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The Causal Factors of Elevator Maintenance: A Perspective from Saudi Arabia Healthcare Facility Management

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Abstract: Maintenance is crucial for healthcare facilities in terms of both the continuity of operations and annual costs. Many maintenance issues are associated with design decisions that pave the way for added costs in later lifecycle stages. Some systems, e.g., elevators, are sources of maintenance costs; additionally, elevator outages are significant issues for multi-floor healthcare facilities. Considering the maintainability of elevators from the early design stages helps to highlight potential maintenance issues in later stages. This also assists in mitigating costs by avoiding design decisions that result in future maintenance costs. This research uses the expertise of facility managers who have experience with maintenance issues resulting from design decisions. A list of 35 elevator maintenance issues caused by design flaws is presented in this paper, based on the literature and semi-structured interviews with a representative sample of six healthcare facility management experts. Then, a questionnaire using convenience sampling was conducted with facility management professionals to evaluate and rank the maintenance issues. While 60 professionals responded, only 30 attempted the four-parameter evaluation of all listed maintenance issues. The results of the questionnaire determined elevator car jams, sudden stops, and working space conditions to be the most critical issues faced by facility managers in healthcare facilities. The output of this study can help designers of new healthcare facilities to avoid decisions that result in unwarranted maintenance issues with costly impacts.

Keywords: facility management; construction management; healthcare facilities; design defects; elevator design; FMECA

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Citation: Alassafi, H.; Al-Gahtani, K.; Almohsen, A.; Alfalah, G. The Causal Factors of Elevator Maintenance: A Perspective from Saudi Arabia Healthcare Facility Management. *Buildings* **2022**, *12*, 532. https://doi.org/10.3390/buildings12050532

Academic Editors: Srinath Perera, Albert P. C. Chan, Dilanthi Amaratunga, Makarand Hastak, Patrizia Lombardi, Sepani Senaratne, Xiaohua Jin and Anil Sawhney

Received: 19 February 2022
Accepted: 20 April 2022
Published: 22 April 2022

1. Introduction

Maintenance plays a vital role in all hospital services and refers to the complicated variety of systems, with various levels of technology, used in hospitals; the potential consequences of the failure of these systems necessitate high availability and functional safety measures [1]. The demand for healthcare services and hospitals is increasing globally, attributable to population growth, population aging, and consumer behavior [2]. Maintenance is essential to hospital performance [3–5]. Furthermore, design-stage problems are considered a more significant source of facility maintenance issues compared to problems in the construction stage [6]. When facility maintenance is not considered sufficiently at the design stage, unforeseen maintenance issues may add a cost parameter to the facility management stage. During the design stage, decisions are usually focused on the initial costs, and this does not reflect the significant impact of these decisions on the later stages [7].

As mentioned, these concerns signify a cost component among buildings' lifecycle costs that can be avoided if maintenance is contemplated sufficiently in the design stage. However, not many owners consider this a priority issue [8,9]. Factors such as cost, longevity, and performance have long been the focus during the design stage, while other factors, including maintainability, have been underrated [10,11]. Al-Hammad et al. cited faulty designs as the reason for maintenance cost escalations [12]. Hence, maintenance problems and faulty designs are related to the level of maintenance input during the design stage. Building maintainability is determined by design selections that address or overlook maintenance concerns at the early stage of design and construction [9]. When maintenance concerns are addressed sufficiently at the design stage, the maintainability of the design is improved, which results in future maintenance cost savings. Feedback from facility management professionals on design-caused maintenance issues is a suitable approach to achieve this maintainability improvement. Designing for building maintainability includes the processes performed to reduce defects and maintenance needs throughout a facility's lifecycle [13]. This issue focuses on the need for a maintainability assessment during the design stages to alleviate the impact of design decisions and predict future maintenance costs. This helps to reduce maintenance by enhancing the maintainability of the design. Therefore, an overall lifecycle cost reduction can be achieved.

Healthcare facilities contain several building service systems that are essential for the continuity of serving their purpose of providing healthcare to the public. The cost component and the annual growth in costs may cause serious concern regarding the continuity of healthcare facilities. In Saudi Arabia, for example, it is projected by the National Committee for Legislation and Standardization of Operation and Maintenance (NCLOM) that the future operation and maintenance of healthcare facilities will grow by an average of 10% annually from 2014 to 2030 if the current rates of growth continue [14]. Investigating the maintainability of healthcare facility service systems during the design stages helps to minimize maintenance needs and can lead to potential maintenance cost reductions. However, it is common to exclude the healthcare facility maintenance perspective while the project is in the design stage because of a lack of communication between the design and maintenance teams [15]. The maintenance of healthcare facilities can be considered with regard to the various systems utilized to run such facilities.

