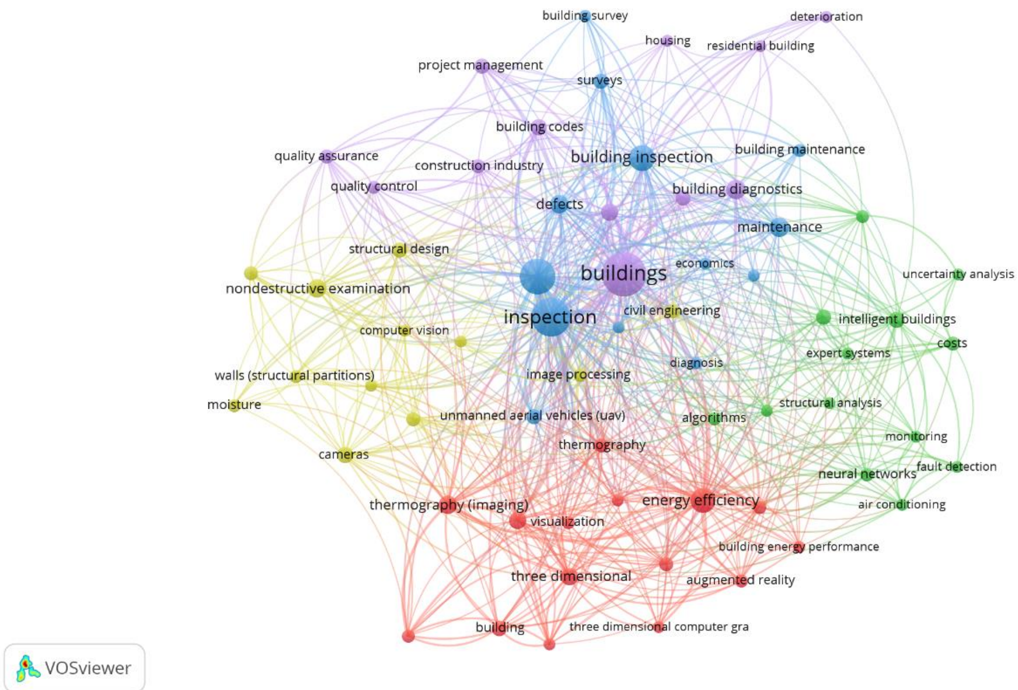


Fig. 4. Network showing the co-occurrence of keywords in research related to building diagnosis.

