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Strategizing Effective Maintenance Strategies for Air Conditioning Systems in Commercial Buildings in Malaysia: A Systematic Literature Review

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ABSTRACT

The use of air conditioning systems is prevalent in many locations in Malaysia due to the elevated temperatures seen in the region. The importance of air conditioning system maintenance has not been accorded due attention. Taking this issue into consideration, this study aims to enhance the maintenance of air conditioning systems by understanding their importance, identifying maintenance issues and proposing solutions to enhance system maintenance, with a specific focus on commercial buildings in Malaysia. The data used in the study was gathered from case studies, images, newspapers, journals and previous theses. This study used fully qualitative methods to obtain data and was acquired through a systematic literature review (SLR) and open-ended interview questionnaire with experts. From the findings, it was found that there were three main strategies, which are preventive maintenance, corrective maintenance and predictive maintenance that are mostly applied for the maintenance of the air conditioning system at the commercial building in Malaysia. The overall findings from the interview with experts highlighted that technical expertise, specialized tools and comprehensive maintenance strategies were important elements to be employed by HVAC technicians and facility managers in Malaysia when managing the HVAC, especially the air conditioning system. This research expands knowledge by investigating air conditioning system maintenance. Furthermore, the findings of this study are useful to the maintenance team and users since they provide the best strategies for the maintenance of the air conditioning systems of commercial buildings in Malaysia.

1. Introduction

The climate in Malaysia is generally hot and humid (tropical) throughout the year, featuring an average annual rainfall of 250 cm and an average temperature of 27 °C. These characteristic subtropical climate conditions in Malaysia significantly impact the indoor environmental comfort conditions of buildings. Positioned near the equator in Southeast Asia, Malaysia experiences a typical tropical climate [5]. Efficient use of energy is very important because Malaysia is running out of fossil

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resources. This influence Malaysia's increasing energy demand due to rapid infrastructure development and economic growth. Therefore, sustainable energy is a challenge facing the Malaysian power industry. Buildings in Malaysia consume 14.3 % of overall energy, with the residential and commercial sectors accounting for 53 % of electricity [10]. This is due 90 % of people spend most of their time inside buildings. Due to improvement in the quality of life, energy consumption in buildings increased dramatically in the past few decades. Therefore, building energy efficiency is important for reducing energy use and improving environmental sustainability [11].

Air conditioning systems are major consumers of energy in buildings. Nowadays, due to the high installation requirements of air conditioner in buildings, designing an effective controller to reduce the energy consumption of the equipment while meeting the thermal comfort requirements of the building is the most important goal of the control designer [6]. Additionally, poor air conditioning system maintenance practices can lead to more frequent outages, which can cause inconvenience or even disaster. So, air conditioning system maintenance must be more consistent, efficient and cost-effective. Only with the support of a good air conditioning system can provide a healthy and comfortable indoor environment to people [13].

The purpose of this study was to examine the challenges faced by the maintenance team in managing air conditioning systems in commercial buildings in Malaysia. Effective strategies for maintenance of air conditioning systems in commercial buildings in Malaysia were discussed. Ideally, this study aimed to identify current strategies applied for the maintenance of air maintenance of air conditioning systems in commercial buildings in Malaysia.

2. Methodology

Through systematic literature review (SLR), researchers gained an understanding of the current strategies that are applied for the maintenance of the air conditioning systems of commercial buildings. The review resulted in three main themes and 19 sub-themes related to the maintenance of air conditioning systems. The three main themes are preventive maintenance (seven sub-themes), corrective maintenance (six sub-themes) and predictive maintenance (six sub-themes) (Table 3). The results provided a comprehensive analysis of the current maintenance of air conditioning systems.

Furthermore, an interview with experts has also been conducted to verify the outcome of the SLR data. Three experts were invited to give their views and share their expertise in strategizing effective maintenance strategies for air conditioning system in commercial buildings in Malaysia.

2.1 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) and SLR

The review adhered to the PRISMA statement, a widely used approach in the environmental management field. PRISMA offers three key benefits: 1) Defining precise research questions that enable systematic investigation, 2) Specifying inclusion and exclusion criteria and 3) Facilitating a comprehensive examination of extensive scientific literature databases within a specified timeframe. By employing the PRISMA statement (Figure 1), a rigorous search of terms related to air conditioning systems and their maintenance reviews can be conducted. This methodology is applicable for monitoring the maintenance of air conditioning systems. This study fully employed qualitative methods and approaches to obtain data. The information used in the study was obtained through a systematic literature review to achieve the objectives, as shown in Table 1, Table 2 and Table 3. The information obtained will be linked to each other to explain and support the results and findings of this study.