Mechanical, electrical, and plumbing (MEP) service systems in complex projects, such as high-tech, healthcare, and transportation projects, comprise up to 50% of the initial costs [16,17]. Among these mechanical systems, elevators are effective systems that are used in the daily operation of healthcare facilities. Although elevator maintenance is considered a cost, it provides a critical service in terms of the transport of patients. A cross-sectional case review study in Australia on incidents relating to the intra-hospital transfer of critically ill patients found that around 39% of the incidents encountered during transport were equipment-related, and 10% were due to elevator accessibility [18]. Hence, this study focuses on the improvement of elevator maintainability.

2. Literature Review

In previous research on building maintainability (Table 1), elevator systems were investigated; however, the focus was only on commercial buildings. Moreover, multiple studies on building maintainability have been conducted for a number of building types, but few have attempted to investigate elevators. The studies in Table 1 followed different methods of approaching the maintainability of buildings and the assessment thereof, but all of them sought to list and evaluate building defects as part of the various methods adopted to improve maintainability. Until now, there have been insufficient numbers of maintainability studies on elevators in healthcare facilities, despite the heavy usage of elevators in healthcare facilities.

Table 1. Previous research on maintainability.

Authors	Building Type	Location	Elevators Defects	Impact Factors of Defects	Comparison
Siti et al. [19]	General buildings	Singapore	26	Not stated	This study provided a framework for an elevator maintainability evaluation and sought to understand maintainability issues via a questionnaire distributed among practitioners.
Chew et al. [20]	High-rise commercial buildings	Singapore	114	This study analyzed elevators' economic defects, system performance, safety, and comfort impact.	This study focused on commercial buildings, and the impact of defects did not consider healthcare-related building use. It includes defects that occurred during the construction and operation stages.
De Silva et al., 2016 [21]	High-rise Building	Sri Lanka	-	10 risk factors	This study followed a risk-based framework that can measure maintainability by listing. It used an artificial neural network (ANN) tool to forecast maintainability in the early stage of a building. It serves as a decision tool to reduce maintenance costs.
De Silva and Ranasinghe [22]	Condominium	Sri Lanka	-	-	This study followed a risk-based maintainability assessment by investigating defects and problems. Although building service defects were the most serious maintainability issues, this study did not specify the defects of the elevator system.
Hassanain et al., 2014 [23]	Higher education	Saudi Arabia	-	-	This study investigated the defects of the heating, ventilating, air-conditioning, and cooling (HVAC) systems from maintenance professionals' point of view. It presented evaluated maintainability lists built to help designers avoid common maintenance issues.

The elevator systems investigated previously in maintainability studies follow a similar breakdown of elevator components, with some differences (Table 2). For one, Siti et al. [19] presented five main component groups that included various common maintainability issues. The breakdown of components adopted by Chew et al. [20] included a larger breakdown that specified subcomponents. The subcomponents may be present within a single component or in more than one. Another study by Chew and Das [24] listed the main components in a manner that combined the main approaches of the studies of both Siti et al. [19] and Chew et al. [20]. This study adopted a synthesis of the component breakdowns presented in the previous studies.

This research aims to use the experience of healthcare facility management experts in a proper framework that helps to improve elevator maintainability by achieving two objectives. The first objective is identifying a list of elevator maintenance issues caused by their design, and the second is evaluating and ranking the maintenance issues based on their criticality.

During the design stage, the designers can utilize this study's output regarding the maintainability of elevators to enhance the decision-making process. Such a proactive approach eliminates unfavorable design decisions and improves the maintainability of healthcare facility design by reducing the undesirable effects of future maintenance needs.

Table 2. Elevator components.

Siti et al. [19]	Chew et al. [20]	Das and Chew [21]
Traveling performance Machine rooms Hoistway and elevator pit Elevator car Elevator lobby	Components: Machine room Lift hoistway Lift car Lift pit Lift landing Sub-components: controller, governor machine, machine room, traction machine, traction motor, brake assembly, guide rail, wire rope, shaft, car interior, car door, car top, car bottom, door operator, travelling, landing door, lift landing, and smoke detector	Machine room and equipment Lift car Car and lobby door Hoistway Ropes Landing Lift pit

3. Materials and Methods

The objective of this research is to eliminate common building defects from the early stages, before they occur. The following steps (Figure 1) were followed to acquire knowledge from practicing facility managers in healthcare facilities to evaluate a wide array of elevator defects collected from the literature.

