Journal of Advanced Research Design 117, Issue 3 (2024) 23-33

Penerbit Akademia Baru

Journal of Advanced Research Design

Journal homepage:
www.akademiabaru.com/ard.html
ISSN: 2289-7984

Implementation of Condition Monitoring and Predictive Maintenance for Building Sustainability

Ahmad Danial Ahmad Subri[1], Mohd Zailan Suleiman[1,*]

[1] School of Housing, Building and Planning, Universiti Sains Malaysia, 11800, Penang, Malaysia

ARTICLE INFO

Article history:
Received 7 April 2024
Received in revised form 26 June 2024
Accepted 28 June 2024
Available online 16 July 2024

Keywords:

Condition monitoring predictive maintenance (CPM); energy savings; building components

ABSTRACT

This research explores the role of Condition Monitoring and Predictive Maintenance (CPM) in improving building sustainability. CPM is a technique that uses advanced sensors and data analysis to anticipate and prevent equipment failure, ensuring the system operates smoothly and efficiently. Through real examples, CPM is of benefit, for energy savings, reduced maintenance costs and extending the lifespan of building components. The research methodology outlines the systematic approach mix-method by applying survey questionnaires to the stakeholders in Malaysia and case studies in selected areas. The findings revealed that CPM can lead to significant sustainability gains in the built environment by optimizing resource use and reducing waste. Challenges encountered such as start-up costs and the need for skilled personnel were also discussed. The results also offer recommendations for successful use of CPM. In overall, this research revealed that CPM is a valuable tool for making buildings more sustainable.

1. Introduction

The growing importance of building sustainability is of paramount in a world facing environmental challenges and limited resources. It emphasizes the significance of Condition Monitoring and Predictive Maintenance (CPM) as crucial strategies for managing and preserving buildings in an ecologically responsible and energy-efficient manner [1]. By continuously monitoring building systems and components, CPM helps identify issues early on, leading to reduced energy consumption, extended building lifespans and improved indoor environmental quality [2]. A crucial element of this holistic approach is proactive management of physical conditions and maintenance requirements, where CPM play a pivotal role [3-5]. The focus of this study is on exploring the implementation of CPM as a transformative tool in building sustainability, addressing issues such as maintenance costs, environmental concerns and the need for sustainable building practices in a rapidly urbanizing world [6]. By providing practical insights and recommendations, the research aimed to guide stakeholders towards embracing environmentally conscious building management practices for a more sustainable future.

* *Corresponding author.*
E-mail address: mzailan@usm.my

https://doi.org/10.37934/ard.117.3.2333

2. Methodology

The research used a multi-faceted approach, integrating various research methods and techniques to investigate the implementation of CPM to build sustainability. The methodology was organized inclusive of literature review, data collection, data analysis, case studies, expert interviews and reports. It aimed to deliver insights, guidelines and actionable policy recommendations to foster transformation in building management practices, aligning them with sustainability goals and increasing environmental responsibility.

2.1 Research Design

i. Building operations sustainability and the efficient application of CPM were inextricably linked. In order to assess the influence of CPM on building sustainability comprehensively, this study employed a Mixed Methods method, combining quantitative data on CPM system performance with qualitative views from facilities management stakeholders.
ii. This project integrated quantitative and qualitative data using a convergent parallel design, enabling a thorough investigation of CPM for building sustainability. The process of gathering data included:
    a. Quantitative data from sensors and maintenance records to establish correlations and patterns in the efficacy of CPM practices.
    b. Qualitative interviews and surveys with stakeholders involved in facilities management to understand their perspective on the practicalities, challenges and benefits of CPM for sustainability.