2.1.1 Identification and screening

The review relied on three main journal databases: Google Scholar (196 articles), Scopus (52 articles) and Emerald Insight (26 articles). Google Scholar is a robust database that provides a comprehensive index of scholarly literature across various disciplines. Its extensive coverage and accessibility make it a valuable resource for researchers conducting systematic reviews.

Scopus, the second database utilized in the review, is one of the largest abstract and citation databases of peer-reviewed literature. It encompasses over 22,800 journals from 5,000 publishers worldwide. Scopus covers a wide range of subject areas, including environmental sciences, social sciences, agriculture and biological sciences. Its broad scope and high-quality content contribute to its reputation as a reliable source for academic research.

Emerald Insight, the third database employed, is a leading publisher of peer-reviewed journals and books in the fields of business, management and social sciences. It offers a diverse collection of high-quality research papers, case studies and theoretical works. Emerald Insight's focus on applied research and practical insights makes it particularly relevant for studies examining the maintenance and management of air conditioning systems.

By leveraging these three databases, the review aimed to capture a comprehensive and diverse set of relevant literature. The combination of Google Scholar's extensive coverage, Scopus's high-quality peer-reviewed content and Emerald Insight's applied research focus strengthens the review's ability to provide a thorough and well-rounded analysis of the topic at hand.

2.1.2 Eligibility and exclusion criteria

This research employed several eligibility and exclusion criteria to ensure the selection of relevant and high-quality literature. Firstly, only empirical research articles were included, excluding review articles, book series, books, book chapters and conference proceedings. This criterion aimed to focus on original research findings and data-driven insights. Secondly to maintain clarity and avoid potential translation issues, the search was limited to articles published in English, excluding non-English publications. This decision streamlined the review process and ensured that all included articles could be easily understood and analyzed by the researcher.

Thirdly, a six-year timeframe (2018-2024) was chosen to capture the recent evolution of research and related publications in the field. This period was considered sufficient to identify current trends, best practices and emerging technologies in air conditioning system maintenance. Lastly, only articles that specifically addressed the types of maintenance used for air conditioning systems were selected. This final criterion ensured that the reviewed literature was directly relevant to the project's core focus, providing insights into the various maintenance approaches and their effectiveness in the context of commercial buildings in Malaysia.

2.1.3 Systematic review process

Four stages were involved in the systematic review process. The first phase identified keywords used for the search process. Relying on previous studies and thesaurus, keywords similar and related to air conditioning system and, type of maintenance. At this stage, after careful screening, 14 duplicated articles were removed. The second stage was screening. At this stage, out of 260 articles eligible to be reviewed, a total of 186 articles were removed. The third stage is eligibility, where the full articles are accessed. After careful examination, a total of 63 articles were excluded as some were

not empirical articles or did not focus on the maintenance of air conditioning system. The last stage of review resulted in a total of 11 articles that were used for the qualitative analysis (Figure 1).