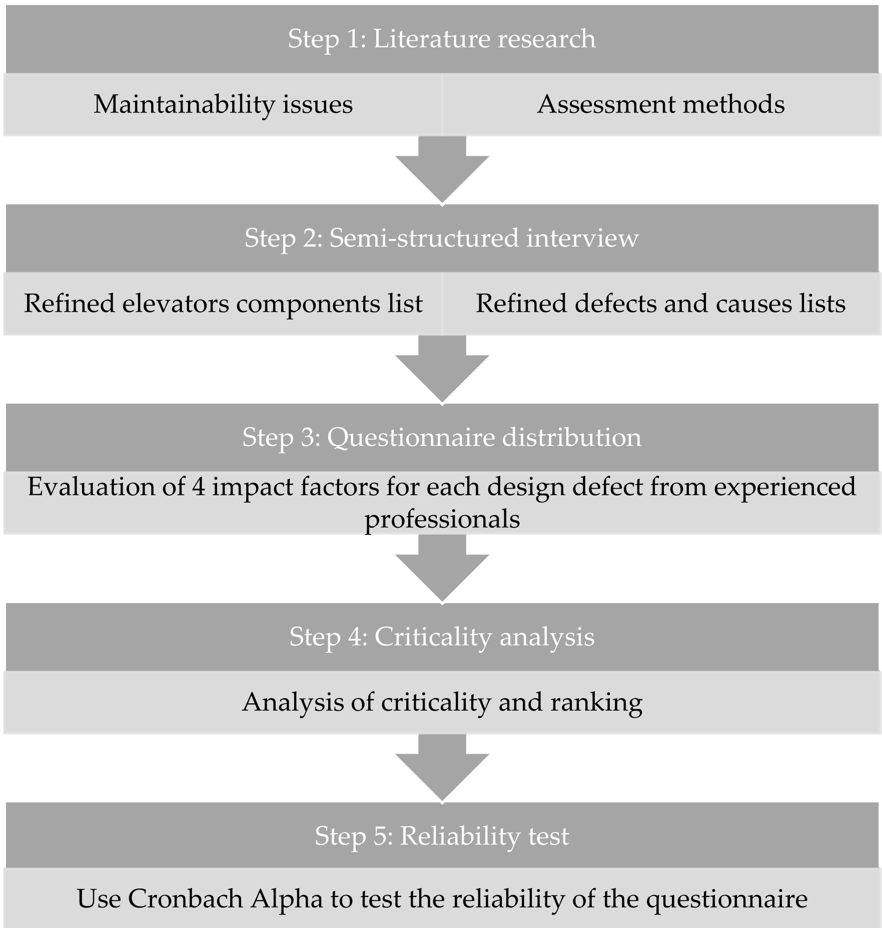

Figure 1. Methodology followed in this research to evaluate critical elevator maintenance issues caused by design.

Step 1. Research was conducted that reviewed the literature regarding elevator maintenance defects and their causes in order to analyze their criticality. Since this study focuses on design-caused maintenance issues, the selection process for defects and causes verified that design decisions regarding the specifics of an elevator component lead to the occurrence of said defects. This included research on the assessment methodology to be utilized. Guided by the maintainability assessment and checklist presented by Das and Chew, four elements were chosen for evaluation in this study for each defect, i.e., hygienic, health, and safety impact; cost impact; performance impact; and defect frequency [24]. These elements added additional factors focused on health and safety in order to respond to the nature of healthcare facilities, compared to the impact factors employed by Das and Chew [24].

Step 2. Semi-structured interviews were conducted with a representative sample of experts in elevator maintenance to collect data on the elements mentioned above and to critique the research content of the literature. A total of 62 elevator maintenance issues were discussed with each expert. The interviews involved discussing each issue in light of two essential elements: the extent to which a defect was design-caused, and healthcare relatedness. There were anomalies in the feedback from the selected 6 participants. To avoid bias or inconsistency, the results from all participants were cross-checked during interviews. This step resulted in a refined list of 35 defects as a final list of maintenance issues caused by design decisions as agreed upon by most interviewees. The targeted interviewees were professionals with a proven record of experience with healthcare facility management. Since some experts may not have dealt with elevator systems directly, experience in elevator maintenance was a prerequisite. Whether in a public or private healthcare facility, the level of experience required of the interviewees was at least 15 years. Table 3 lists the responses collected from the interviewees after cross-checking the literature review data of each elevator defect and its cause.