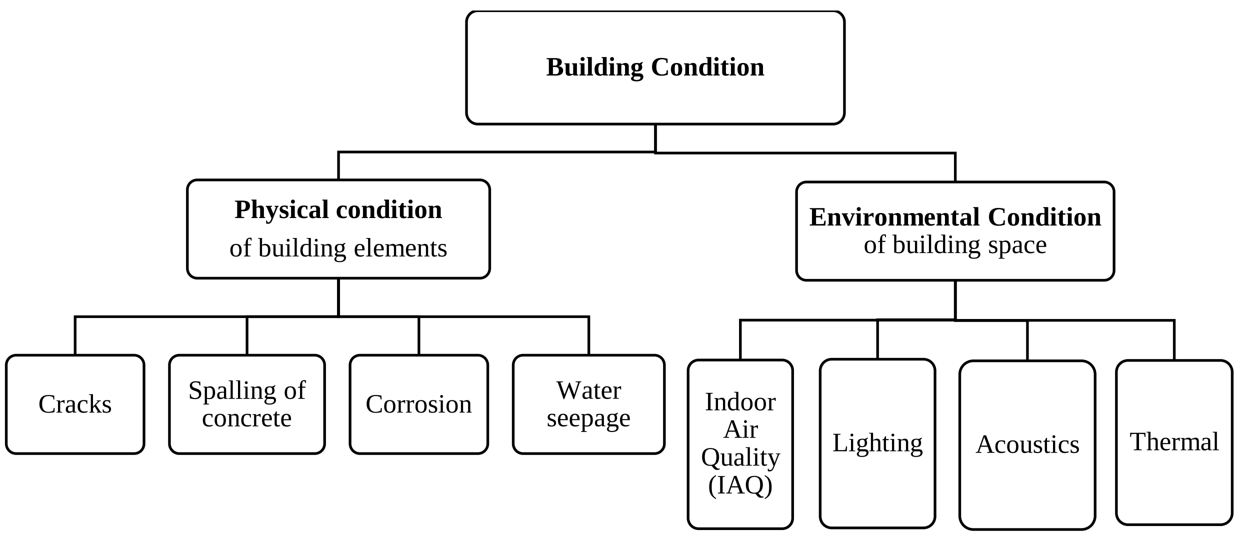


Fig. 5. Physical defects and environmental factors affecting building condition

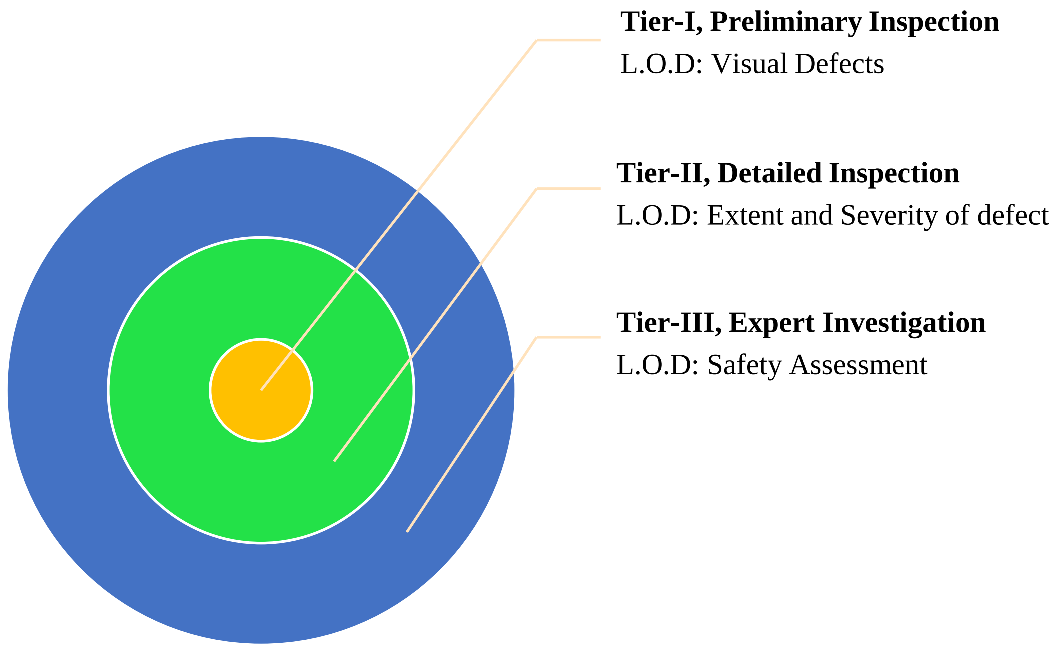


Fig. 6. Multi-Tiered Inspection and Level of Details (L.O.D).