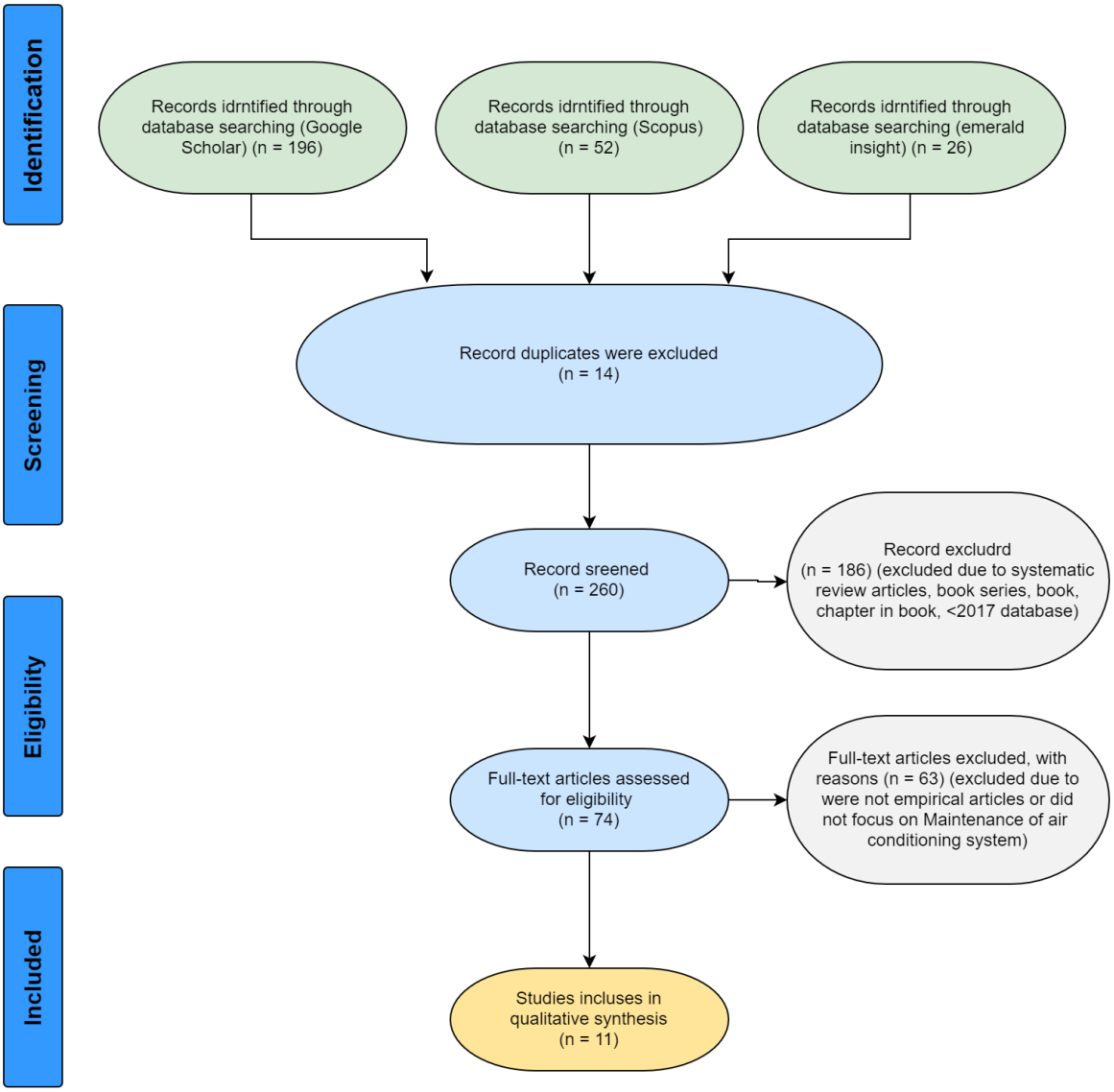

Fig. 1. The flow diagram of the study

2.1.4 Data abstraction and analysis

The remaining articles underwent a thorough assessment and analysis process. The focus was directed towards studies that specifically addressed the predetermined research questions. Data extraction involved initially reviewing the abstracts, followed by an in-depth examination of the full articles to identify relevant themes and sub-themes. A qualitative content analysis was conducted to pinpoint themes pertaining to the maintenance of air conditioning systems. Subsequently, the researcher organized the sub-themes around the primary themes established through a typological approach.

2.2 Interviews Construction

Constructing a well-designed questionnaire form for interviews is crucial for collecting reliable and meaningful data in a research study. The purpose of the questionnaire interview for this study was to get an overview from experts. A question-and-answer format was used to conduct the open-ended interview. The researcher has set the questions, and then the respondents were required to give the answers in their own words and ideas, based on their experience and knowledge. Therefore, the answer obtained by the researcher was not limited to a definite answer.

The choice to use an open-ended questionnaire format for interviews in this research study was driven by several key considerations. First, open-ended questions allowed participants to express their opinions in their own words, which will provide the researcher with many different and diverse responses. Secondly, open-ended questionnaires allowed participants to elaborate on their views in more detail so that researchers can better understand their insights and opinions.

In addition, participants can share their experience in a conversational manner, which may yield details and context that may be missed in other data methods. In summary, the choice of open-ended questionnaire format interviews was motivated by the need for a comprehensive and in-depth exploration of the research topic, the desire to capture the rich perspectives of participants and the flexibility to adapt to reality.

2.2.1 Thematic analysis

The analytical method used in this study was thematic analysis, a robust and versatile method for extracting valuable insights from qualitative data collected through interviews with open-ended questionnaires. This approach helped identify recurring patterns and themes in participants' responses, allowing for a nuanced exploration of their experiences, challenges and perspectives related to air conditioning systems maintenance.