Step 3. A questionnaire was distributed among facility management experts in Saudi Arabia, asking them to evaluate the list generated in Step 2 based on a 5-point Likert scale. This questionnaire adopted convenience sampling, which is a non-probability sampling technique that selects a sample of participants from a population based on convenient accessibility of the data sources [25]. Failure mode, effects, and criticality analysis (FMECA) was used to reflect upon the perspectives of the interviewees to produce their evaluations. The targeted experts were required to have more than ten years of experience in a public or private healthcare facility. All the respondents had to disclose whether their professional background included elevator maintenance experience in healthcare facilities.

Step 4. Criticality analysis was applied to the results that reflected the most severe design decisions, leading to the determination of the most common elevator maintenance issues.

Step 5. We performed a reliability test on the questionnaire, utilizing Cronbach's alpha (α).

$$\alpha = (k \div (k-1)) \times (1 - ((\sum_{i=1}^{k} \sigma_i^2) \div \sigma_X^2))) \quad (1)$$

where k is the number of test items, σ_i^2 is the variance of a single test item X_i, and σ_X^2 is the variance of the overall test items, X.

Cronbach's alpha is a test reliability evaluation technique, and it is imperative to employ it when using Likert-type scales to ensure internal consistency and reliability [26]. A reliable test requires the alpha coefficient to be very close to 1.0 [26,27].

Table 3. Defects detected in the facility management phase that were caused by design decisions.

Sn	Component	Defect	Causes
1	Elevator general performance	Long waiting time for elevator to come	Design consideration for traffic load is improper
2		Elevator car vibrations	Overloading when counterweight ropes are not perfectly matched, especially if less than three, or poor machine room and hoistway building tightness, which allows dust in
3		Elevator car jams	Limit switch placement is near the governor rope, which causes the car to stop
4	Machine room	Existence of debris and lubricants	Dust from finished or window AC usage or inadequate space and clearance around equipment in the machine room
5		Falling on machines while performing maintenance or being hit by them	Inadequate space in the machine room, hoistway, or pit, or water or lubricant spills forming slippery working surfaces
6		Insufficient lighting level	Inadequate lighting level or short-lamp-life design
7		Poor air quality	No air conditioning or proper ventilation, or high humidity coming from water leaks in the wall or ceiling without proper drainage
8	Controller	Dirt or noise	Not configured for the environment of the area, i.e., cold versus arid environments and weather conditions, and Ingress Protection (IP) rating does not match
9		Voltage mismatch	The voltage of imported controllers may differ under many circumstances, allowing a potential voltage mismatch
10	Traction machine	Dirt and oil on the traction machine	Insufficient accessibility and limited space to allow adequate general cleaning or spillage removal during lubrication
11		Wearing marks on ropes	Selection of the rope is mismatched and improper for long sustainment of friction, and possible tension unevenness or improper sheave geometry and design, allowing fast sheave wear that damages ropes
12		Noise and vibrations	Insufficient specs for traction machine strength, leading to faster inner wearing, or a proper machine bed rubber is unavailable to absorb vibrations and add more durability
13	Speed governor machine	Dirt or noise	High friction due to unsuitable components and rope selection, or inadequate accessibility causing insufficient cleaning for dirt and spillages
14		Sudden stops	Improper selection, sizing, and specifications of the tripping mechanism
15	Elevator car	Maintenance working conditions unsafe	Insufficient clearances, low overhead above, guards unavailable, or lighting is poor or unavailable
16		Noisy traveling cable	Cable selection does not secure proper acoustic performance
17		Darkness or low lighting level	No guard for lights, which may become damaged
18		Poor air quality	Inadequate air conditioning or ventilation
19		Noisy interior	Finished materials for the car have poor acoustical design; low specs are selected; ventilation fan is noisy due to low quality; trapdoor lock design allows minor movement, thus making sounds
20		Car Operating Panel (COP) button not working	Nondurable design for buttons allowing faster damage
21		Damaged flooring	Nondurable flooring materials are selected
22	Hoistway	Noise and vibration	Guide rail specifications are poorly selected, which may lead to denting
23		Dirt and dust	Materials selected to build the hoistway generate dust
24		Poor air quality	Inadequate ventilation inside the hoistway, walls allow for water seepage, no existing waterproofing
25	Roping system	Corroded wires	Rope materials are not rust-resistant and are thus susceptible to corrosion, or poor pulley geometry or grooves causing wires to undergo repetitive bending or excessive friction
26		Rope vibrations	Deep dust accumulations in pulleys