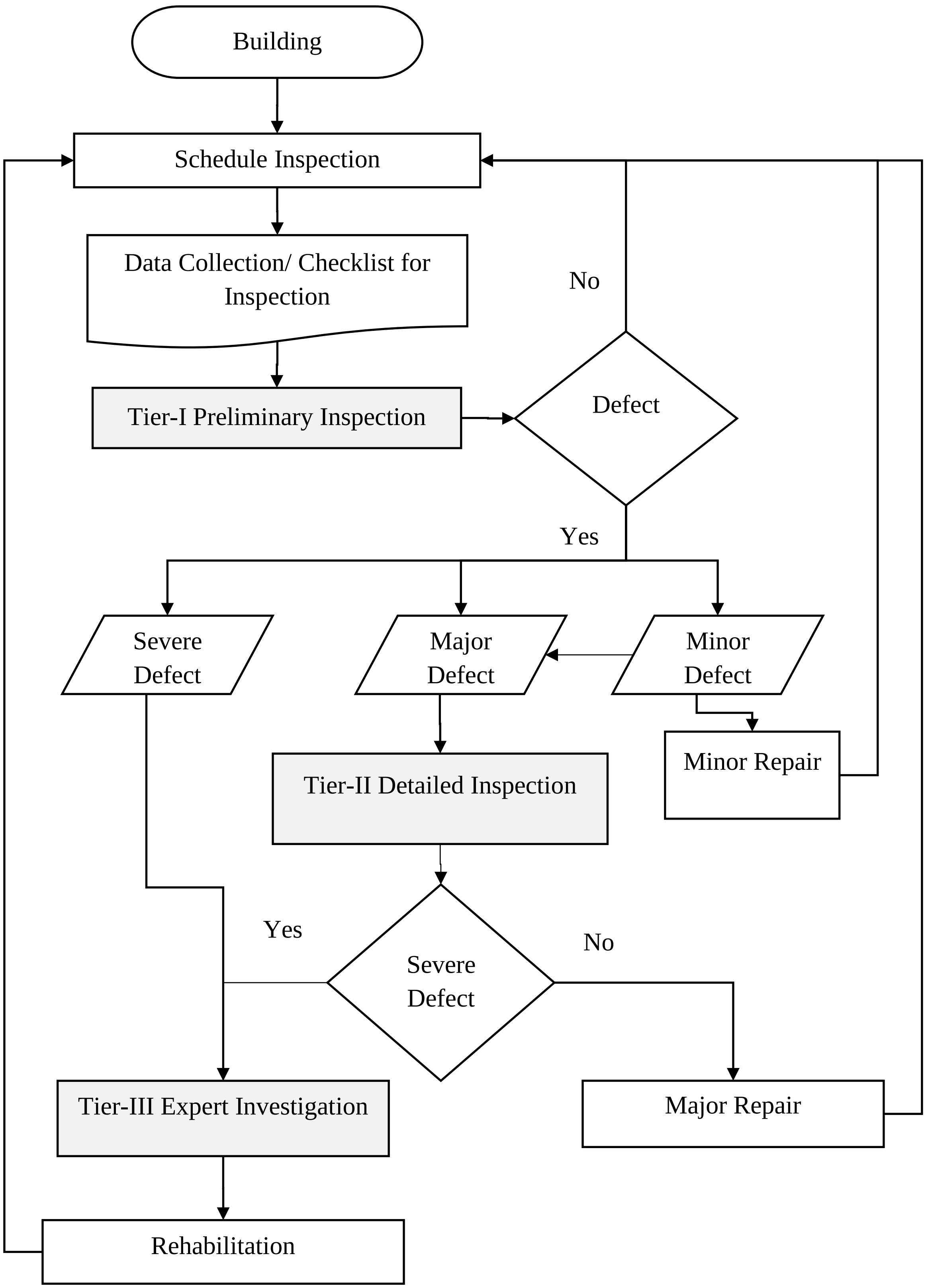


Fig. 7. Proposed multi-tiered building inspection model.