Thematic analysis also aids in the systematic coding and classification of data, which helps structure and organize a range of qualitative data. It can generate in-depth insights that place participants' perspectives within the wider context of air conditioning systems maintenance in commercial buildings in Malaysia. Through the identification and development of themes, the approach highlights different perspectives and supports the research objectives.

2.2.2 ATLAS.ti

This study used software to help researchers conduct data analysis, which is ATLAS.ti. ATLAS.ti is a qualitative data analysis software that can improve the efficiency and rigor of this research. In the initial phase, the software helps organize different data types, which also include open-ended questionnaire interview transcripts, thus simplifying management within the platform.

ATLAS.ti also enables the systematic development of codes to represent key concepts, themes and patterns that emerge from the qualitative data. This facilitates detailed text analysis, allowing researchers to explore and understand the context of coded data segments. Researchers still use its visual representation tools, such as concept maps and network views, to identify interconnected patterns in the data. Finally, ATLAS.ti facilitates report generation and export of research results in various formats, simplifying the presentation of results for integration into the final research output. Overall, ATLAS.ti provides a comprehensive platform for the systematic coding, exploration and interpretation of qualitative data, helping to increase the depth and rigor of research.

3. Results and Discussion

3.1 SLR Result and Discussion

From the findings, it was found that there were three main strategies that are applied for the maintenance of the air conditioning system at the commercial building in Malaysia, namely preventive maintenance, corrective maintenance and predictive maintenance.

3.1.1 Preventive maintenance

The reviewed studies underscore the significance of proactive preventive maintenance strategies for ensuring efficient and reliable air conditioning systems in commercial buildings. These strategies aim to maintain the optimal performance of the air conditioning systems and prevent major breakdowns or failures.

Table 1 shows the results and findings of the data collected in preventive maintenance. Regularly scheduled inspections and servicing [5,9,15] help identify and address potential issues before they escalate, thereby ensuring the continuous and reliable operation of the systems. Regular inspections and servicing allow for early identification and resolution of potential issues, preventing major breakdowns and ensuring continuous system operation.

Regular maintenance through routine cleaning of filters, coils and ducts [1,3,14] is essential for maintaining system efficiency and indoor air quality, which is essential for the well-being of building occupants. Routine cleaning and lubrication maintain system efficiency and component lifespan, while calibration of controls optimises energy usage and minimises operational costs.

Proper lubrication of moving parts [1,2,13] can reduce wear and tear, extend component lifespans and improve overall system performance. Calibration of system controls [7,12] is another important aspect of preventive maintenance, as it ensures optimal operation and energy efficiency, thereby minimizing energy consumption and operational costs. Calibration of system controls ensures optimal operation and energy efficiency, minimizing energy consumption and operational costs.

Examining refrigerant levels and addressing any leaks [4,8,12,14] is important for maintaining system efficiency and reducing the environmental impact. Furthermore, system upgrades and retrofits [1,2,13], as well as compliance with relevant regulations and standards [2,13,15], can enhance the overall performance and reliability of the air conditioning systems in commercial buildings. Upgrades, retrofits and compliance with regulations further enhance the overall performance and reliability of the air conditioning systems.

These proactive measures help ensure the long-term efficiency, reliability and environmental sustainability of the air conditioning systems, ultimately benefiting both building owners and occupants. By implementing these comprehensive preventive maintenance strategies, building owners and managers can maintain the optimal performance of their air conditioning systems, improve energy efficiency and ensure the comfort and well-being of occupants over the long term.

Table 1
The SLR findings on theme 1: Preventive maintenance

Authors	Main study design	Preventive maintenance						
		PM01	PM02	PM03	PM04	PM05	PM06	PM07
Fangzhou [4]	QL	✓				✓	✓	
Tracie Magdeline [13]	MM			✓			✓	✓
C. Nzukam [2]	QL	✓		✓			✓	✓
Niima Es-sakalia [9]	QL	✓						
Mirza Rayana Sanzana [7]	QL	✓			✓			
Simone Baldi [12]	QL				✓	✓		
Mohammad A. Hassanain [8]	MM		✓	✓		✓	✓	
Cheong Peng Au-Yong [3]	MM	✓	✓					✓
Azhar [1]	QL	✓	✓	✓			✓	
Angong, Macdayu [15]	QL	✓			✓			✓

