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HVAC maintainability risks in healthcare facilities: a design optimization perspective

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Abstract

Purpose – Heating, ventilating, air-conditioning and cooling (HVAC) systems are crucial in daily health-care facility services. Design-related defects can lead to maintenance issues, causing service disruptions and cost overruns. These defects can be avoided if a link between the early design stages and maintenance feedback is established. This study aims to use experts' experience in HVAC maintenance in health-care facilities to list and evaluate the risk of each maintenance issue caused by a design defect, supported by the literature.

Design/methodology/approach – Following semistructured interviews with experts, 41 maintenance issues were identified as the most encountered issues. Subsequently, a survey was conducted in which 44 participants evaluated the probability and impact of each design-caused issue.

Findings – Chillers were identified as the HVAC components most prone to design defects and cost impact. However, air distribution ducts and air handling units are the most critical HVAC components for maintaining healthy conditions inside health-care facilities.

Research limitations/implications – The unavailability of comprehensive data on the cost impacts of all design-related defects from multiple health-care facilities limits the ability of HVAC designers to furnish case studies and quantitative approaches.

Originality/value – This study helps HVAC designers acquire prior knowledge of decisions that may have led to unnecessary and avoidable maintenance. These design-related maintenance issues may cause unfavorable health and cost consequences.

Keywords Facility management, Maintenance, Health-care facilities, Design defects, HVAC design, Health care, Building life cycle, Air-conditioning, Design for quality

Paper type Research paper

Introduction

Health-care facilities include multiple building service systems that are key to their operation. Heating, ventilating, air-conditioning and cooling (HVAC) systems maintain are

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responsible for indoor air quality (IAQ) as well as pollutant exposure. HVAC is the most demanding system for surgical and health-care services (Balaras *et al.*, 2007; Joppolo and Romano, 2017). Its maintenance is vital for the provision of services in health-care facilities. During COVID-19 pandemic, the HVAC performance played a crucial role in controlling airborne viral transmission within health-care facilities (Marr and Gleba, 2022). Moreover, during COVID-19, some HVAC challenges were encountered, which may cause re-evaluation in some engineering design specifications, especially ventilation systems (Marr and Gleba, 2022). Besides *Legionella*, pathogens that cause serious health issues such as, *Staphylococcus aureus* and *Aspergillus*, may occur due to HVAC systems performance (Sánchez-Barroso and Sanz-Calcedo, 2019). Consequently, HVAC systems are the primary source of hospital-caused infections in health-care facilities (Faure *et al.*, 2002). This finding indicates the criticality of HVAC performance in health-care facilities, particularly in susceptible sections, such as operating rooms. Hospital-acquired infections are the fourth leading cause of death in the USA and can be prevented by optimizing HVAC engineering designs (Balaras *et al.*, 2007).

Life-cycle costs of health-care facilities involves various parameters, including the correctness of design, accuracy of construction and proper maintenance. For HVAC systems, these parameters may increase or decrease the cost of operating a health-care facility. However, design decisions from the outset are vital to avoid future maintenance problems. Design decisions are considered the primary source of maintenance issues (Al-Hammad *et al.*, 1997; Mohammed and Hassanain, 2010) and inherent risks (de Silva and Ranasinghe, 2010a). A prudent approach would suggest optimizing the design-stage decisions for minimizing maintenance issues. Maintenance issues are considered maintainability risks that can be identified by addressing their causes (De Silva *et al.*, 2008, 2012). Therefore, if maintainability hazards are eliminated initially, the total maintainability of health-care facilities can be enhanced.

Health-care facility management participation in hospital design is crucial for improving maintainability and preventing health-care-associated infections (Njuangang *et al.*, 2018). The lessons learned from health-care facility management professionals regarding typical design-related issues can contribute to alerting designers. Using the expertise of facility managers in maintenance is an approach to enhance the maintainability of designs (Lavy and Shohet, 2009; Mohammed and Hassanain, 2010). This need for involvement has become more critical because health-care facilities are complex and maintaining and operating them is a challenge (Lavy and Shohet, 2009). This study aims to list and evaluate most commonly observed HVAC maintenance issues in health-care facilities. These maintenance issues represent design defects that trigger the maintenance of souring issues. Therefore, these design defects pose maintenance risks.

This study supports the minimization of these risks, which can allow designers to envision maintenance issues and the impacts and causes of their decisions based on real-life experience. Therefore, this research helps to bridge the gap between HVAC design and maintenance, which can achieve an optimum maintenance-friendly HVAC design in health-care facilities. By analyzing the influence level of different risks, designers can prioritize their efforts to address (Kim *et al.*, 2014) critical areas of concern. For example, if a specific risk has a high influence on design defects, it may require more rigorous testing or quality control measures during the manufacturing process. The importance of this research is considerable to the industry since it compiles enormous maintenance issues, formulate the feedback of experienced facility managers and establishes the link between facility management and design teams in an attempt of improving HVAC maintainability in health-care facilities (Figure 1).

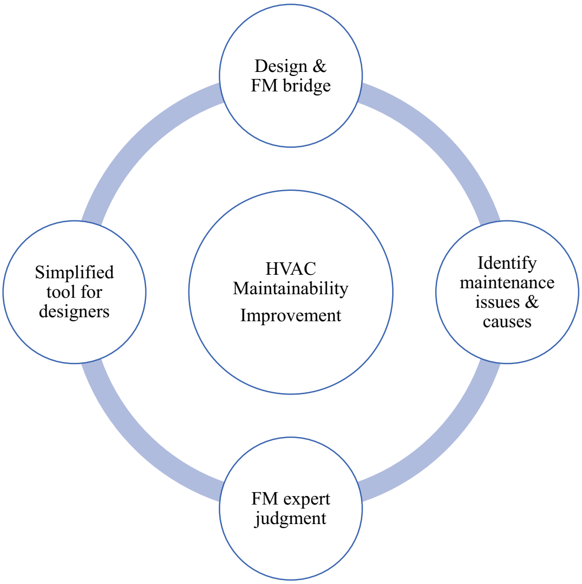

Figure 1.
HVAC maintainability research association with the industry

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Literature review

HVAC maintenance has been addressed in several previous studies. Some studies have been conducted on maintenance related to energy and thermal comfort simulations to address faults (Alavi and Forcada, 2022; Yan *et al.*, 2017). Fault detection and diagnosis systems are continuously growing that require knowledge of HVAC system behavior which is obtained through either expert knowledge or quantitative models (Haves, 1997). The nuanced difference between the abovementioned research and this paper is collecting maintenance issues from the point of operation stage and for a whole system experience.