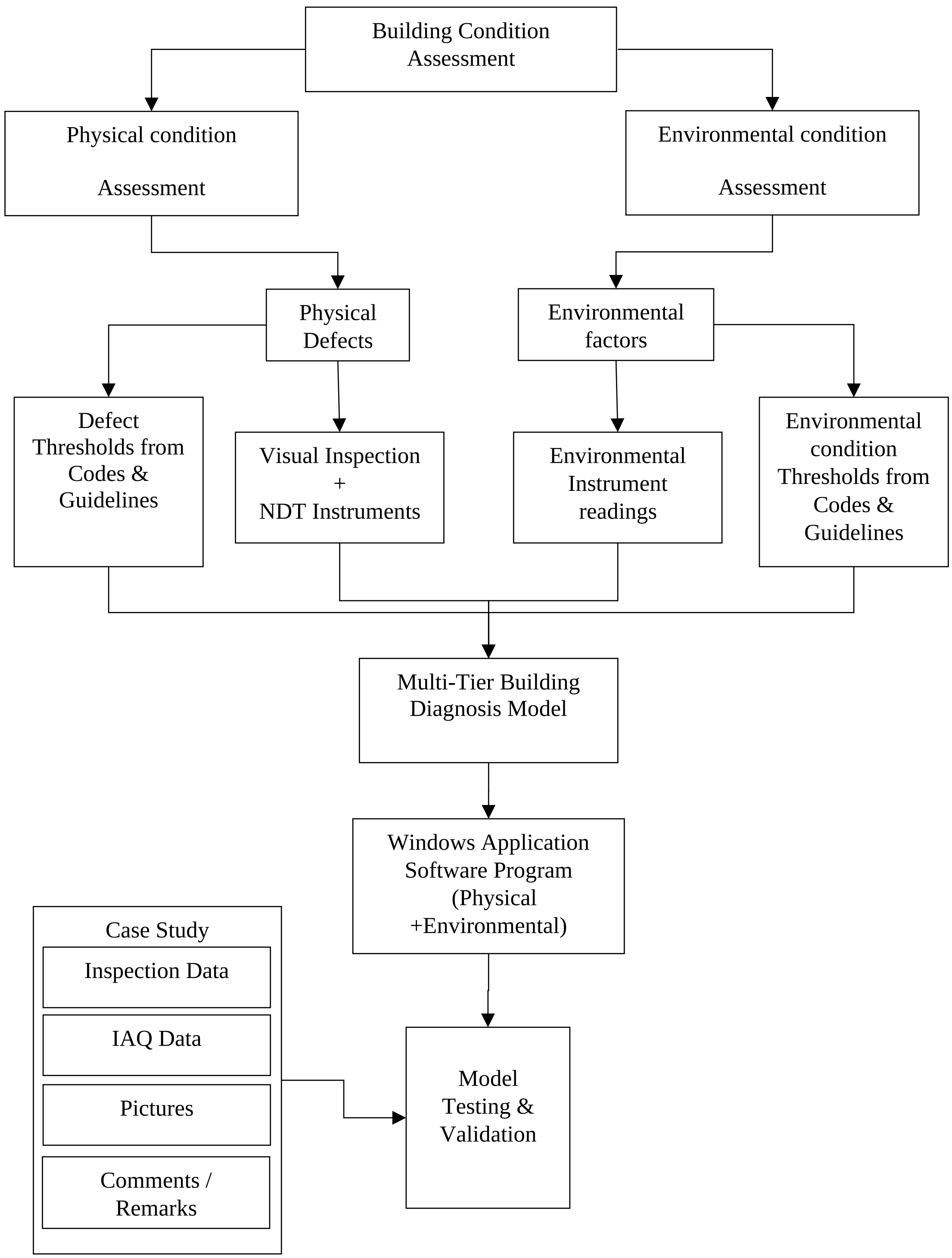


Fig. 8. Methodology adopted for proposed model implementation

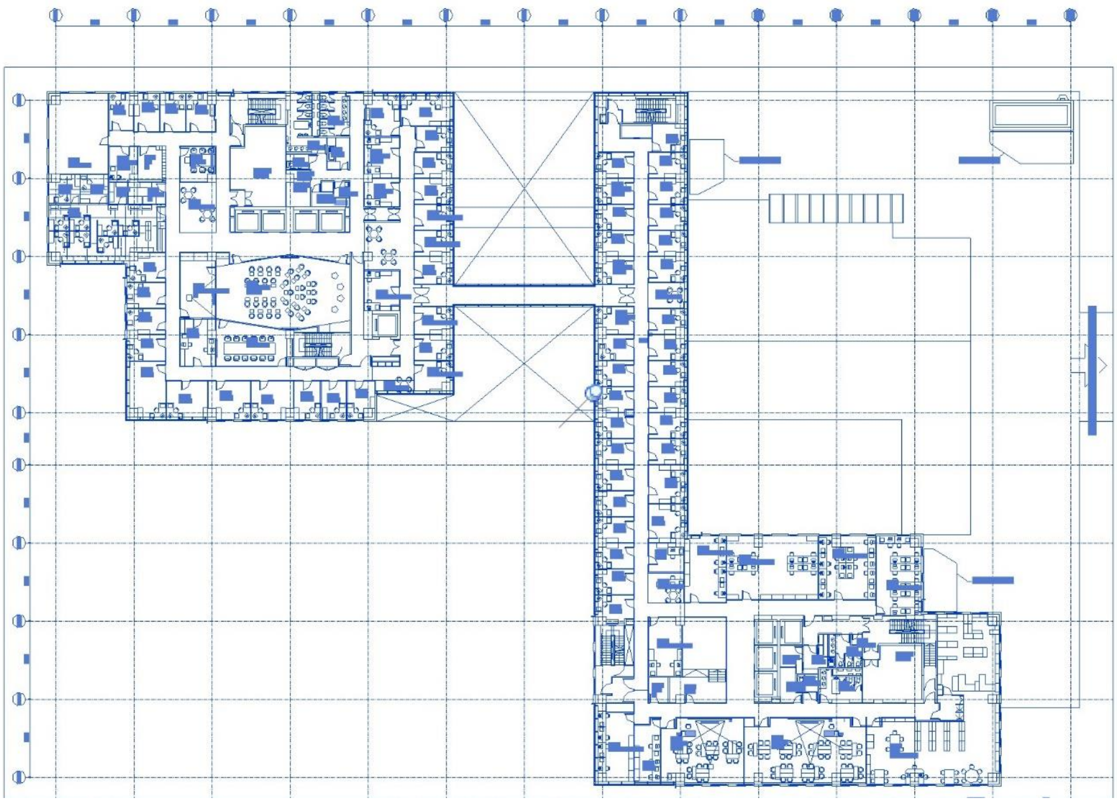
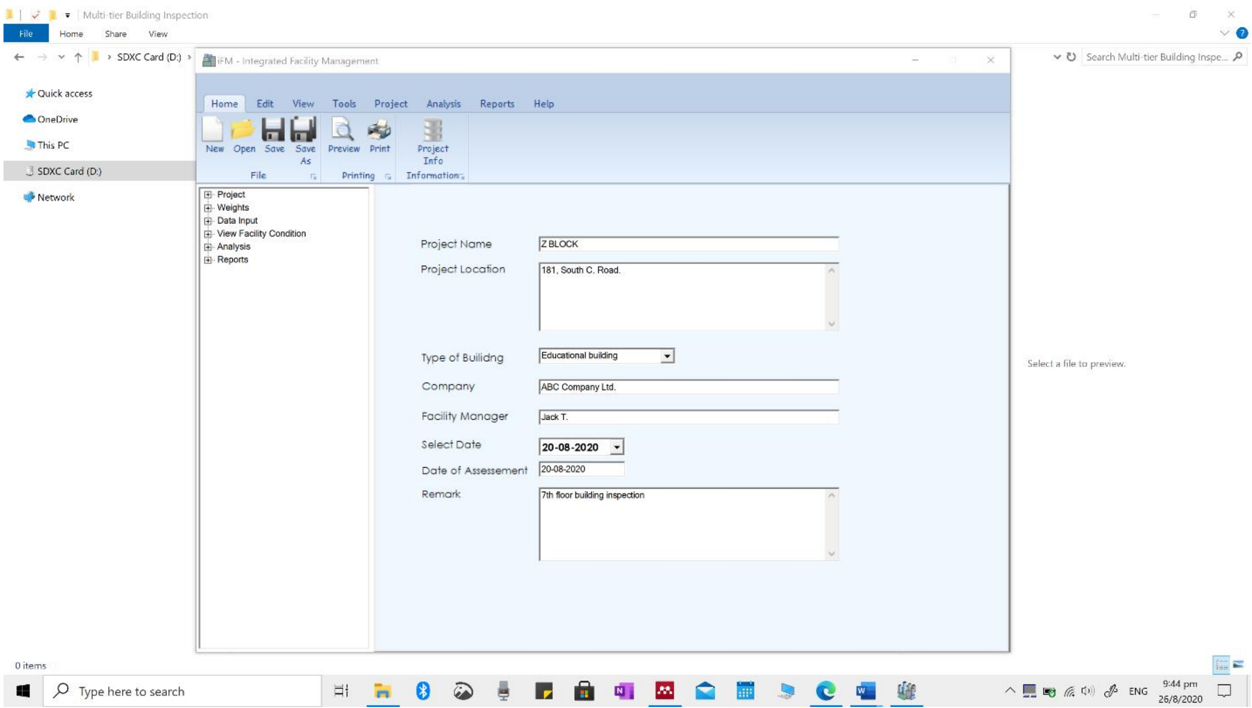
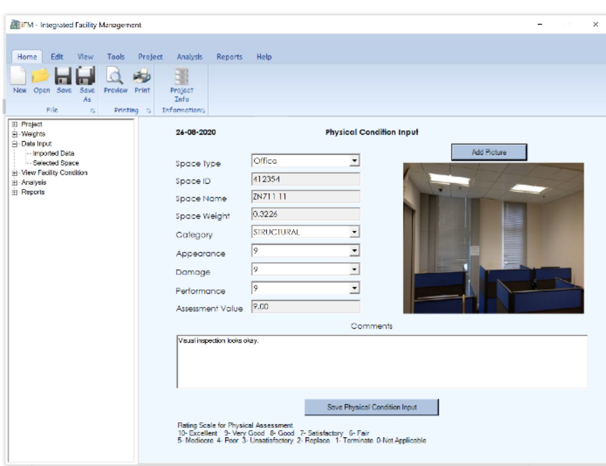
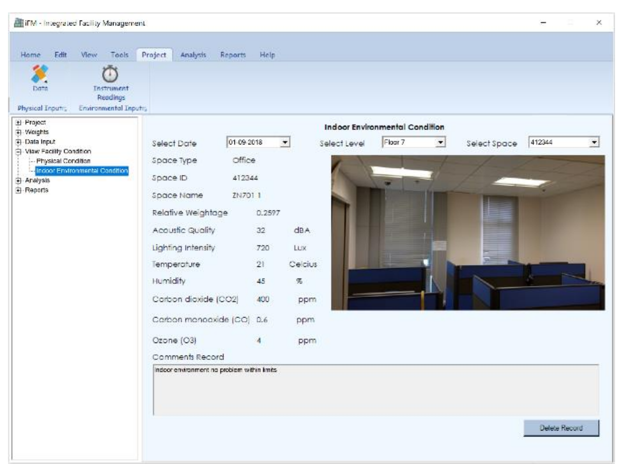


Fig. 9. 2D CAD floor plan of 7th floor of Block Z of case study building



(a) Screenshot showing initial window of application program for creating new project





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

Fig. 10. Screenshot showing different windows of developed software application program for implementation of multi-tier inspection model

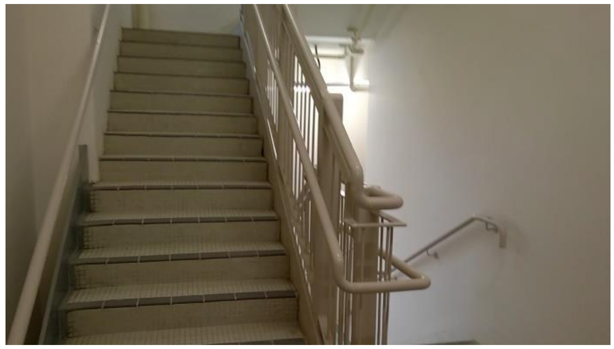
(i) Portable Infrared thermal cameras (ii) Moisture Meter (iii) Crack width Scale