Study design	Theme 1: Preventive maintenance
QN = Quantitative	7 sub-themes:
QL = Qualitative	PM01 = Schedule regular inspections and servicing
MM = Mixed-Method	PM02 = Routine cleaning of filters, coils and ducts
	PM03 = Lubrication of moving parts
	PM04 = Calibration of system controls
	PM05 = Examination of refrigerant levels and leaks
	PM06 = System upgrades and retrofits
	PM07 = Compliance and regulation

3.1.2 Corrective maintenance

The reviewed studies emphasized of effective corrective maintenance practices to promptly address system faults and breakdowns and restore the functionality of air conditioning systems in commercial buildings. Table 2 shows the results and findings of the data collected in corrective maintenance. Quickly addressing system faults and breakdowns [1,4,12,14] as it minimizes downtime and maintains the comfort levels of building occupants. By responding swiftly to issues, building managers can ensure that the air conditioning system remains operational, preventing disruptions to the indoor environment and occupant's well-being.

Repairing or replacing malfunctioning components [1-3,12,14,15] is a corrective strategy to restore the system's proper functioning. This may involve identifying and fixing damaged or worn-out parts, or completely replacing components that are beyond repair. Efficient component restoration and replacement helps to bring the air conditioning system back to its optimal operating condition.

Thorough troubleshooting to identify the root causes of issues [1,2,4,8,13] is a step in the corrective maintenance process. By conducting in-depth analyses to determine the underlying reasons for system malfunctions, maintenance teams can implement appropriate corrective actions to address the core problems. This systematic approach ensures that the system's functionality is fully restored and that the same issues do not recur in the future.

Implementing appropriate corrective actions to address the underlying problems and restore the system's functionality [2,4,8,13,15] is the final step in the corrective maintenance process. Based on the insights gained from the root cause analysis, maintenance teams can take the necessary measures to fix the system, such as replacing faulty components, recalibrating controls, or addressing any underlying issues. This holistic approach ensures that the air conditioning system is fully operational and ready to provide reliable performance.

Root cause analysis [8,13,15] and well-defined emergency response plans [2,3,9,13,15] further enhance the effectiveness of corrective maintenance practices. By thoroughly investigating the underlying causes of system failures and having a clear emergency response protocol in place, building managers can ensure that corrective actions are taken promptly and efficiently, minimizing the impact of system breakdowns on building occupants.

Effective corrective maintenance practices for promptly addressing system faults and breakdowns in commercial building air conditioning systems, minimizing downtime and maintaining occupant comfort and indoor environmental quality. The reviewed studies highlight the importance of swift response, thorough troubleshooting, root cause analysis and well-defined corrective actions to restore system functionality, with the support of emergency response plans and a systematic approach to identifying and resolving underlying issues. By implementing this comprehensive corrective maintenance strategy, building managers can ensure the reliable and efficient operation of air conditioning systems, ultimately enhancing the overall performance and sustainability of the building.

Table 2
The SLR findings on theme 2: Corrective maintenance

Authors	Main study design	Corrective maintenance					
		CM01	CM02	CM03	CM04	CM05	CM06
Fangzhou Guo [4]	QL	✓		✓	✓		
Tracie Magdeline [13]	MM			✓	✓	✓	✓
C. Nzukam [2]	QL		✓	✓	✓		✓
Niima Es-sakalia [9]	QL						✓
Mirza Rayana Sanzana [7]	QL	✓					
Simone Baldi [12]	QL	✓	✓				✓
Mohammad A. Hassanain [8]	MM			✓	✓	✓	
Cheong Peng Au-Yong [3]	MM		✓			✓	✓
Azhar [1]	QL	✓	✓	✓	✓		
Angong, Macdayu [15]	QL	✓	✓		✓	✓	

Study design	Theme 2: Corrective maintenance
QN = Quantitative	6 sub-themes:
QL = Qualitative	CM01 = Promptly address system faults and breakdowns
MM = Mixed-Method	CM02 = Repair or replace malfunctioning components
	CM03 = Conduct troubleshooting to identify root causes
	CM04 = Implement corrective actions to restore system functionality
	CM05 = Root cause analysis
	CM06 = Emergency response plan

3.1.3 Predictive maintenance

The reviewed studies highlight the potential benefits of adopting predictive maintenance strategies to enhance the overall performance and reliability of air conditioning systems in commercial buildings. These strategies aim to anticipate and address maintenance needs proactively, minimizing unexpected breakdowns and optimizing maintenance planning. Table 3 shows the results and findings of the data collected in predictive maintenance. Data analytics to predict equipment failures and anticipate maintenance needs [3,4,9,13,14] can help commercial building owners and facility managers plan and schedule maintenance activities more effectively. By leveraging data-driven predictive models, building managers can forecast when specific components or systems are likely to fail, enabling them to proactively schedule maintenance and replacement activities before

breakdowns occur. This strategic approach helps minimize unplanned downtime, optimize resource allocation and ensure the continuous operation of the air conditioning system.