Some research might focus on a specific fault and conduct a particular methodology to propose improvements. Besides, there is research on HVAC selection methods when system alternatives are proposed based on quantitative approaches and case studies to best address decision-makers' preferences (Kim *et al.*, 2014). Some studies have combined approaches in which HAVC experts provide inputs for the weights used in the analysis and ranking (Wang *et al.*, 2009). Other studies have focused on quantitative approaches (Avgelis and Papadopoulos, 2009; Korolija *et al.*, 2009). It is observed that quantitative approaches tend to investigate faults comprehensively, which limit an overall study of HVAC system collectively.

Furthermore, occupant satisfaction in buildings is an active research domain and there are studies on the impact of HVAC systems on certain types of buildings. (Au-Yong *et al.*, 2014) investigated the maintenance attributes of HVAC systems in office buildings. They sought to present the relationship between these attributes and occupant satisfaction. This type of study gives more importance to observing the planning and operations of maintenance rather than the design defects triggering maintenance. (Lee *et al.*, 2020) used occupant feedback on their satisfaction to build simulation models for personalized thermal preference models to improve occupant satisfaction and energy efficiency. They stated that this was achieved by optimizing the HVAC operation based on occupants' feedback. After reviewing similar studies (Albuainain *et al.*, 2021; Zhang *et al.*, 2018), the authors observed that occupants might be oblivious to maintenance issues in a facility. Besides, certain studies have investigated building performance evaluation and postoccupancy evaluation, which addressed HVAC systems in health-care facilities (Brambilla and Capolongo, 2019; Dilrukshi *et al.*, 2014; Forouharmajd *et al.*, 2012). However, these studies are limited and mainly focus on certain HVAC performance elements such as noise. These approaches need to inform further on the causes of maintenance issues sufficiently. Although use experience is a trigger point, the overall system maintainability needs a maintenance eye to address the potential failures, their magnitude, maintenance cost and health impact.

In alignment with Chew Yit Lin (2010), who investigated HVAC maintainability in commercial buildings, five components of HVAC systems have been defined as the initial stage of literature review under which most defects are present. These components align with the commonly used HVAC systems, especially in the area where the questionnaire was conducted. Most practitioners incline to generalize the HVAC variations and address the essential systems, which this paper made sure to include. In health-care facilities, chillers are the most used system in the area this research was conducted. Namely, cooling health-care facilities need, in most applications, to adopt chillers machines. The chillers remove, pressurize and regulate the temperature of a circulating liquid, which transfers heat from the inner parts of facilities via heat exchangers or coils. Heat exchange occurs in the air handling units (AHUs) or fan coil units (FCUs), which alter the facility's air temperature. Moreover, other components of such HVAC systems are crucial, such as air distribution and terminal systems (Figure 2).

Studies exist which address HVAC design, modeling and maintenance; however, HVAC maintenance issues caused solely by designers in health-care facilities require further study. An optimum HVAC system for health-care facilities requires higher standards and requirements than those of other types of buildings (Moscato *et al.*, 2017). Table 1 lists several studies on HVAC system maintenance in various buildings. After carefully reviewing relevant papers, the authors listed only the relevant to the nature of this paper in Table 1. That being said, not all these ten papers fall on the same path. However, they all listed several HVAC-related issues that could have been avoided earlier in the design stage. They vary in the focus, tools and feedback to design. However, there is insufficient research

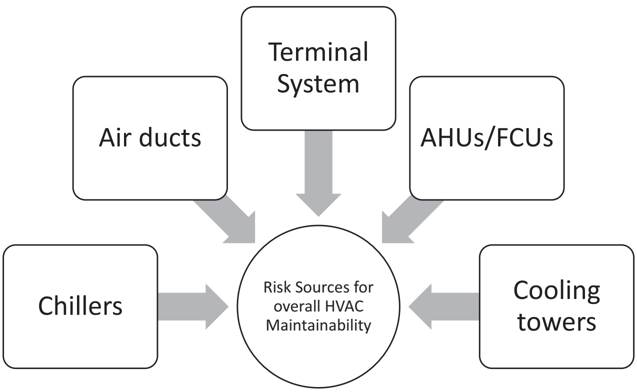

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Figure 2. Risk sources for overall HVAC maintainability

Table 1. Related research on HVAC maintainability

Research	Primary investigation	No. of issues investigated	Output	Defects ranking analysis
Hassanain *et al.* (2014)	– HVAC maintenance in 13 public Saudi Arabian universities. – Design decisions and maintenance issues. – Lack of communication and feedback from maintenance to design teams	12 HVAC maintenance defects	– A list of maintenance issues – Developed three sets of validated design stage maintainability guidelines, at 30%, 60% and 90% design completion stages	Relative importance index (RII)
Chew Yit Lin (2010)	– Design, construction and maintenance-related issues affecting commercial buildings' maintenance costs	39 HVAC defects	A list of HVAC defects and FMECA-based criticality weights	Weights for each defect were calculated using a modified failure mode effects and criticality analysis (FMECA)
Chew (2016)	– Integration of buildings' maintainability with green facility management approaches	39 HVAC maintenance issue	A list of HVAC defects and FMECA-based criticality weights	Weights for each defect were calculated using FMECA
Chew *et al.* (2018)	– Visual inspection of HVAC defects in buildings	19 HVAC maintenance issue	A list of HVAC maintenance issues supported by design-stage guidelines for design, construction and maintenance	
Arroyo *et al.* (2016)	– Choosing by advantage (CBA) as a method to improve HVAC design decisions – Optimization of HVAC's LCC by building a communication and decision framework between all stakeholders, including the maintenance team	7 HVAC design factors to apply through CBA	A framework of CBA methodology for selection of HVAC for a museum	CBA

(*continued*)

Table 1.