2.2 Justification for Chosen Methods

i. **Complexity of Sustainability**: Building sustainability is a broad concept that takes into account social and economic factors in addition to environmental impact. Facilities managers make complex decisions and experiences that might affect sustainability outcomes, and these factors cannot be fully captured by a quantitative assessment alone.
ii. **Implementation Dynamics**: While qualitative data sheds light on the organizational, technical and human elements that affect the successful adoption of CPM, quantitative data will highlight trends and efficiencies in the CPM lifecycle, providing a more comprehensive picture.
iii. **Evidence Triangulation**: Triangulation is made possible using both qualitative and quantitative methodologies, which increases the validity of the research by validating findings through several streams of evidence.
iv. **Stakeholder Engagement**: The use of qualitative approaches will allow for the recording of stakeholder viewpoints, which is crucial when analyzing the success of CPM because it grounds the analysis in the reality of operational experiences.
v. **Gap in Literature**: Previous research may have focused more heavily on either quantitative performance metrics or qualitative case studies. Combining these approaches addresses a gap in the literature, creating a more holistic understanding of CPM's role in sustainability.

2.3 Data Collection

Quantitative data collecting was the method employed for this study. A Google Form-created questionnaire served as the source of the information gathered during the study. Using programs like

WhatsApp and Telegram, all of the group members circulated the questionnaire to factory employer. It was done to ensure only the respondents who were specifically targeted and matched the study's topic got and responded to the questionnaire. The dissemination of the questionnaire took place from 10 January 2024, for a total of 5 days. Since the questionnaires were created using Google Forms and the data was gathered using search engines like Google Search, the procedure and technique of data collection were carefully thought out in order to be practical and appropriate for our research.

Primary data, as well as secondary data, were the two main categories into which data may be divided. The term "primary data" refers to the unprocessed information that researchers gather through a variety of research techniques, like conducting interviews, performing experiments or monitoring their subjects or target population. However, for this study, the factory employer responses to a questionnaire survey were used to collect the primary data. Additionally, secondary data were often gathered from a variety of sources, including websites, journals, database releases and more.

2.4 Data Analysis

The quantitative data acquired through surveys and performance metrics were analyzed using Google form. The decision to conduct online surveys provided convenience to the students and eliminated the need for printing questionnaire papers, resulting in time and energy savings. The survey forms were easily distributed to the participants by utilizing e-platforms such as WhatsApp, Telegram and Instagram. This digital survey initiative aimed to enhance accessibility, reduce costs and streamline the data collection process. Techniques like regression analysis, frequency distribution and cross-tabulation will help identify patterns, correlations and inferential insights about the effectiveness of CPM. Qualitative responses and case study content will be subjected to thematic analysis to identify commonalities and deviations in perspectives on sustainability impacts of CPM. Coding and categorization will be instrumental in the qualitative analysis, helping to identify trends and create a comprehensive narrative around the adoption and consequences of CPM strategies. Combining these diverse approaches to data gathering and analysis will provide a multifaceted understanding of CPM's contribution to improving building operations sustainability, offering comprehensive insights that can support well-informed decision-making in the industry.

3. Results and Discussion

3.1 Pressure Distribution

The research focuses on the implementation of CPM technology to enhance the sustainability of building operations and management. CPM involves continuously monitoring building systems and components to detect issues early and predict maintenance needs, with the goal of improving energy efficiency, extending asset lifespans and reducing operational disruptions and costs [7]. The importance of this research stems from the need to address challenges posed by deteriorating building infrastructure, rising maintenance costs and growing environmental concerns. Neglected maintenance can lead to inefficiency, costly repairs and shorter building lifespans, which is contrary to the principles of sustainability.

3.2 Building Sustainability

Building sustainability is important for urban development and in line with industry standards and environmental ethics to ensure economic stability in development and the global ecosystem in maintaining that sustainability [8]. If not eradicated properly, it will cause erosion of the earth's layer. Key principles include quality energy efficiency, waste reduction so that it can be filtered properly, water conservation and indoor environmental quality either during or after. It is very important to apply in maintaining the sustainability of buildings in development. Certification programs such as LEED and BREEAM provide a framework to assess the sustainability of buildings and ensure safety in building construction and if damage occurs, the responsible party will manage it quickly and efficiently [9]. Global initiatives such as the Paris Agreement and the UN's Sustainable Development Goals set ambitious targets to reduce carbon emissions to ensure a reduction in smoke pollution in the air in every factory.