Table 3. *Cont.*

Sn	Component	Defect	Causes
27	Car door	Frequent door closing while users step in	Poor sensing system design, such as single-point photoelectric eyes sensors, that allows such performance
28		Car doors remain open	COP buttons are nondurable and become unable to function properly without intervention and second attempts
29		Noisy doors and abnormal operation	The door roller shoe is poorly designed, and its materials are not adequately selected with rubber lining
30		The front frame (jamb) is rusty or damaged	Poor material selection in terms of durability and corrosion resistance
31	Lobby and Landing	Button damage	Poor material selection for nondurable buttons that cannot withstand heavy use
32		The in-car service switch is jammed/broken	Inadequate design to protect the switch from possible vandalism
33	Lift pit	Wet and dirt issues	Inaccessible pits or limited access for cleaning, or seepage through structural members with no proper waterproofing
34		Poor lighting	The lighting is either not provided by the design or not adequately guarded, or the selected lighting level is insufficient
35		Falling on or being hit by an adjacent machine while performing maintenance	The pit does not include a partition when accommodating more than one car

FMECA Assessment

Since the mitigation of defects is a maintainability approach to reducing maintenance, FMECA was adopted by Das and Chew to analyze building defects and grade defects to enhance the maintainability of buildings [24]. Their work proposed a modified FMECA approach as a defect-grading tool to adopt a more suitable building industry version of the FMECA approach, and the scope of their study included only commercial buildings in Singapore. Their efforts included investigating the suitability of applying classic FMECA to grade commercial building defects, including elevators, which resulted in considering the inability to use the quantitative aspect of FMECA in grading building defects due to several obstacles, i.e., the difficulty of obtaining defect data and the inapplicability of the operating time data for some building systems. Thus, the qualitative data were deemed appropriate for FMECA, and the FMECA risk parameter numbers were measured to produce an overall criticality estimate of a specific defect. This provided a deeper analysis, comparing other studies on building maintenance utilizing relative importance [28] and the relative importance index (RII) [29].

Research in healthcare facility management and maintenance has adopted failure mode and effects analysis (FMEA) to analyze facility failures, which is a similar approach and a subset of FMECA that excludes the criticality analysis and can be considered to be a troubleshooting guide for maintainability [30–32]. Even though FMECA and FMEA originated in other engineering fields, they were introduced for use in buildings [24,33–35].

Using a similar approach, this study adopted a modified FMECA. In light of the work of Das and Chew on building maintainability [24], FMECA provided a suitable tool to analyze the defects presented by this study according to a number of parameters. FMECA focuses on linking each defect with the issues that may cause its occurrence, and it provides a criticality evaluation built on multiple parameters. The parameters of defect impacts were used to grade design-caused defects triggering maintenance issues, conducted by experts in healthcare facility management. In this research, elevator defects were categorized according to a questionnaire regarding ten elevator components, which was sent out to experts. Grouped according to components, the defects differed by focusing only on design-caused defects (Table 4). The grading of defects was then established based on the questionnaire that gathered expert judgment for each defect's frequency and the severity of the impact of the defect occurrence. The impacts of the defects were classified into three impact parameters, i.e., economic, system performance, and comfort. The research presented here added another impact parameter for defects: the hygienic, health, and safety impact, which signified the additional sensitivity to maintenance defects present in healthcare facilities. Although cost was considered among the other factors, evaluation based on expert judgment is merely an indicator. Actual cost analysis may be considered for more accuracy when investigating specific case studies. The parameters to be rated were: A = hygienic, health, and safety impact; B = cost impact; C = performance impact; D = defect frequency. Hence, the formulation of the criticality of defects in this research can be represented as follows, with criticality being represented on a 5-point Likert scale:

$$\mathrm{Sv} = (\mathrm{A} + \mathrm{B} + \mathrm{C}) \div 3 \quad (2)$$

$$\mathrm{Cr} = (\mathrm{Sv} \div 5) \times (\mathrm{D} \div 5) \quad (3)$$

where Sv is severity, and Cr is criticality (Table 4).