Research	Primary investigation	No. of issues investigated	Output	Defects ranking analysis
Hassanain and Harkness (2000)	– Design guidelines for fresh air system replacement based on a case study	27 Design factors	27 design factors with explanations for the design team	
Balaras *et al.* (2007)	– HVAC indoor environmental conditions for operating rooms	6 Design components representing indoor conditions	Design guidelines	
Thiel and Mroz (2001)	– HVAC selection method for museums based on the decision-maker's performance preferences		A selected system	Multiple criteria decision-making (MCDM)
Wang *et al.* (2009a)	– Selecting an optimal HVAC system using a fuzzy multicriteria evaluation model to	16 Criteria	A selected system	Fuzzy analytic hierarchy process (AHP) and TOPSIS
Chinese *et al.* (2011)	– Selecting a heating system for an industrial facility using an AHP approach	9 Criteria		AHP

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on HVAC design-related maintenance issues that can be used to optimize the HVAC design stage in health-care facilities, considering commonly encountered maintenance issues in practice as the trigger.

Research methodology

This research aims to list and identify the HVAC maintenance risks. The statistical analysis represents the relative importance index (RII) method based on the HVAC expert judgments. Therefore, the methodology consists of five sequence steps as; collect data to define all HVAC maintenance risks of HVAC from literature; evaluate the collected risks by conducting a semistructure interview with experts; implement survey to measure degree influence of the maintenance risks using five points Likert scale; examine the reliability of the survey data by determining Cronbach's alpha; and identify and rank the significant risks based on risk impact (RI). The methodology flow chart is shown in Figure 3.

Collect data

The literature review aimed to gather and identify relevant and accurate information about potential maintenance defects associated with HVAC systems. This focus on maintenance

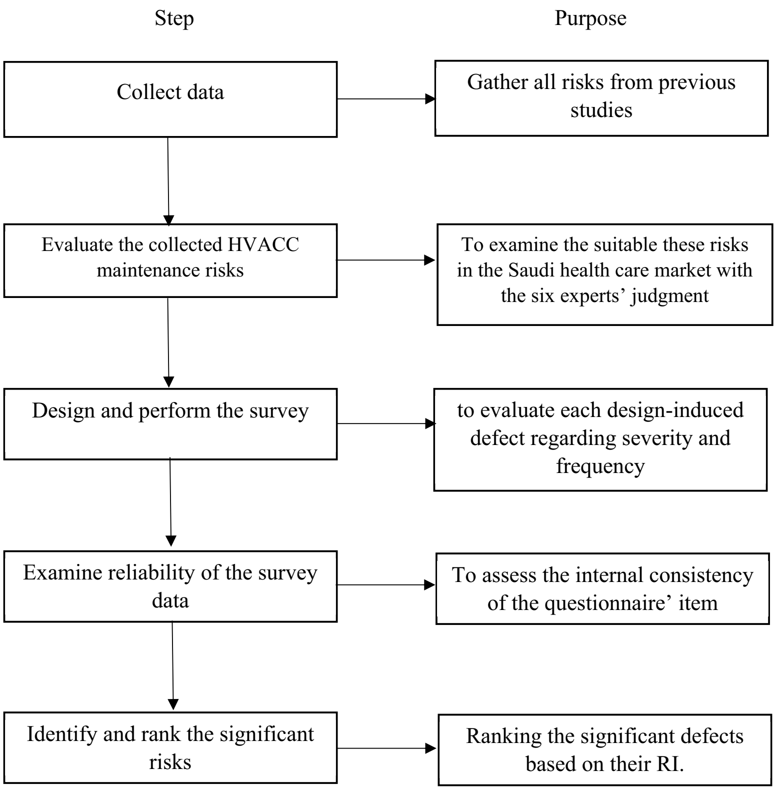

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Figure 3. Research methodology steps for HVAC maintainability optimization using experts' knowledge

defects is particularly relevant in health-care facilities due to their connection to design-related defects. These defects were grouped according to Chew (2016) and Chew Yit Lin (2010) for a better enumeration of various defects. As a part of the literature review, a Boolean search string was used to explore pertinent research on the databases such as Google Scholar, ScienceDirect and Scopus. This string was «Design Issues» OR «design Errors» OR «Design Mistakes» AND «Faulty Design» OR «Design Errors» AND «Maintenance Issues» OR «Costly Maintenance» OR «Design Caused Maintenance» AND «Design Optimization» OR «Design Improvement. Besides, several other databases were used to investigate the literature, such as ASCE, and publishers search engines such as, Emerald and Elsevier. The results contained a variety in relevant research which was sorted carefully to include substantial input of maintenance issues faced in the operation stage and design optimization approaches, as shown in Table 1.

Evaluate the collected heating, ventilating, air-conditioning and cooling maintenance risks

The initial assessment of the collected health facilities risks from the literature review was initially assessed by experts to examine the suitability of these risks in the Saudi health-care market. The semistructured interviews were conducted with a representative HVAC maintenance specialist group. With every expert, more than 45 HVAC maintainability risks were explored. During the interviews, each topic was covered in relation to two key components: the degree to which a problem developed by design and its significance in health care. The responses from the six participants that were chosen had several anomalies. During the interviews, the findings from every participant were cross-checked to prevent bias or inconsistencies. Consequently, a final list of 41 defects – which most respondents felt were maintenance concerns resulting from design decisions – was produced. Professionals with a track record of success managing health-care facilities made up the targeted interview pool. Maintenance experience was a requirement because some experts might not have worked directly with HVAC systems. At least 15 years of experience was required of the interviewers, regardless of whether they worked in a public or private health-care facility. The authors synthesized the interviews' feedback into this paper's defects list, causes and implications. The main aspects investigated in the interviews were the severity, frequency of occurrence and causes of each maintenance issue. The causes (risks) were classified into four groups: internal environment, AHU and FCU, air distribution and terminal systems, chillers and cooling tower. The number of causes for these groups was 10, 9, 7 and 15 causes, respectively, as shown in Table 2.