(a) Tools and instruments for physical defects inspection

(i)Air Quality Monitoring Device (ii)Temp. & Humidty Meter (iii) Lux Meter (iv) Sound level meter

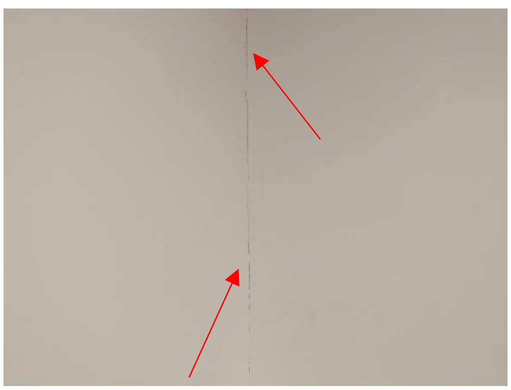
(a) Tools and instruments for environmental measurements

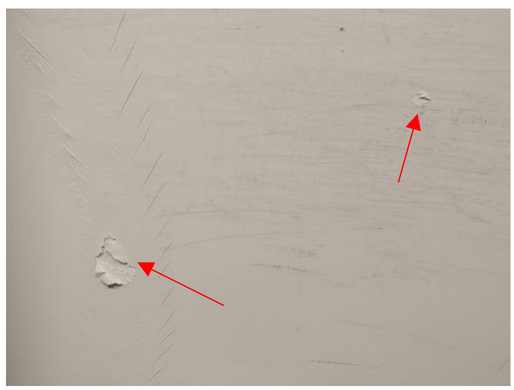
Fig. 11. Portable instruments to measure physical defects and environment



(a) Office space (b) Staircase

(c) South Corridor (d) North Corridor





(e) Hairline cracks (f) Blistering and peeling of paint

Fig. 12. Photos taken during inspection of case study

TABLES

Table 1. Research institutions contribution of papers related to building diagnosis from 1994 up to 2019.

Institution/ University	Country/Region	No. of publications
Universiti Teknologi	Malaysia	11
Universidade de Lisboa	Portugal	10
Universidade de Vigo	Spain	5
University of Illinois at Urbana-Champaign	United States	4
The Hong Kong Polytechnic University	Hong Kong, SAR PRC	4
Széchényi István Egyetem	Hungary	4
National University of Singapore	Singapore	4
University of Colorado	United States	3
Universite de Liege	Belgium	3
City University of Hong Kong	Hong Kong, SAR PRC	3
Auckland University of Technology	New Zealand	3
University of Seville	Spain	3

Table 2. Factors affecting the environmental condition of buildings and environmental defects.

Criteria	Factors Affecting Environmental condition	References	Environmental defects affecting Human comfort	**Detection Instruments or Equipment**
Indoor Air Quality (IAQ)	Carbon dioxide (CO_2)	IAQMG HKSAR (2019), ASHRAE 62.1 (2016), World Health Organization (2010), World Health Organization (2009)	High Concentration	Carbon dioxide meter
	Respirable Suspended Particulates Matter (RSPM)		High Concentration	Particulate monitor
	Carbon monoxide (CO)		High Concentration	Carbon monoxide meter
	Nitrogen dioxide (NO_2)		High Concentration	Nitrogen dioxide meter
	Ozone (O_3)		High Concentration	Ozone monitor
	Formaldehyde (HCHO)		High Concentration	Formaldehyde detector
	Total volatile organic compounds (TVOC)		High Concentration	VOC monitor
Lighting	Artificial Lighting	BS EN 12464-1 (2011)	High/Low light intensity Visual Discomfort	Luminance Meter
Thermal	Temperature	ASHRAE 55 (2017), ASHRAE 62.1 (2016), IAQMG HKSAR (2019)	High/Low temperature Thermal Discomfort	Thermometer
	Humidity		High/Low humidity	Relative Humidity Meter
Acoustics	Noise	ASHRAE Handbook (2017)	High Noise discomfort	Sound Level Meter