Condition-based monitoring techniques [2-4,12,13,15] provide valuable insights into system performance and enable predictive maintenance decisions. By continuously monitoring the key performance indicators of the air conditioning system, such as temperature, humidity, energy consumption and vibration patterns, building managers can detect early signs of deterioration or impending failures. This real-time data can inform predictive maintenance strategies, allowing for targeted interventions and proactive maintenance scheduling to address issues before they escalate.

Thorough troubleshooting [2,7,8] and anticipating maintenance needs based on system performance trends [1,4,7,13,14] can lead to proactive maintenance strategies and improved system reliability. By conducting in-depth analyses to identify the root causes of system issues and monitoring performance trends over time, building managers can develop a deeper understanding of the system's behavior and potential failure modes. This knowledge enables them to implement tailored preventive and predictive maintenance actions, addressing the underlying causes of problems and anticipating future maintenance needs before they disrupt the system's operation.

Additionally, the integration of machine learning and artificial intelligence [7,9,13] as well as remote monitoring and diagnostics [2,4,7,9] can further enhance the predictive maintenance capabilities of commercial building owners and facility managers. Machine learning algorithms can analyze vast amounts of system data to identify complex patterns and anomalies, enabling more accurate failure predictions and optimal maintenance scheduling. Remote monitoring and diagnostics, on the other hand, allow building managers to continuously monitor the system's performance and receive real-time alerts, facilitating prompt response and proactive maintenance interventions.

These strategies, which leverage data analytics, condition-based monitoring, thorough troubleshooting and the integration of advanced technologies, enable commercial building owners and facility managers to anticipate maintenance needs, minimize unexpected breakdowns and optimize maintenance planning. By proactively addressing issues before they escalate, building managers can ensure the continuous operation of the air conditioning system, optimize resource allocation and improve overall system reliability. The integration of predictive maintenance approaches, combined with the latest advancements in data analysis, machine learning and remote monitoring, can empower commercial building stakeholders to adopt a more proactive and strategic approach to maintaining their critical HVAC infrastructure, ultimately enhancing building performance, energy efficiency and tenant satisfaction.

Table 3
The SLR findings on theme 3: Predictive maintenance

Authors	Main study design	Predictive maintenance					
		DM01	DM02	DM03	DM04	DM05	DM06
Fangzhou Guo [4]	QL	✓	✓		✓		✓
Tracie Magdeline [13]	MM	✓	✓		✓	✓	
C. Nzukam [2]	QL		✓	✓			✓
Niima Es-sakalia [9]	QL	✓	✓			✓	✓
Mirza Rayana Sanzana [7]	QL	✓		✓	✓	✓	✓
Simone Baldi [12]	QL		✓			✓	✓
Mohammad A. Hassanain [8]	MM			✓			
Cheong Peng Au-Yong [3]	MM	✓	✓				
Azhar [1]	QL				✓		
Angong, Macdayu [15]	QL	✓	✓				

Study design	Theme 3: Predictive maintenance
QN = Quantitative	6 sub-themes:
QL = Qualitative	DM01 = Utilize data analytics to predict equipment failures
MM = Mixed-Method	DM02 = Implement condition-based monitoring techniques
	DM03 = Conduct troubleshooting to identify root causes
	DM04 = Anticipate maintenance needs based on system performance trends
	DM05 = Machine learning and artificial intelligence
	DM06 = Remote monitoring and diagnostics

3.2 Interview Results and Discussion

Table 4 shows the results and findings of the data collected from the interview approach. Based on the provided responsibilities, it seems that the overall goal is to ensure the proper functioning and maintenance of the air conditioning systems in the facility. The key responsibilities include ensuring the air conditioning systems are operational and functioning properly at all times without fail, which involves daily checks, regular inspections and routine maintenance tasks such as cleaning, lubrication and minor adjustments to keep the air conditioning components (compressors, condensers, evaporators, ductwork, etc.) in good condition. Additionally, any problems or issues with the air conditioning systems should be promptly addressed and repaired to maintain the building's comfort and energy efficiency