Perform survey to measure degree influence of the maintenance risks

After the assignment of HVAC maintenance risks through semistructured interviews, a questionnaire was designed and shared with Saudi Arabian facility management experts. The questionnaire asked the experts to evaluate each design-induced defect that triggered a maintenance issue. The evaluation addressed the severity and frequency of occurrence based on a five-point Likert scale. Convenience sampling, a nonprobability selection strategy, was used in this questionnaire to choose a sample of respondents from a population based on how easily accessible the data sources are. Failure mode, effects and criticality analysis (FMECA) was used to generate the interviewees' judgments by considering their viewpoints. More than ten years of work experience in a public or private health-care facility was a prerequisite for the selected specialists. Each respondent was required to reveal if they had experience working in HVAC in health care facilities.

Table 2. Possible causes for maintenance issues caused by design defects

System component	Defect SN	Maintenance issue	Possible causes
Internal environment	1	Insufficient cooling level	Thermostat insensitivity owing to wrong location Improper selection of cooling coil valves Sensors are not recalibrated at regular intervals. It may be owing to poor accessibility or poor maintenance practices
	2	Fungal growth and stains on walls	Moisture entry from the fresh air inlet Infiltration of external warm air – short circuiting Moisture carry-over from cooling coil
	3	Noticeable noise from machines rooms	Location of AHU plant room within occupancy space Improper selection of the low-static FCU fan type Poor acoustical insulation of the mechanical room
	4	Users' dissatisfaction or discomfort	Air from the cooling tower gets sucked by air intakes. It may cause legionella infection Mold growth in return air plenum Dumping of cold air or malfunction of VAV terminal/FCU
	5	Hygiene risk of infections or sick building syndrome (SBS)	When air intake sucks air from a cooling tower, legionella infection may be caused Mold growth in the return air plenum Cold air dumping at users or malfunction of VAV terminal/FCU
	6	Foul smell	Lack or inefficiency of exhaust fans, especially in the toilets and kitchen
	7	Thermal discomfort	Temperature instability resulting from the inadequacy of the HVAC system
	8	Static electricity	Insufficient humidification of outside air coming inside the facility
	9	Noise or pollution threat from maintenance crews' movement across corridors	Several nonadjacent HVAC technical rooms will result in more trips between them Location selected for machinery rooms is ill-advised and very close to the patients' area Insufficient acoustical insulation for machinery rooms
	10	Limited HVAC control over some unoccupied spots	Some unoccupied locations have a full operating mode
Air handling unit (AHU) and fan coil unit (FCU)	11	Fan motor noise	Improper selection of the low-static FCU fan type Inadequate, fatigued, or rusty vibration isolation

(*continued*)

System component	Defect SN	Maintenance issue	Possible causes
	12	Corrosion/scaling of cooling coils	Selection of coils and coats, especially in harsh weather locations A large volume of fresh water is added to refill substantial leaks and the different minerals piles of the coils The housing is not designed to be adequately sealed, which allows continuous contact with moist air and dampness
	13	Buildup or dust on coils affecting airflow	Insufficient or lack of cleaning because of the poor accessibility for maintenance Improper filter selection or sizing in the design
	14	Water leakage	Condensate pan material's poor selection, especially when the material is corrosion-resistant but with low-quality considerations Fine dust accumulations may block fins Poor accessibility to clean tubes
	15	Water retention and buildup on the drain pan	Undersized drain trap Drain-off pipe damage because of insufficient pipe fittings design
	16	Condensation on the exterior of components	Poor specifications for the casing of the AHU/FCU, which provides insufficient insulation
	17	Air filter clogging causes air pressure drops	Mostly occur when the inlets are located nearby an exhaust outlet or a pollution source such as cooling towers and parking lots Poor accessibility for maintenance which causes inadequate cleaning for filters or late replacements When the pressure gauge location is at an inaccessible location or hidden, which inhibits adequate maintenance and calibration BMS-linked differential pressure (DP) is not added to AHU, which limits real-time monitoring
	18	Poor maintenance accessibility	Crowded layout of piping and ducting around AHU/FCU AHU/FCU location at very high levels Existence of structural obstructions that impede the accessibility Insufficient or wrong access panels that lead to the above-ceiling AHU/FCU
	19	Control valves not closing appropriately	Improper selection of balancing valves of coils

(*continued*)

Table 2.

System component	Defect SN	Maintenance issue	Possible causes
Air distribution and terminal systems	20	Condensation on air conduits and their components	Inadequate insulation The diffuser's location is near an external air infiltration into the facility or near entry areas Lack of proper recalibration of sensors because of accessibility challenges
	21	Air leakage	Flanged joints are subject to air leakages because of their quality, material selection or sizing Avoidance of flexible duct connectors
	22	Corrosion	Rainwater-related moisture is transported from the fresh air into the ducts Especially in coastal areas, the wet exhaust inability to drain out the moisture Especially in coastal areas, AHU-related moisture carry-over into supply air ducts The lack of a heating coil may increase the chances of corrosion occurrences
	23	Dirt and stains on ducts	Inadequate or lack of cleaning of ducts because of poor accessibility for maintenance
	24	Noisy airflow	Turbulence occurrence because of under-sized ducts Air movement in the ducting system is not balanced Rapid air movement in the duct system because of insufficient or undersized diffusers Improper allocation of VAV dampers controls Unavailability of sound attenuator
	25	Dumping of cold air or poor air balance	Short-circuiting occurrence causing air to return before it is circulated. This case occurs if a diffuser location is near return air grilles Blockage of furniture, false ceiling, or equipment for diffusers Dirt accumulation because of maintenance inaccessibility Poor selection of diffusers and their layout, which aim cold air directly at users, especially in patient rooms
	26	Pneumatic controls inefficiency	Air compressor failure, especially the open type Lack of redundant systems since this system is obsolete and needs frequent maintenance

Table 2.