Table 4. Questionnaire results for elevator design defect evaluation by facility managers.

Sn	Component	Defect	Number of Responses				Severity (Sv)	Criticality (Cr)	Defect Rank	Avg Component Criticality	Component Rank
			A	B	C	D					
1	Elevator general performance	Long waiting time for elevator to come	27	27	27	27	3.5432	0.4462	10	0.4703	1
2		Elevator car vibrations	27	27	27	27	3.6049	0.4700	4		
3		Elevator car jams	27	27	27	27	3.6296	0.4947	1		
4	Machine room	Existence of debris and lubricants	27	27	27	27	3.2593	0.3959	28	0.4074	3
5		Falling on machines while performing maintenance or being hit by them	27	27	27	27	3.4938	0.4296	17		
6		Insufficient lighting level	27	27	27	27	3.4074	0.3988	26		
7		Poor air quality	27	27	27	27	3.4198	0.4053	25		
8	Controller	Dirt or noise	15	25	25	25	3.4133	0.4260	19	0.4359	2
9		Voltage mismatch	25	25	25	25	3.6667	0.4459	11		
10	Traction machine	Dirt and oil on traction machine	25	25	25	25	3.2400	0.4199	20	0.4124	2
11		Wearing marks on ropes	25	25	25	25	3.1467	0.3877	32		
12		Noise and vibrations	25	25	25	25	3.4000	0.4298	15		
13	Speed governor machine	Dirt or noise	25	25	25	25	3.5067	0.4657	5	0.4701	1
14		Sudden stops	25	25	25	24	3.5733	0.4745	3		

Table 4. *Cont.*

Sn	Component	Defect	Number of Responses				Severity (Sv)	Criticality (Cr)	Defect Rank	Avg Component Criticality	Component Rank
			A	B	C	D					
15	Elevator car	Maintenance working conditions unsafe	25	25	25	25	3.6667	0.4928	2	0.4167	3
16		Noisy traveling cable	25	25	25	25	3.4400	0.3963	27		
17		Darkness or low lighting level	25	25	25	25	3.2667	0.4077	23		
18		Poor air quality	25	25	25	25	3.0667	0.3925	30		
19		Noisy interior	25	25	25	25	3.0400	0.3843	33		
20		Car Operating Panel (COP) button not working	25	25	25	25	3.3733	0.4480	9		
21		Damaged flooring	25	25	25	25	3.2933	0.3952	29		
22	Hoistway	Noise and vibration	25	25	25	25	3.5067	0.4096	22	0.3772	4
23		Dirt and dust	25	25	25	25	3.1600	0.3741	34		
24		Poor air quality	25	25	25	25	3.2933	0.3478	35		
25	Roping system	Corroded wires	25	25	25	25	3.4400	0.4293	18	0.4097	3
26		Rope vibrations	25	25	25	25	3.3867	0.3901	31		
27	Car door	Frequent door closing while users step in	25	25	25	25	3.4267	0.4331	12	0.4387	2
28		Car doors remain open	25	25	25	25	3.5067	0.4601	7		
29		Noisy doors and abnormal operation	25	25	25	25	3.4000	0.4298	15		
30		Front frame (jamb) is rusty or damaged	25	25	25	25	3.3733	0.4318	14		
31	Lobby and landing	Button damage	25	25	25	25	3.2400	0.4510	8	0.4330	2
32		In-car service switch is jammed/broken	25	25	25	25	3.4133	0.4151	21		
33	Lift pit	Wet and dirt issues	25	25	25	25	3.3333	0.4320	13	0.4333	2
34		Poor lighting	25	25	25	25	3.3067	0.4074	24		
35		Falling on or being hit by an adjacent machine while performing maintenance	25	25	25	25	3.4667	0.4604	6		

4. Results

Only 30 responses attempted to answer all the questions in the questionnaire out of the total population of 60 responses. However, all the answers received from the targeted group were considered; these range from as low as 15 respondents to as many as 27 respondents.

Although defects can vary in criticality within each component of an elevator system and when standing alone, the overall criticality of components was ranked based on the average Cr values that comprise the components. The same rankings were assigned to the components where the difference in the criticality values was less than 5%. Table 4 summarizes the questionnaire results, which revealed that the design defects that affect general elevator performance, such as extended waiting times, vibrations, and car jams, were the most critical maintenance issues caused by design decisions. Car jams caused by the placement of limit switches carried the highest criticality with a Cr value of 0.4947.