Table 4
The findings of interview with experts in field

No.	Questions	Expert	Remarks
1.	Can you describe your role and responsibilities as a member of the maintenance team responsible for air conditioning systems in commercial buildings in Malaysia?	A	"…to make sure all facilities include air conditioning system under responsibilities operational and functioning at all time without fail…"
		B	"…to ensure the air conditioning system for the building premises is in good condition and working, to repair the air conditioning system unit if any problems occur and do a daily check on the air conditioning unit…"
		C	"…conducting scheduled inspections and routine checks on the air conditioning systems, including components such as compressors, condensers, evaporators, and ductwork and performing regular cleaning, lubrication, and minor adjustments to ensure the optimal functioning of the systems…"
2.	What tools or technologies do you rely on to effectively maintain air conditioning systems in commercial buildings?	A	"…leak Detectors. These specialized devices help determine the location of refrigerant leaks, which are a common cause of reduced system performance, wasted energy, and potential failure. By using leak detection equipment, we can quickly pinpoint the source of any refrigerant loss…"
		B	"…gauges and manifold sets as essential tools to maintain the efficiency of commercial air conditioning systems. These tools allow us to accurately measure refrigerant pressures and temperatures, which helps identify issues like leaks, blockages, or improper charge levels that impact cooling performance…."
		C	"…we use refrigerant recovery machines. These specialized machines allow technicians to safely remove and store refrigerant from the system during maintenance or repair work, preventing the release of harmful gases into the atmosphere and ensuring compliance with environmental regulations…"

3.	Can you share any specific preventive maintenance practices or routines that you recommend for prolonging the lifespan of air conditioning systems in commercial buildings?	A	"…establishing a regular preventive maintenance schedule, such as quarterly or semi-annual checkups. This scheduled maintenance routine should involve inspecting the system's key components, including cleaning or replacing air filters, checking refrigerant levels, cleaning condenser and evaporator coils, and inspecting electrical connections…."
		B	"…monitor compressors and fan motors for signs of wear, such as unusual noise or vibration. By proactively addressing any issues and performing routine maintenance tasks, including lubrication and cleaning, you can prevent failures and improve system performance…"
		C	"…regularly cleaning the condenser and evaporator coils. Dirty or clogged coils can significantly impact the system's efficiency and performance. So must use specialized coil cleaning chemicals and methods to thoroughly remove dirt, debris, and buildup from the coils on a regular basis. This proactive coil cleaning helps maintain the system's cooling capacity and energy efficiency, ultimately prolonging the lifespan of the air conditioner equipment…"
4.	How do you approach scheduling maintenance tasks for air conditioning systems in commercial buildings to minimize disruption to occupants while ensuring thorough upkeep?	A	"…to minimize disruption to building occupants, facility managers should leverage weekends and off-hours for scheduling major maintenance tasks for air conditioning systems in commercial buildings. Whenever possible, equipment overhauls, system shutdowns, and other major maintenance activities should be planned during periods of low occupancy, such as weekends or overnight hours. This approach can significantly reduce the impact on day-to-day business operations and help maintain a comfortable environment for occupants during normal working hours…"
		B	"…leveraging remote monitoring and control capabilities through building automation systems can be highly beneficial in minimizing disruption to occupants during air conditioning system maintenance in commercial buildings. By integrating these advanced systems, facility managers can remotely monitor the performance and status of air conditioning system equipment, allowing maintenance teams to diagnose and, in some cases, address issues without the need to physically access the building. This remote management approach significantly reduces the impact on occupants, as maintenance personnel can troubleshoot and resolve certain problems without directly interfering with the building's daily operations…"
		C	"…Coordinating with building occupants when scheduling maintenance tasks for air conditioning systems in commercial buildings. This involves proactively communicating the maintenance schedule with building managers and occupants well in advance, providing clear details on the planned activities and their expected impact on operations. Additionally, it is important to solicit feedback from occupants to understand peak usage periods, enabling the scheduling of maintenance tasks during low-occupancy times to minimize disruptions to their daily activities…"

HVAC technicians in Penang rely on a suite of specialized tools and technologies to effectively maintain the air conditioning systems in commercial buildings. Leak detectors help identify the location of refrigerant leaks, a common cause of reduced system efficiency and potential breakdowns, allowing technicians to promptly address the issue. Gauges and manifold sets enable them to accurately measure refrigerant pressures and temperatures, providing crucial data to diagnose problems like blockages or improper charge levels that impact cooling performance. Additionally, refrigerant recovery machines allow technicians to safely remove and store refrigerant

during maintenance, ensuring compliance with environmental regulations and promoting sustainable practices.