(*continued*)

System component	Defect SN	Maintenance issue	Possible causes
Chillers	27	Condenser scaling	The use of the open-loop design of condenser water, mainly in a large application
	28	Corrosion of inside parts of condenser; face plate and tubes	The tubing material is not resistant to all forms of corrosion Unaccounted factors of harsh conditions of dust, temperature and humidity
	29	Refrigerant leakage	Unavailability of the refrigerant leakage detection system
	30	Refrigerant contamination	Moisture occurrence around refrigerant because of leakages of condenser tubes Air and moisture leak into the chiller, which necessitates purging Improper selection of refrigerant, which may allow for mixing of metallic moving parts of compressor motor or lubricant
	31	Leakage from coils (Fins)	Fins become blocked with dust which is mainly a location issue
	32	Surging of the chiller	Operating the chiller under its load capacity lower than 25% of its handling capacity. The type of chillers may vary; thus, the effect of this cause varies Condenser pressure because of corroded tubes that may cause surging Non-condensable matter increases in the refrigerant, caused by either leakage in the evaporator or periodic purging. This noted for subatmospheric refrigerants
	33	Noise and noticeable vibration	Damaged or insufficient spring isolators Poor acoustical insulation around the machine's locations and mechanical rooms Compressor aging because of continuous running or repeated start-stop.
	34	Poor access to maintenance	Insufficient access for system components for maintenance and replacement Limited space for routine maintenance around machines and parts, especially in mechanical rooms
	35	Condensation on chilled water pipes	Inadequate insulation causes the pipes to get cold
	36	Water is coming out from monitoring devices	Remotely installed, which makes it difficult to fit perfectly due to the accessibility challenge

(*continued*)

Table 2.

System component	Defect SN	Maintenance issue	Possible causes
Cooling tower	37	Biofouling	Occurs when the cooling tower is not perfectly designed to prevent dirt accumulation and stagnation. This consideration is more critical when treated water is used for cooling
	38	Corroded body and components	The materials of cooling tower components, such as louver and collection basin, are not corrosion resistant
	39	Condenser water foaming	Cleaning challenges because of inaccessibility to all parts
	40	Inadequate heat rejection	Obstruction of structures around, above or inside the cooling tower The cooling tower is located near heat exhausts allowing for short-circuiting Over supplying or undersupplying of condenser water pump, in which the flow rate is too high to reject heat perfectly
	41	Poor access to maintenance or replacement	Improper consideration for maintenance accessibility in the design

Table 2.

Source: Created by the authors

Examine reliability of the survey data

Reliability analysis in questionnaire data assesses the internal consistency or reliability of the measures or items used in the questionnaire. The reliability analysis ensures that the responses obtained from participants are reliable and can be trusted to make accurate interpretations and draw valid conclusions. The reliability test was performed based on Cronbach's alpha. Cronbach's alpha is a test reliability evaluation technique used when using Likert-type scales to ensure internal consistency and reliability (Gliem and Gliem, 2003):

$$\alpha = (\mathrm{k} \div (\mathrm{k} - 1)) \times \left(1 - \left(\left(\sum_{i=1}^{k} \sigma_i^2\right) \div \sigma_X^2\right)\right) \tag{1}$$

where k is the number of test items, σ_i^2 i is the variance of a single test item X_i and σ_X^2 is the variance of the overall test items X. This research considered addressing design defects as maintainability risks, following earlier maintainability studies. These studies considered maintainability risks in several methodologies to identify, evaluate or rank design defects (Chew *et al.*, 2006; De Silva *et al.*, 2008, 2016; de Silva and Ranasinghe, 2010b; Sulaiman *et al.*, 2013). In previous maintainability risk studies, expert knowledge was acquired to assign risk values to the detected design defects (De Silva *et al.*, 2016). In construction projects, risk assessment methodologies primarily depend on defining the probability and impact values of risks based on judgment (Yildiz *et al.*, 2014).

Identify and rank the significant risks

Identifying and classifying the significant defects of HVAC maintenance problems enables decision-makers to identify and focus on the most severe risks that require immediate attention and mitigation efforts. Therefore, the appropriate method is using descriptive statistics that measure the pooled scores' central tendency and variance for each maintenance defect's probability and impact. The RII method allows for a quantitative comparison of factors. Researchers can objectively evaluate and rank the relative importance of different factors by assigning numerical values to each factor.

Some studies sought to evaluate the probability and impact of addressing risk values estimated by experts (A. Kassem *et al.*, 2020; Mahamid *et al.*, 2015), other studies adopted the RII in risk assessment, as in Kassem's (2022) work that evaluates the RII based on a survey and reflects the RII value on a probability–impact matrix. The PMI (2021) indicates that the multiplication of probability by a monetary value of the impact yields the expected value of an outcome. Accordingly, the authors attempted to use the RI for all the defects within a single HVAC component. Although the impact is presented in this study as a value suggested by experts on a five-point Likert scale, it represents their perception of the monetary impact it can cause directly and indirectly. The RI can be interpreted to differentiate among other components if the causes of the defects compiled in this study are not mutually exclusive. Therefore, the RII was used in this paper to calculate the probability and impact of each maintenance defect. Then, the RI of each defect was determined by multiplying the RII of the probability of an occurrence of a risk event (P) and the RII of impact (I), as shown in equation (2). (Cox, 2008; El-Sayegh *et al.*, 2018; Mills, 2001). The maintenance defects were ranked based on the RI values:

$$RI = P \times I \tag{2}$$

Results

The questionnaire targeted professionals with experience in the maintenance of health-care facilities. Of all facility management professionals invited to participate, 44 attempted to participate (Table 3). Only four participants missed the questionnaire questions, which was accounted for in the analysis of the survey results. Facility managers and maintenance professionals were the most common participants because of the nature of the questionnaire. Most participants were mechanical engineers, with a percentage of 75%. The participants had diplomas (2%), bachelor's (68%), master's (21%) and doctorate (9%). In addition, the participants' experience was more than 10 years, with 25% having more than 20 years of experience.