The causes of the other defects for this component, which came fourth and tenth in rank, mainly stemmed from underestimating the design considerations for traffic load and counterweight ropes, poor machine room layout design, and hoistway building tightness.

Despite the overall rank of the average criticality for elevator components, the second critical elevator defect focused on the causes of unsafe conditions of maintenance activities. With a Cr equal to 0.4928, elevators with a low overhead clearance above the car, poor lighting, or unavailable lighting were ranked the second most critical by experts. From the questionnaire results, the frequency and impact of this defect were the main drivers behind this evaluation. The speed governor component of elevators included two defects, with a Cr of 0.4745 for sudden stops and a Cr of 0.4657 for dirt and noise, and it ranked first alongside the elevator's general performance component. These defects came third and fifth, respectively, in the list of overall defect criticality.

5. Discussion

The results show an inconstant evaluation for defects related to cleanliness. As dirt accumulation impact varies from one component to another, the respondents changed their evaluation of the various cleanliness-related impacts. This can be observed for other defects that have a low Cr for one component while scoring a higher Cr for a different component. For example, air quality ranged from a more serious Cr in machine rooms to a lesser one in the hoistway. This can be explained by the spacious volume of the hoistway compared to the machine rooms, and the fact that the opening and closing of doors allow air movement.

The facility management experts linked the sudden stopping of elevators to the improper selection, sizing, and specifications of the tripping mechanism. Among all the impacts evaluated for the latter defect, sudden stopping affected overall elevator performance more than the other impacts evaluated in this study. On the other hand, dirt or noise in the speed governor component was mainly caused by high friction or inadequate accessibility of the system components.

Maintenance working conditions for elevator car maintenance were evaluated to be the second-highest-ranked critical defect. Most of the facility managers agreed that insufficient design considerations regarding the safety of the technicians while performing maintenance work was significant; such issues include the space surrounding the elevator, machine and tool setup and clearance, safety measures for falling items while working at the top of the elevator car, and low overheads. Falling in the lift pit represented a maintenance issue that experts emphasized. This defect concerns performing maintenance anywhere in the shaft but the elevator car. There is a risk of falling from car doors when performing maintenance. The unavailability of design decisions that lead to safer conditions for performing maintenance in elevators remains an alarming issue. This defect had a Cr value of 0.4604, which was ranked sixth among all defects.

Various types of healthcare facilities likely have various scenarios regarding elevators maintenance. However, this study approached various types of facility management together to simplify the process of designing for maintainability. Moreover, there are several maintenance approaches and processes, including corrective, preventive, risk-based, and condition-based maintenance, and they differ in terms of their impact on maintainability. Since design stage decision impacts on maintainability were the focus of this study, the processes and decisions associated with maintenance stages were beyond the boundaries of this research.

The ranking based on Cr values may be a limitation since Cr values tend to cluster with minute differences. Further studies that incorporate additional parameters would introduce a wider range among the results. Table 5 provides more details for each elevator component according to the results of the questionnaire.

Table 5. Observations on the questionnaire results grouped by components.