Table 3. Indoor air pollutant sources and their effects on human health

Indoor Air Pollutant	Emission Source	Health effect on building occupants
Carbon dioxide (CO_2)	By-product of human exhalation	Difficulty in breathing, sweating, tiredness, increased heart rate
Respirable Suspended Particulates Matter (RSPM)	Dust, copiers, printers, cigarette smoking	Affects respiratory system, Coughing, Allergic effects
Carbon monoxide (CO)	Flue gas of burning stove, diesel car exhaust, cigarette smoking	Impaired vision and coordination; Headaches; Dizziness; Nausea at high concentration
Nitrogen dioxide (NO_2)	Flue gas of burning stove, diesel car exhaust, cigarette smoking	Eye, nose, and throat irritation. Respiratory infections, affects lungs
Ozone (O_3)	Refrigerators, Air conditioners, Copiers, Laser printers	Affects respiratory system, Chronic respiratory disease
Formaldehyde (HCHO)	Pressed wood products, Paint and Glues	Affects respiratory system, watery eyes
Total volatile organic compounds (TVOC)	Paint, Solvents and aerosol products	Sensitive and irritation symptom, Nuisance odour, Carcinogenic
Particulates Matter (PM 2.5)	Dust, copiers, printers, cigarette smoking	Affects respiratory system, Coughing, Allergic effects

Table 4. Qualitative Comparison of Methods, Tests, and Technologies

Category	**Methods/Test /Technologies**	**Description**	**References**	**Ease of Use**	**Interpret results**	**Cost**
Visual	Visual Inspection	Visible defects such as cracks, stains, delamination, debonding, visible corrosion can be detected by visual inspection	(Kwan and Ng 2015; Mayo and Karanja 2018)	Easy	Easy	Low
	Crack width Scale	To determine crack width in concrete	(Stawiski and Kania 2018)	Easy	Easy	Low
Acoustic technique	Tapping hammer	To determine delamination in concrete, loose plaster	(D’Aloisio 2017)	Easy	Easy	Low
Imaging	Camera Imaging	All visible defects can be captured for record	(El Masri and Rakha 2020; Mayo and Karanja 2018)	Easy	Easy	Moderate
Thermal Imaging	Infrared Thermal Camera	Thermal image helps detect voids, debonding, delamination, moisture path	(Fox et al. 2016)	Moderate	Moderate	High
Concrete Strength	Rebound Hammer	Used to assess surface hardness of concrete	(Wiyanto et al. 2020)	Moderate	Moderate	Moderate
	Concrete Core Strength Test	Used to determine concrete strength	(Ali-Benyahia et al. 2017)	Difficult	Moderate	High
	Pull out test	Used to determine bonding strength	(Wróblewska and Kowalski 2020)	Moderate	Moderate	Moderate
	Pull off test	Used to determine bond strength of interface	(Wróblewska and Kowalski 2020)	Moderate	Moderate	Moderate
Concrete Quality	Ultrasonic Pulse Velocity	To detect anomalies or voids in material	(El Masri and Rakha 2020; Wiyanto et al. 2020)	Moderate	Moderate	Moderate
	Impact Echo Test	Analysis of reflected sound waves from a hammer tap to detect some subsurface flaws	(Azari et al. 2014; Ohtsu 2016)	Moderate	Moderate	Moderate

Electro-magnetic	Ground Penetrating Radar (GPR)	Electromagnetic radar pulses to view subsurface features such as reinforcement	(Szymczyk and Szymczyk 2015; Zaki et al. 2018)	Difficult	Difficult	High
Corrosion likelihood of embedded steel	Cover meter	Measures thickness of concrete cover	(Kwan and Ng 2015)	Easy	Easy	Moderate
	Half Cell Potentiometer	Measures electrochemical potential in concrete can indicate likelihood of corrosion	(Ismail 2017)	Moderate	Moderate	Moderate
	Electrical Resistivity	Indication of likelihood of corrosion occurring	(James et al. 2019; Tavukçuoğlu 2018)	Moderate	Moderate	Moderate
	Linear Polarization Resistance	Indication of likelihood of corrosion occurring	(Samson et al. 2020)	Moderate	Moderate	Moderate
	Phenolphthalein test	Carbonation depth	(Demčenko et al. 2016; Kwan and Ng 2015)	Easy	Easy	Low
	Chloride content	Estimate the level of chloride ions	(Angst 2018; Torres-Luque et al. 2014)	Moderate	Moderate	Moderate
Leakage	Moisture meter	Measure moisture level on surfaces, helps to detect dampness	(Mendell et al. 2018)	Easy	Easy	Low
	Colour Penetration test	Detect water seepage through cracks or leakage	(Lam et al. 2016)	Easy	Easy	Low
IAQ	Air Quality Meters	Measure different Indoor Air Quality parameters	(Abraham and Li 2014; Thomas et al. 2019)	Moderate	Moderate	High
Lighting	Luminance Meter	Measure light intensity in room	(Ricciardi and Buratti 2018)	Easy	Easy	Moderate
Thermal	Thermometer	Measure temperature in room	(Merabtine et al. 2018; Zuhaib et al. 2018)	Easy	Easy	Low
Humidity	Relative Humidity Meter	Measure relative humidity	(Zuhaib et al. 2018)	Easy	Easy	Low
Noise	Sound Level Meter	Measure sound level in room	(Yang and Moon 2019)	Easy	Easy	Moderate

Table 5. Methods, Tests and Technologies recommended for multi-tiered inspection.