The questionnaire results were examined to determine each Likert scale item's weighted mean, RII and standard deviation (SD). Table 4 presents the respondents' evaluations of each design defect in terms of their probability of occurrence and severity. The Likert scale contained 5 system components and 41 design-related defects that triggered maintenance issues. The mean five-point evaluation for each maintainability issue shapes the weight given to address either the seriousness or the frequency of occurrences. RI combines those two weights as a single risk measure. The overall results show compactness, which implies a level of agreement among the respondents. Consistent results provide more confidence in the results that represent the judgments of multiple experts.

HVAC system components, such as chillers, can have design defects of varying severities. This design defects might provide equivocal interpretations if ranking systems are attempted instead of each design defect. Regardless of the overall HVAC component, the ranking of defects can be more indicative. However, the RI value is the total risk value that can be combined with other risk values of defects related to the same HVAC component. The RI for defects within a single HVAC component can be interpreted as the total risk undertaken for the entire system component.

Table 3. Demographic characteristic analysis

Criteria	No. of respondents	%
Experience		
Less than 5 years		
10–20 years	33	75
More than 20 years	11	25
Education		
Diploma	1	2
Bachelor	30	68
Masters	9	20
Doctorate	4	9
Other	0	0
Discipline		
Civil engineering	5	11
Mechanical engineering	33	75
Electrical engineering	3	7
Architecture	3	7
Others	0	0
Role		
Owner representative	12	27
Maintenance contractor	13	30
Inspection or third auditing party	10	23
Other	9	20

Source: Created by the authors

The Cronbach's alpha was used to evaluate the reliability of the survey results. Values over 0.7 indicate that the results are reliable and consistent (Kassem, 2022) (Table 5). Table 5 displays the reliability test for each component and overall constructs separated by probability and impact. The results revealed that Cronbach's alpha of the four groups ranged from 0.70 to 0.884 for probability ranging from 0.705 to 0.973 for seriousness (impact), as shown in Table 5. Therefore, the results are reliable and consistent for the four groups. Based on RI, all defects were ranked. Ranking helps to prioritize defects that require higher recognition. It does not only rely on the severity of the impact of a design-caused defect on maintenance, but also synthesizes the concept of the frequency of this particular defect.

Discussion

In this study, 41 design defects were evaluated by the experts. Table 4 presents the statistical analysis of each design defect. RI indicates the risk value that any designer of new health-care facilities should consider. According to experts, the most critical design defect is the occurrence of buildup or dust on coils in the HVAC components of AHUs and FCUs. This impact affects airflow in which maintenance interventions are required. The criticality of this defect is based on the probability of its occurrence and impact. The RII for both probability and impact was the same at 0.697. Nonetheless, the impact of this defect has shown a higher evaluation, and the weighted mean of probability and impact are marginally different at 3.40 and 3.487, respectively. The contributing experts stated that a defect having highest probability of all the problems does not necessarily suggest that its impact is the worst.

Dust buildup on coils creates a layer of insulation, reducing the heat transfer efficiency of the coils. This defect can decrease the HVAC system's cooling or heating capacity. As a

System component	Defect SN	Probability Mean	Probability RII	Probability SD	Impact Mean	Impact RII	Impact SD	RI	Rank
Internal environment	1	3.14	0.628	2.26	2.975	0.595	2.00	9.340	27
	2	2.88	0.577	1.89	2.975	0.595	2.01	8.579	31
	3	3.09	0.619	2.11	3.575	0.715	2.42	11.058	6
	4	2.84	0.567	1.70	3.300	0.660	2.46	9.363	26
	5	3.09	0.619	2.04	3.350	0.670	2.14	10.362	13
	6	2.95	0.591	2.39	3.150	0.630	2.23	9.303	28
	7	2.79	0.558	1.67	2.900	0.580	1.53	8.093	37
	8	2.65	0.530	2.28	3.125	0.625	2.38	8.285	35
	9	2.51	0.502	1.72	2.538	0.508	1.99	6.376	41
	10	2.88	0.577	2.03	2.769	0.554	2.03	7.986	39
Air handling unit (AHU) and fan coil unit (FCU)	11	3.32	0.664	2.56	3.333	0.667	2.42	11.061	5
	12	3.33	0.665	2.60	3.282	0.656	2.04	10.915	7
	13	3.40	0.679	2.84	3.487	0.697	2.37	11.840	1
	14	3.02	0.605	2.08	3.333	0.667	2.34	10.078	16
	15	3.16	0.633	2.41	3.154	0.631	2.38	9.975	19
	16	2.93	0.586	2.30	2.974	0.595	2.00	8.716	30
	17	3.35	0.670	2.62	3.256	0.651	2.53	10.905	8
	18	3.00	0.600	1.94	2.769	0.554	2.38	8.308	34
	19	2.86	0.572	1.51	3.282	0.656	2.37	9.388	24
Air distribution and terminal systems	20	3.19	0.637	2.09	3.333	0.667	2.42	10.620	10
	21	3.23	0.647	1.84	3.615	0.723	2.47	11.687	2
	22	3.21	0.642	2.61	3.385	0.677	2.81	10.862	9
	23	3.33	0.665	2.30	3.128	0.626	2.44	10.403	12
	24	3.30	0.660	2.49	3.205	0.641	2.20	10.584	11
	25	3.19	0.637	1.61	3.154	0.631	2.10	10.048	17
	26	3.07	0.614	1.73	3.333	0.667	2.25	10.233	14
Chillers	27	3.33	0.665	2.31	3.333	0.667	2.43	11.085	4
	28	3.02	0.605	2.16	3.359	0.672	2.64	10.155	15
	29	3.12	0.623	2.03	3.205	0.641	2.62	9.988	18
	30	2.77	0.553	2.08	3.385	0.677	2.76	9.367	25
	31	2.72	0.544	1.76	3.128	0.626	2.71	8.512	33
	32	2.74	0.549	1.74	3.359	0.672	2.28	9.218	29
	33	2.93	0.586	2.23	3.385	0.677	2.63	9.918	20
	34	2.84	0.567	2.35	3.000	0.600	2.10	8.512	32
	35	2.60	0.521	1.78	3.128	0.626	2.27	8.148	36
	36	2.47	0.493	1.87	3.026	0.605	2.25	7.459	40
Cooling tower	37	3.09	0.619	2.02	3.179	0.636	2.50	9.834	21
	38	3.19	0.637	2.22	3.564	0.713	2.43	11.355	3
	39	3.09	0.619	2.36	3.179	0.636	2.66	9.834	21
	40	2.84	0.567	1.84	3.385	0.677	2.46	9.603	23
	41	2.74	0.549	2.28	2.925	0.585	2.11	8.027	38