3.3 CPM Integration in Building Sustainability

The research demonstrates that the integration of CPM technology with building automation systems can lead to significant energy savings and reductions in operating costs. This is exemplified by the case of The Edge building in Amsterdam, which has successfully implemented advanced predictive maintenance and smart technologies to enhance its sustainability and occupant comfort. The key features that contribute to The Edge's success include:

i. Flexible workspaces that accommodate both in-office and remote employees, promoting collaboration.
ii. Advanced digital systems that connect employees to the building through a mobile app, allowing control over lighting, temperature and other settings.
iii. Sustainable features like solar panels, rainwater reuse and thermal energy storage, which reduce the building's environmental impact.
iv. A Building Management System (BMS) that integrates with digital actuators to provide detailed insights into energy usage and enable predictive maintenance.
v. Predictive maintenance capabilities that help identify and address issues before they become major problems, reducing downtime and ensuring optimal building performance.
vi. BREEAM certification, which recognizes The Edge as one of the most sustainable office buildings in the world.
vii. Occupant-centric design, with features like automated energy performance visualization, building usage monitoring and predictive facilities maintenance, ensuring a comfortable and productive environment for occupants.

Overall, the research highlights how the strategic integration of CPM and smart technologies can significantly enhance the sustainability and operational efficiency of buildings, while also prioritizing the well-being of occupants.

3.4 Challenges to CPM Implementation

The integration of technological advances such as the Internet of Things (IoT), cloud computing and Artificial Intelligence (AI) is essential in integrating Condition Based Predictive Maintenance (CBPM) into building sustainability and creating a smart building environment.

i. **IoT sensors**: IoT sensors are installed throughout the building to collect data on various parameters such as temperature, humidity, light and air quality. This data is then transmitted to the cloud for analysis and processing.

ii. **Cloud computing**: Cloud computing enables the storage and processing of large amounts of data generated by IoT sensors. This allows for real-time monitoring and analysis of building performance, enabling predictive maintenance and energy efficiency optimization.
iii. **Artificial intelligence**: AI algorithms are applied to the data collected from IoT sensors and cloud computing to identify patterns and anomalies. This enables predictive maintenance, where potential issues are identified and addressed before they become major problems.
iv. **Predictive maintenance**: AI-powered predictive maintenance uses machine learning algorithms to analyze data and predict when maintenance is required. This proactive approach reduces downtime, extends equipment lifespan and enhances overall building performance.
v. **Real-time monitoring**: IoT sensors and cloud computing enable real-time monitoring of building performance. This allows for immediate response to any issues that arise, ensuring optimal building conditions and occupant comfort.
vi. **Energy efficiency optimization**: AI-powered energy efficiency optimization analyzes data from IoT sensors to identify areas of energy waste. This information is used to optimize energy consumption, reducing the building's environmental impact and energy costs.
vii. **Building automation systems (BAS)**: IoT sensors and AI-powered predictive maintenance integrate with BAS to automate building operations. This ensures that the building operates at optimal levels, with minimal human intervention.
viii. **Occupant comfort**: AI-powered predictive maintenance and real-time monitoring ensure that the building remains comfortable and productive for occupants. This includes maintaining optimal temperatures, humidity levels and air quality.
ix. **Data analytics**: The integration of IoT sensors, cloud computing, and AI provides valuable insights into building performance. This data can be used to optimize building operations, identify areas for improvement and make data-driven decisions.
x. **Scalability and flexibility**: The use of IoT sensors, cloud computing and AI enables the creation of a scalable and flexible smart building environment. This allows for easy integration of new technologies and systems as they become available [10].