To prolong the lifespan of air conditioning systems in commercial buildings in Penang, the recommended preventive maintenance practices include establishing a regular preventive maintenance schedule, such as quarterly or semi-annual check-ups, which involve inspecting key components, cleaning or replacing air filters, checking refrigerant levels and cleaning condenser and evaporator coils. Regularly monitoring the compressors and fan motors for signs of wear, such as unusual noise or vibration, and promptly addressing any issues through lubrication and cleaning, can prevent failures and improve system performance. Additionally, thorough and frequent cleaning of the condenser and evaporator coils using specialized chemicals and methods is crucial, as dirty or clogged coils can significantly impact the system's efficiency and cooling capacity.

To minimize disruption to occupants while ensuring thorough upkeep of air conditioning systems in commercial buildings in Penang, facility managers employ a multi-faceted approach. Firstly, they leverage weekends and off-hours for scheduling major maintenance tasks, such as equipment overhauls and system shutdowns, to avoid impacting normal business operations. Secondly, they utilize remote monitoring and control capabilities through building automation systems, allowing maintenance teams to diagnose and address certain issues without physically accessing the building, further reducing the impact on occupants. Thirdly, they coordinate closely with building managers and occupants, communicating the maintenance schedule in advance and soliciting feedback to understand peak usage periods, enabling the scheduling of maintenance tasks during low-occupancy times. By adopting this comprehensive approach, facility managers can ensure the thorough upkeep of air conditioning systems while minimizing disruptions to the building's daily activities and occupants' comfort.

4. Conclusions

This systematic review has highlighted the aim of identifying the current strategies applied for the maintenance of air conditioning systems in commercial buildings in Penang. The researchers sought to explore the various maintenance approaches employed by building owners and facility managers to ensure the optimal performance and longevity of their air conditioning systems.

In response to this objective, maintenance teams have practiced several maintenance strategies. Based on the systematic reviews performed, the authors have identified three main types of maintenance: preventive, corrective and predictive maintenance. These three overarching maintenance approaches were further expanded into 19 sub-themes, each addressing specific aspects of air conditioning system upkeep.

The 19 sub-themes encompass a comprehensive range of maintenance practices. Preventive maintenance focuses on proactive measures to minimize the risk of system failures, such as scheduled inspections, periodic cleaning, component replacement and regular maintenance of critical parts like cooling towers and ductwork. Corrective maintenance, on the other hand, deals with fault diagnosis, emergency repairs and addressing issues as they arise, including refrigerant leaks, condensate drainage problems and coil cleaning. Predictive maintenance leverages advanced techniques like performance monitoring, thermographic inspections and vibration analysis to anticipate potential problems and schedule interventions before system failures occur, enabling a more proactive and cost-effective approach to maintenance.

The comprehensive implementation of these 19 maintenance strategies, tailored to the unique environmental and operational challenges faced in Malaysia's commercial buildings, ensure the optimal performance, energy efficiency and longevity of air conditioning systems. By adopting a

multi-faceted maintenance approach, building owners and facility managers can mitigate the impact of Penang's tropical climate, coastal location and other factors that can adversely affect air conditioning system performance and reliability.

In summary, the key responsibilities of air conditioning maintenance team in Malaysia are to ensure the proper functioning and maintenance of air conditioning systems in commercial buildings. This involves daily checks, regular inspections and routine maintenance tasks such as cleaning, lubrication and minor adjustments to keep the air conditioning components in good condition. Specialized tools and technologies, including leak detectors, gauges and refrigerant recovery machines, are utilized to effectively diagnose and address any issues with the systems. Preventive maintenance practices, such as quarterly or semi-annual checkups, are recommended to prolong the lifespan of the air conditioning systems. Facility managers also employ a multi-faceted approach to minimize disruption to occupants during maintenance, including scheduling major tasks during off-hours, utilizing remote monitoring and control capabilities and coordinating with building managers and occupants to understand peak usage periods.

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