Source: Created by the authors

Table 4. Statistical analysis of maintenance issues risks

result, the system may need to work harder and consume more energy to achieve the desired temperature, leading to increased energy costs. In addition, the presence of dust buildup on coils necessitates more frequent maintenance interventions. HVAC technicians may need to schedule regular cleaning and inspections of coils to prevent excessive buildup and maintain optimal system performance. This process increases maintenance personnel's workload and can impact maintenance budgets. To mitigate the implications of dust buildup on coils, HVAC maintenance practices should include regular inspection and cleaning of coils.

Table 5.
Reliability statistics

S.no.		Component groups	No. of defects	Cronbach's alpha
1	Probability	Internal environment	10	0.70
2		Air handling unit (AHU) and fan coil unit (FCU)	8	0.805
3		Air distribution and terminal systems	8	0.884
4		Chillers	10	0.880
5		Cooling tower	5	0.732
6	Impact	Internal environment	10	0.741
7		Air handling unit (AHU) and fan coil unit (FCU)	8	0.822
8		Air distribution and terminal systems	8	0.825
9		Chillers	10	0.876
10		Cooling tower	5	0.705
11	All constructs		82	0.973

Source: Created by the authors

These practices can involve using appropriate cleaning methods and materials to remove dust and debris effectively. In addition, implementing proper air filtration systems and regular replacement of air filters can help reduce the amount of dust entering the HVAC system and accumulating on the coils. By addressing dust buildup promptly and adopting preventive maintenance measures, the HVAC system can operate efficiently, maintain good air quality and minimize the risk of costly repairs or replacements.

The RII of the impact value of air leakage in the air distribution and terminal systems was evaluated as 0.723, a weighted mean of 3.615. This result is the highest impact of all design defects in the study. The implication of this finding coincides with the findings that signify airflow and distribution as a highly critical item to combat COVID-19 in health-care facilities (Marr and Gleba, 2022). Controlling infection within hospital sections depends highly on the tightness of the air distribution systems, therefore, leakages may compromise the safety of patients and medical staff during pandemics. Air leakage in the air distribution and terminal systems effects in the loss of conditioned air. When air runs through leaks in the ductwork or terminal units, the HVAC system needs to compensate by running longer or at higher power levels to keep the desired temperature and airflow. This raised demand for conditioned air leads to increased energy consumption, reduced energy efficiency and expanded operational costs. Moreover, air leakage disrupts the planned airflow patterns within the HVAC system. As air escapes through leaks, the balance and distribution of airflow are compromised. This defect can result in unstable air distribution, insufficient ventilation and inadequate thermal comfort in different building areas. Inefficient airflow can also lead to stress imbalances, causing air to be drawn in from undesirable locations (e.g. unconditioned spaces or contaminated areas) and potentially affecting IAQ. Air leakage reduces the amount of conditioned air reaching the intended spaces. The defects can lead to decreased cooling or heating capacity as the system struggles to deliver the required airflow and temperature control. Occupied areas may experience compromised comfort levels, with insufficient cooling or heating capabilities to meet occupants' needs. The defect can result in occupant dissatisfaction and complaints. In addition, Air leakage can introduce unfiltered and unconditioned air into the HVAC system. This uncontrolled air infiltration can bring outdoor pollutants, allergens and contaminants into the building. In addition leaks in the recovery air ducts can result in stale or contaminated air re-circulation. These factors can negatively influence IAQ, leading to health issues, allergies and discomfort for occupants. Air leakage in the air distribution and terminal systems requires additional maintenance and repair efforts. Locating and sealing leaks in ductwork or terminal units requires specialized expertise. Regular inspections and maintenance are necessary to identify and address leakage issues promptly. Neglected air leakage can result in ongoing performance problems, increased energy costs and potential equipment failures, requiring costly repairs or replacements.

The corroded body of the cooling towers is rated third, based on an RI value of 11.355. Cooling towers have a high impact consideration because maintenance may require more preparation for repair or replacement owing to the size and location. Furthermore, Legionella contamination commonly occurs in cooling towers and is considered a health concern. The design-related part can be attributed to the type of material used in the cooling towers and piping, which may erode the coating layers over time. Moreover, it reduces the ability to control the temperature and perform maintenance, which may lead to corrosion and an unfavorable environment that can unleash Legionella. Corrosion significantly reduces the lifespan of cooling towers. Continuous exposure to moisture, chemicals and environmental factors accelerates corrosion. With proper maintenance to address corroded areas, the cooling tower's integrity and functionality can be maintained, leading to premature replacement and increased capital costs. In addition, Severe corrosion on the cooling tower bodies can weaken the structure to the point of failure. This defect can result in catastrophic incidents, such as the collapse of the cooling tower, which could cause damage to surrounding equipment or pose a safety hazard. Regular maintenance practices, including inspections and repairs, are crucial to promptly identify and address corroded areas and prevent potential equipment failures. To mitigate the implications of corroded bodies in cooling towers, HVAC maintenance practices should include regular inspections and maintenance of cooling tower bodies. This procedure can involve cleaning and treating the surfaces to prevent corrosion, applying protective coatings and conducting necessary repairs. Implementing proper water treatment programs and monitoring corrosion inhibitors can also help minimize the risk of corrosion. The cooling tower's performance, efficiency and lifespan can be optimized by addressing corroded areas promptly and adopting preventive maintenance measures.