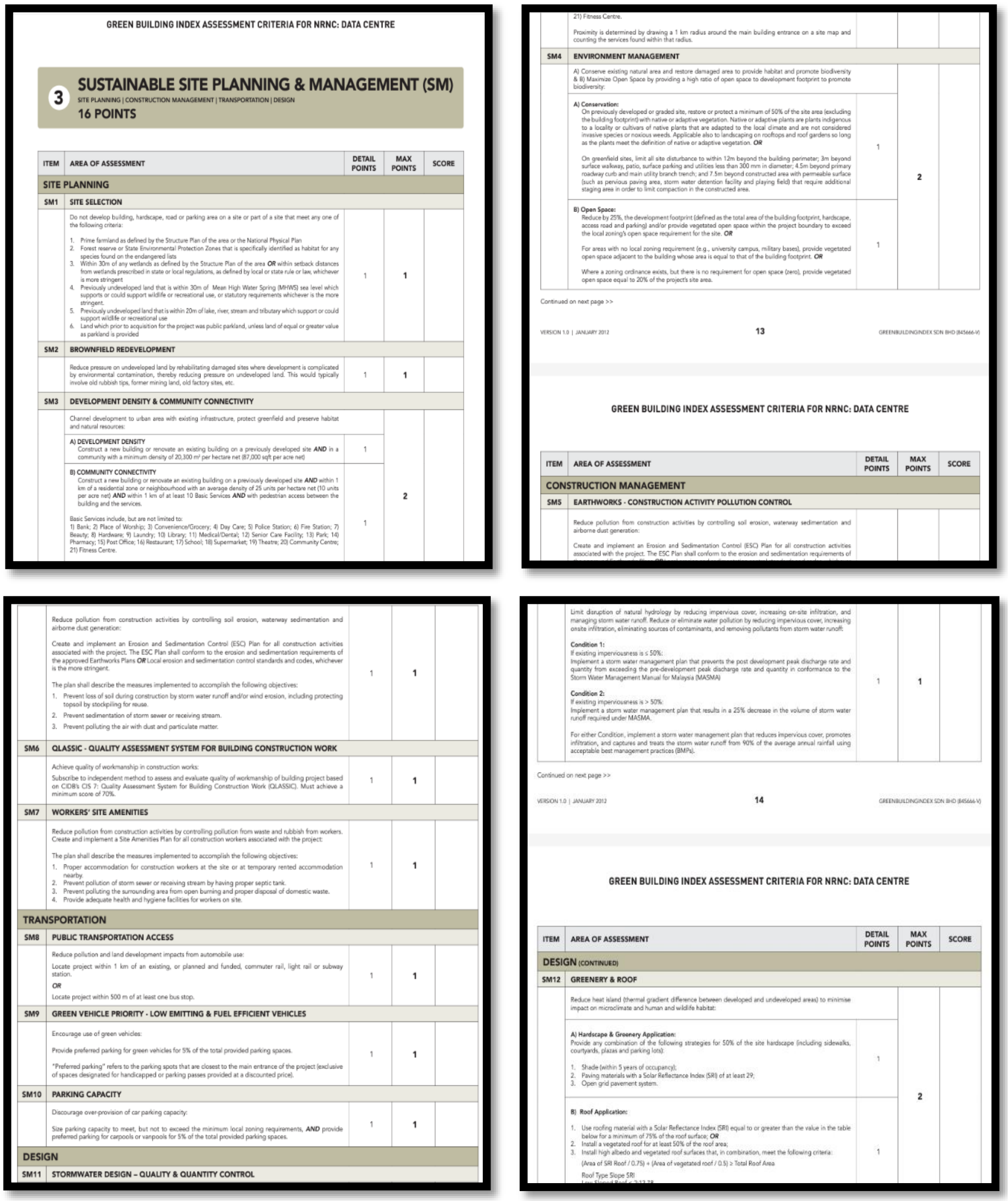
3.5 The Current State of Building Sustainability

In examining the assessment of the development to ensure that every work done must be scrutinized and in accordance with the wishes of the local authorities to maintain the sustainability of the building. This is because there is an environmental quality act (AMENDMENT) 2007 which according to section 34B (4) any person who violates this section commits an offense and when convicted shall be sentenced to imprisonment for a period not exceeding five years and shall also be fined not exceeding five hundred thousand ringgit [11]. Therefore, on this occasion we examined the results carried out by the contractor in making the project a success, having followed the conditions to avoid being charged a compound.

In addition, in ensuring the sustainability of this building also plays an important role in the health aspects of the building and workers. It is very important in taking care of the health of the workers who are doing the work that has been carried out to ensure the preservation of environmental sustainability even in the construction of buildings. Unhealthy conditions can cause diseases and are easily infected by every worker, for workers who do not look at the cleanliness of the building, there will also be water reservoirs, the condition of the building filled with fungus and undergrowth by creeping trees and making it easier for insects to nest [12].