Category	Methods/Test /Technologies	Reference Standard	Tier-I Preliminary Inspection	Tier-II Detailed Inspection	Tier-III Expert Investigation
Visual	Visual Inspection	-	✓	✓	✓
Acoustic	Tapping hammer	-	✓	✓	✓
Imaging	Camera Imaging	-	✓	✓	✓
Thermal Imaging	Infrared Thermal Camera	-	✓	✓	✓
Concrete Strength	Rebound Hammer	ASTM C805 (2018)		✓	✓
	Concrete Core Strength Test	ASTM C42/C42M (2018)			✓
	Pull out test	ASTM C900 (2015)			✓
	Pull off test	ASTM D4541 (2017)			✓
Concrete Quality	Ultrasonic Pulse Velocity	ASTM C597 (2016)		✓	✓
	Impact Echo Test	ASTM C1383 (2015)		✓	✓
Electro- magnetic	Ground Penetrating Radar (GPR)	ASTM D6432 (2011)			✓
Corrosion likelihood of embedded steel	Cover meter	BS 1881-204 (1988)		✓	✓
	Half Cell Potentiometer	ASTM C876 (2015)		✓	✓
	Electrical Resistivity	ASTM C1202 (2019)		✓	✓
	Linear Polarization Resistance	ASTM G59 (2014)		✓	✓
	Phenolphthalein test	ISO 1920 (2012)		✓	✓
	Chloride content	ASTM C1218/C1218M (2017)		✓	✓
Leakage	Moisture meter	ASTM F2659 (2015)	✓	✓	✓
	Colour Penetration test	ASTM E165/E165M (2018)		✓	✓
IAQ	Air Quality Meters	ASHRAE 62.1 (2016)	✓	✓	✓
Lighting	Luminance Meter	BS EN 12464-1 (2011)	✓	✓	✓
Thermal	Thermometer	ASHRAE 55 (2017)	✓	✓	✓
Humidity	Relative Humidity Meter	ASHRAE 55 (2017)	✓	✓	✓
Noise	Sound Level Meter	ASHRAE Handbook (2017)	✓	✓	✓

Table 6. Defect thresholds adopted in this study

Criteria	Defect	Methods/Test /Technologies	Reference	Minor Defect	Major Defect	Severe Defect
Physical	Structural Cracks	Visual Inspection, Crack width scale	Buildings Department (2013)	>0.0 mm	>0.3 mm	>1.0 mm
	Spalling	Visual Inspection, Tapping hammer	EN 1992-1-2 (2004)	>0.0 mm	>40 mm	>60 mm
	Corrosion	Visual Inspection, Half Cell Potential	ASTM C876 (2015)	>0 %	>10 %	>90 %
	Water Seepage	Visual Inspection, Moisture meter, Infrared Thermal Camera	HKIS (2014), ASTM F2659 (2015)	>0 %	>10 %	>90 %
Environmental	Carbon dioxide (CO_2)	Carbon dioxide meter	IAQMG HKSAR (2019), ASHRAE 62.1 (2016), World Health Organization (2010), World Health Organization (2009), US EPA (2016)	>800ppmv	>1000ppmv	>3500ppmv
	Respirable Suspended Particulates Matter (RSPM)	Particulate monitor		>20 $\mu g/m^3$	>100 $\mu g/m^3$	>150 $\mu g/m^3$
	Carbon monoxide (CO)	Carbon monoxide meter		>1.7 ppmv	>6.1 ppmv	>9 ppmv
	Nitrogen dioxide (NO_2)	Nitrogen dioxide meter		>40 $\mu g/m^3$	>150 $\mu g/m^3$	>200 $\mu g/m^3$
	Ozone (O_3)	Ozone monitor		>25 ppbv	>61 ppbv	>100 ppbv
	Formaldehyde (HCHO)	Formaldehyde detector		>24 ppbv	>81 ppbv	>100 ppbv
	Total volatile organic compounds (TVOC)	VOC monitor		>87 ppbv	>261 ppbv	>300 ppbv
	Lighting	Luminance Meter	BS EN 12464-1 (2011)	<750	<500	<200
	Thermal	Thermometer	ASHRAE 55 (2017)	<20°C	>26.5°C	>32°C
	Humidity	Relative Humidity Meter	ASHRAE 55 (2017)	<40%	>65%	>70%
	Noise	Sound Level Meter	ASHRAE Handbook (2017)	>30dB	>45dB	>55dB