When comparing the RI for each HVAC component, the chiller component had the maximum RI value. Therefore, HVAC chillers are the most critical HVAC components. The causes of the defects listed for the chillers are not mutually exclusive. Hence, mistakes in the engineering design process are responsible for the highest RI, making it the most critical design process in the design stage. The AHUs and FCUs were second. In quantitative approaches, impacts are assessed in monetary values to yield a monetary value of risk when multiplied by the probability of occurrence of a specific event. The chiller plays a crucial role in providing cooling for HVAC systems. If the chiller components are not adequately maintained, it can lead to reduced cooling capacity, decreased efficiency and compromised system performance. Regular maintenance of chiller components, such as cleaning heat exchangers, inspecting refrigerant levels and checking for leaks, is essential to ensure optimal system performance. The chiller plays a crucial role in providing cooling for HVAC systems. If the chiller components are not adequately maintained, it can lead to reduced cooling capacity, decreased efficiency and compromised system performance. Regular maintenance of chiller components, such as cleaning heat exchangers, inspecting refrigerant levels and checking for leaks, is essential to ensure an optimal system. Furthermore, a well-maintained chiller maintains the desired indoor temperature and humidity levels, ensuring occupant comfort. If chiller components are not adequately maintained, it can result in inadequate cooling capacity or inconsistent temperature control, leading to discomfort for building occupants. Regular maintenance practices (monitoring and adjusting refrigerant levels, cleaning filters and inspecting sensors) are necessary to optimize occupant comfort. A comprehensive maintenance plan should be implemented to address the implications of chiller components on HVAC maintenance. This plan should include regular inspections, cleaning, lubrication and calibration of chiller components. Following manufacturer guidelines and industry best practices for maintaining chiller components is essential. In addition, proactive measures such as condition monitoring, predictive maintenance techniques and implementing energy management strategies can further optimize chiller performance and reduce maintenance costs.

This study encompasses the maintainability of HVAC by the aid of facility managers. Owners of health-care facilities, however, have adversary interests. The alignment of their opinions may start with addressing the most serious maintainability issues as presented in this study. However, there are more gaps to highlight by analyzing the design and construction phases about latent causes for unnecessary future maintenance costs. This is noted as a limitation that can be covered in further investigation of the design and construction.

Previous conclusions on system criticality are based on the overall defects observed within a particular system. This conclusion should not be mixed with the most critical system based only on impact. To illustrate, the air distribution and terminal systems listed defects recorded more weight in impact. Regardless of their occurrence, the impact values attribute air distribution and terminal as the most critical systems, which should be regarded in the HVAC engineering design process. As air distribution and terminal components are responsible for air transfer through a complex duct network using conduits and controls, it highly affects the IAQ level inside the facility. Although dirt cleaning from air conduits and duct issues recorded an RI of 10.403 and impacted IQA, its effectiveness in removing contaminants is debatable. The air pollutant concentrations postcleaning can be higher than that of precleaning owing to insufficient scientific evidence (Moscato *et al.*, 2017).

One aspect the interviewee stressed is that the manufacturers' instructions for maintenance might be insufficient to justify future performance and highly dependent on the operating conditions. They emphasized the designer's role in investigating accurate operating conditions to improve their design decisions regarding sizing and specifications. The manufacturer's instructions for maintenance are built on general operation conditions of temperature, weather, humidity, dirt and dust surroundings, water quality, improper operation and human error (Firdaus *et al.*, 2016).

From another perspective, HVAC maintainability is interconnected with value engineering through their shared objective of optimizing HVAC system design. The optimization seeks to improve performance and advance cost-effectiveness on the long-term facilities' life cycle costs. HVAC value engineering attempts to reduce life cycle costs by optimizing design options and enhancing the quality of functionality over time. Al-Ghamdi and Al-Gahtani (2022) demonstrated this reduction by comparing five life cycle costs using the Monte Carlo simulation technique for selecting five HVAC systems in one of the Saudi office buildings using the analytic hierarchy process (AHP) integrated with the value engineering concept. Thus, maintainability factors and value engineering principles are integrated during the early stages of facilities projects.

Conclusion

This study listed 41 design-related defects that compromised maintenance of health-care facilities. Facility manager experts were selected as the source of knowledge to bridge the gap between designers and facility-management stage feedback. The 44 experts who attempted to participate were from different backgrounds; however, all had experience in health-care facility management that qualified them to address the maintenance issues of HVAC. This feedback is vital for determining the practical maintenance issues encountered because of design decisions.

Based on the experts' evaluation, the probability and impact of these defects are evaluated to obtain a risk value. A commonly encountered defect is the buildup of coils that results in airborne particles, which also has the highest RI value, indicating the risk response level. This affects airflow in which maintenance interventions are required. The criticality of this defect is based on the probability of its occurrence and impact. The RII for both probability and impact was the same at 0.697. Nonetheless, the impact of this defect has shown a higher evaluation, and the weighted mean of probability and impact is marginally different at 3.40 and 3.487, respectively. However, the most severe issue is air leakage in the air distribution and terminal systems. The RII of the impact value of air leakage in the air distribution and terminal systems was evaluated as 0.723, with a weighted mean of 3.615. This result is the highest impact of all design defects in the study.

Designers of HVAC systems of health-care facilities should be more careful in the chiller design process because of the number of maintenance issues it may cause. This study listed 10 common design-related defects in chillers by consensus of most facility managers. Their collective impact on maintenance was the highest compared with that of other systems. However, air distribution ducts, AHUs and FCUs have a greater impact on health. Their role is significant in defining the IAQ level inside facilities, therefore, design defects may lead to serious health issues. Air distribution in health-care facilities is among the cause of the spread of hospital-related COVID-19.

HVAC designers for health-care facilities can use the results of this study to enhance HVAC maintainability in future projects. The list of design-related defects and the values proposed by experts for probabilities and impacts provide several dimensions to assess design decisions compared with RII only. A description of the causes of each maintenance issue helps to establish a link to the responsible design process.

Future research may enhance HVAC maintainability by several paths. One path is adopting decision trees for design decisions, whereas each decision has a probability of being made and a monetary value proposed to address the impact of each decision. In addition, maintenance research can further investigate risk responses based on preventive maintenance concepts, which reflect on mitigating the risks of design-related defects that cause more maintenance costs. Each HVAC system component can be investigated further through several paths that help reduce unnecessary maintenance, such as detailed design criteria, construction procedures and preventive maintenance.

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