Next, the contractor will ensure that the surrounding conditions are safe and clean after a day of project work to ensure that the project site is in a safe and clean condition [24]. To avoid being affected by the environmental quality act and also the Green Building Index (GBI) will ensure that every area is in a comfortable condition one example is: -Site Planning (Figure 1),

i. Site Selection
ii. Brownfield Redevelopment
iii. Environment Management
iv. Construction Management
v. Transport
vi. Public Transport
vii. Green Vehicle Priority
viii. Parking Capacity


GREEN BUILDING INDEX ASSESSMENT CRITERIA FOR NRNC: DATA CENTRE

3 SUSTAINABLE SITE PLANNING & MANAGEMENT (SM)
SITE PLANNING | CONSTRUCTION MANAGEMENT | TRANSPORTATION | DESIGN
16 POINTS

ITEM	AREA OF ASSESSMENT	DETAIL POINTS	MAX POINTS	SCORE
SITE PLANNING				
SM1	SITE SELECTION	1	1	
SM2	BROWNFIELD REDEVELOPMENT	1	1	
SM3	DEVELOPMENT DENSITY & COMMUNITY CONNECTIVITY	1, 1	2	
SM4	ENVIRONMENT MANAGEMENT	1, 1	2	
CONSTRUCTION MANAGEMENT				
SM5	EARTHWORKS - CONSTRUCTION ACTIVITY POLLUTION CONTROL	1	1	
SM6	QLASSIC - QUALITY ASSESSMENT SYSTEM FOR BUILDING CONSTRUCTION WORK	1	1	
SM7	WORKERS' SITE AMENITIES	1	1	
TRANSPORTATION				
SM8	PUBLIC TRANSPORTATION ACCESS	1	1	
SM9	GREEN VEHICLE PRIORITY - LOW EMITTING & FUEL EFFICIENT VEHICLES	1	1	
SM10	PARKING CAPACITY	1	1	
DESIGN				
SM11	STORMWATER DESIGN – QUALITY & QUANTITY CONTROL	1	1	
SM12	GREENERY & ROOF	1, 1	2	

DESIGN (CONTINUED)				
SM12	GREENERY & ROOF			
	Reduce heat island (thermal gradient difference between developed and undeveloped areas) to minimise impact on microclimate and human and wildlife habitat:		2	
	A) Hardscape & Greenery Application: Provide any combination of the following strategies for 50% of the site hardscape (including sidewalks, courtyards, plazas and parking lots): 1. Shade (within 5 years of occupancy); 2. Paving materials with a Solar Reflectance Index (SRI) of at least 29; 3. Open grid pavement system.	1		
	B) Roof Application: 1. Use roofing material with a Solar Reflectance Index (SRI) equal to or greater than the value in the table below for a minimum of 75% of the roof surface; ***OR*** 2. Install a vegetated roof for at least 50% of the roof area; 3. Install high albedo and vegetated roof surfaces that, in combination, meet the following criteria: (Area of SRI Roof / 0.75) + (Area of vegetated roof / 0.5) ≥ Total Roof Area Roof Type Slope SRI Low-Sloped Roof < 2:12 78 Steep-Sloped Roof > 2:12 29	1		
SM13	BUILDING USER MANUAL			
	Document Green building design features and strategies for user information and guide to sustain performance during occupancy: Provide a Building User Manual which documents passive and active features that should not be downgraded.	1	1	
	SUSTAINABLE SITE PLANNING & MANAGEMENT (SM) TOTAL		16	

Fig. 1. Sustainable site planning management

3.5.1 Sensor technologies

The successful application of CPM for sustainable building practices depends heavily on sensor technologies. The primary instruments that make it possible to gather data in real time on a variety of characteristics from the systems and parts of a building are sensors. These sensors play a critical role in spotting variations from the norm, seeing possible problems and offering guidance for preventative maintenance procedures. To further explain sensor technology, consider the following important points:

i. **Types of sensors**: Sensors used in CPM can range from simple temperature and humidity sensors to more advanced ones like vibration sensors, acoustic sensors, pressure sensors and flow sensors. Each type of sensor serves a specific purpose in monitoring and assessing the health of different building systems.
ii. **IoT connectivity**: Sensors are often connected through the IoT technology, allowing them to communicate data wirelessly to a central system or cloud platform. This connectivity enables seamless data collection, monitoring and analysis across various building locations and systems [13]. Data collection and transmission sensors continuously collect data on environmental conditions, equipment performance, energy consumption and more. This data is transmitted in real-time to centralized monitoring systems where it can be processed, analyzed and used to trigger maintenance alerts or actions.
iii. **Predictive analytics**: Sensor data, when combined with predictive analytics algorithms, helps in identifying patterns, trends and anomalies that indicate potential maintenance issues or system malfunctions. By analyzing sensor data over time, predictive maintenance schedules can be optimized for maximum efficiency.
iv. **Remote monitoring**: Sensor technology enables remote monitoring of building systems, allowing facilities managers and maintenance teams to access real-time data and insights from anywhere. This remote monitoring capability enhances operational efficiency and enables quick responses to emerging issues.
v. **Optimization of energy efficiency**: Sensors are essential for maximizing energy efficiency in buildings. Sensors offer important information that can aid in finding opportunities for energy savings and enhancing the sustainability of buildings overall by tracking patterns in energy usage and equipment performance.

vi. **Integration with building management systems (BMS)**: Sensor data is often integrated with BMS to create a comprehensive view of building operations. This integration allows for centralized control, monitoring and automation of various building systems based on real-time sensor data.
vii. **Scalability and flexibility**: Sensor technology is designed to be scalable and flexible, enabling easy integration with existing building infrastructure and the ability to expand sensor networks as needed [14]. This scalability ensures that buildings can adapt to changing requirements and incorporate new sensor technologies over time.

In summary, sensor technology serves as the cornerstone for the use of CPM in sustainable building practices. It offers essential data insights that propel preventive maintenance plans, maximize energy efficiency and improve overall building performance and occupant comfort. Buildings can attain greater levels of sustainability, dependability and efficiency in their operations and maintenance procedures by utilizing cutting-edge sensor technologies and IoT connectivity.

3.5.2 Predictive maintenance algorithms

The effective use of CPM for building sustainability depends on predictive maintenance algorithms. These algorithms forecast equipment breakdowns and maintenance requirements ahead of time by utilizing machine learning, data analysis and historical data. An explanation of predictive maintenance algorithms is provided below:

i. **Data analysis**: Predictive maintenance algorithms analyze vast amounts of data collected from sensors, historical maintenance records and other sources. By examining trends, patterns and anomalies in this data, the algorithms can identify early indicators of potential equipment failures.
ii. **Machine learning**: Machine learning techniques are employed to train predictive maintenance algorithms to recognize behaviour patterns that precede equipment failures. These algorithms learn from historical data to make accurate predictions about maintenance requirements [15].
iii. **Anomaly detection**: Predictive maintenance algorithms are designed to detect anomalies in equipment performance metrics. By comparing real-time data against expected patterns, the algorithms can flag deviations that may signal impending issues.
iv. **Predictive analytics**: Using advanced analytics, predictive maintenance algorithms forecast the remaining useful life of equipment and components. By estimating when maintenance is required, these algorithms enable proactive maintenance actions to prevent unexpected failures.
v. **Condition-based alerts**: Predictive maintenance algorithms generate alerts and notifications based on predictive models and predefined thresholds. Maintenance teams receive actionable insights regarding equipment health and performance, allowing them to take preventive measures before breakdowns occur.
vi. **Integration with IoT**: Predictive maintenance algorithms often integrate with IoT devices and sensors to gather real-time data on equipment conditions. This seamless connectivity enables continuous monitoring and predictive analysis for optimal maintenance planning.
vii. **Optimization of maintenance schedules**: By utilizing predictive maintenance algorithms, organizations can optimize maintenance schedules based on equipment health and performance predictions. This proactive approach minimizes downtime, reduces maintenance costs and extends the lifespan of building components.

viii. **Continuous improvement**: Predictive maintenance algorithms are continuously refined and improved through feedback loops and ongoing data analysis. By incorporating new data and insights, these algorithms enhance their predictive accuracy and effectiveness over time.

To sum up, predictive maintenance algorithms are advanced instruments that utilize data-driven insights to anticipate maintenance requirements, avert equipment malfunctions and improve the sustainability of buildings. The long-term durability of building infrastructure is ensured, operating efficiency is optimized and proactive maintenance policies are driven by these algorithms.

3.5.3 The potential of CPM

The integration of Critical Path Method with Condition-Based Predictive Maintenance (CBPM) offers significant potential for enhancing the sustainability of buildings. The first key point is integrating sustainability metrics directly into project schedules. This involves incorporating factors like energy consumption, emissions and resource usage into the critical path analysis to optimize construction schedules and prioritize environmental impact alongside traditional project constraints [23]. Resource-Constrained Scheduling advancements in Generalized Resource-Constrained CPM (eRCPM) enable the integration of resource availability and usage into the critical path analysis, ensuring the availability of maintenance resources when needed [16-20].

The second key point is predictive maintenance integration. The integration of CPM with CBPM provides valuable insights into the timing and scheduling of maintenance activities. By analyzing the critical path and resource requirements, project managers can identify optimal windows for preventive maintenance, reducing downtime and ensuring the long-term sustainability of the building. This proactive approach to maintenance can extend the lifespan of building systems and reduce overall lifecycle costs.

The third key point is the collaborative approach. The successful implementation of CBPM in building projects often requires a collaborative effort among various stakeholders, including the client, developer, architect and contractors [24]. CPM can facilitate this collaboration by providing a common framework for project planning and decision-making. By aligning sustainability goals and maintenance requirements across the project team, CBPM can be more effectively integrated into the overall construction process, leading to a more sustainable and well-maintained building [21-24].

3.5.4 Challenges and barriers to CPM

In the search to study according to the presented title, which is the Implementation of Condition Monitoring and Forecasting Maintenance for Building Sustainability, there are several results that are searched and studied, one of which uses primary data which is a source from the internet by the first person in analyzing the material and also does not miss using secondary data that has been studied by certain parties and we added from the remaining gaps. The primary data taken was from internet sources that produce many problems that will be faced by every researcher, the problem is with the uncertainty of the weather by nature and even Malaysia is on the equator line which does not have 4 seasons like other countries. Malaysia is a country with slow temperature. In addition to that, using secondary data that is data that has been studied by previous researchers, because previous researchers have made but not continued successfully also has certain problems such as incomplete and inaccurate data.

The method of data collection also used two methods that have been explained, namely using quantitative and qualitative methods. This method can help in the retrieval of data that has been planned. Quantitative is using tabulations that have been done such as pie charts, bars or statistics. Qualitative is a way of taking data through going down to the construction site, seeing the real situation, evaluating all aspects of the construction site, creating a space to fill out questionnaires and so on.

The challenges faced by the developer or owner of the project site when conducting an interview with the management was to ensure that the workers follow the instructions, the health of the workers must be taken seriously, the progress of the construction must be in line with the planned target, control the logistic route for the delivery of goods so that there is no congestion in the construction site and the main problem in maintaining cleanliness in the project site [25,26].

4. Conclusions

Condition Monitoring and Predictive Maintenance play a crucial role in promoting environmental sustainability by ensuring the efficient use of resources and reducing wastage in building operations. Condition monitoring involves the real-time monitoring of various parameters such as temperature, pressure, vibration and energy usage within a building. By continuously tracking these metrics, potential issues or anomalies can be detected early on, allowing for proactive maintenance to prevent costly breakdowns and reduce energy consumption. Predictive maintenance, on the other hand, utilizes data analytics and predictive modelling to forecast the future performance of building systems and equipment. By analyzing historical data and identifying trends, maintenance schedules can be optimized, minimizing downtime and extending the lifespan of assets. This proactive approach not only enhances operational efficiency but also reduces unnecessary resource consumption and waste.

By implementing CPM practices, buildings can operate more sustainably by maximizing energy efficiency, minimizing resource use and reducing the environmental impact of maintenance activities. Ultimately, CPM contributes to the overall well-being of the building, its occupants and the environment.

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