Sn	Elevator Component	Notes
1	Elevator general performance	Contains the highest weight of overly critical maintenance issues. The major critical design-caused defect is elevator car jams caused by the limit switch placement in elevators near the governor rope, making the elevator car stop moving.
2	Machine room	Comes tenth among the overall less-critical components. The defects associated with the machine room are pertinent to other systems and mostly focus on accessibility and cleanliness obstacles.
3	Controller	Includes the most critical design-caused defect seen in the area experts worked in, i.e., the voltage mismatch of controllers. Since controllers are mostly imported from abroad, there are frequent cases of voltage mismatch, which could be avoided if additional measures were taken at the design stage.
4	Traction machine	The most critical defect within the traction machine category is the noise and vibrations caused by insufficient specifications for traction machine strength, leading to faster inner wearing. A proper machine bed rubber is unavailable to absorb vibrations and add more durability.
5	Over-speed governor machine	This component comes second among all others for two primary defects, i.e., dirt or noise, caused by high friction due to unsuitable components and rope selection, or is otherwise caused by inadequate accessibility causing insufficient cleaning of dirt and spillages. The second is a sudden stop due to the improper selection, sizing, or specifications of the tripping mechanism.
6	Elevator car	The primary defect that causes maintenance issues is unsafe working conditions caused by a low overhead above the elevator car or poor or unavailable lighting.
7	Hoistway	From inside the hoistway or shafts, host elevators have a moderate critical defect affecting their maintenance. The primary design-caused defects rated for this component are noise and vibration, dirt and dust, and low air quality.
8	Roping system	Corrosion is the primary defect that affects this component caused by non-rust-resistant rope materials, which are thus susceptible to corrosion, poor pulley geometry, or grooves, causing the wire to undergo repetitive bending or excessive friction.
9	Car door	Overall, this component comes third compared to other components. Its primary defect is that the doors may remain open because the car's operating panel (COP) buttons are nondurable and become unable to function appropriately without intervention and second attempts.
10	Lobby and landing	The in-car service switch being jammed or broken is the most critical defect for lobby and landing components. This is caused mostly by inadequate designs to protect the switch from possible vandalism.
11	Lift pit	As a component, this is among the components that are second in criticality. The most critical defect, ranked eleventh among all component defects, is the possibility of falling on or being hit by an adjacent machine while performing maintenance. The reason for this is that some elevator pits do not include a partition when accommodating more than one car.

The main issues related to healthcare facilities that the interviewees emphasized were the stoppage of service in elevators, air quality, and maintenance practices. While stoppage is linked directly to elevator components, the air quality may be associated with another building system. However, the inclusion of air quality is consistent with the hygienic role of elevators in a healthcare facility. The design decisions that handle air passage and circulation through elevator systems affect elevator safety in transporting patients and visitors. Although maintenance practices may not be part of the design stage decisions, the inclusion of maintenance considerations, including safety tools and attachments, accessibility, light availability, and air quality, is important to safe operation.

This paper approached the evaluation of maintainability without detailed cost analyses. The rating of cost impacts by experts was used as the essential reference for the cost of maintenance in a generalized form. Previous studies have approached maintainability assessments in a similar manner. For example, the work of de Silva & Ranasinghe [21] followed a risk analysis approach to evaluate maintainability, which considered expert evaluations of costs of maintenance as a trigger for risk seriousness. Additionally, the work of Das & Chew [24] adopted FMECA, which included a cost parameter evaluated by experts. In the work of Hassanain et al. [23] that ranked HVAC maintenance issues, they listed design-caused maintenance issues and evaluated their seriousness based on expert judgments.

To verify the internal consistency of the Likert-scale questionnaire employed in this study, Cronbach's alpha coefficient was calculated, and the result was 0.9968 (Table 6). Although high alpha coefficient scores are sought, a high score such as this one does not necessarily reflect a higher internal consistency because it is impacted by the length of the test [36].

Table 6. Cronbach's alpha of the questionnaire results.

Number of Questions	Sum of Variances	The Variance of Total Scores	Cronbach's Alpha, α
140	129.35	12,564.74	0.9968

6. Conclusions

This research assessed the criticality of maintenance issues caused by design decisions based on a modified FMECA approach, aiming to improve the maintainability of elevators in healthcare facilities. Data regarding elevator components, defects, and their causes were gathered from the literature to verify the input of facility management experts. The design defects that cause the maintenance issues studied in this paper considered the four aspects of: (1) hygienic, health, and safety concerns; (2) cost; (3) performance; and (4) frequency of occurrences.

The questionnaire outcomes included a list of criticality evaluations by experts regarding the sources of 35 elevator maintenance issues. The general performance of elevators, as represented by waiting time, vibrations, and car jams, presented the most serious maintenance issues. In particular, jamming issues caused by the limit switch placement were evaluated in this study to be a source of the most critical design decisions affecting the maintainability of elevators in healthcare facilities.

Designers of new healthcare facilities will benefit from the approach proposed in this research by having access to the knowledge produced, particularly for elevators in healthcare facilities. The outcomes of this research may aid designers in promoting maintainability for new healthcare facility designs.

One limitation of this research can be described as being due to the limited number of studies on elevator maintainability to compare against, especially in healthcare facilities. Moreover, we focused on experts from one geographical area, which may have yielded different results from those of other areas with different climates and industry practices.

Future research may advance the maintainability of elevators by integrating maintainability-based technical specifications into Building Information Modeling (BIM) software. BIM tools can enable designers to be aware of the impact of their early decisions on the lifecycle maintainability of facilities based on the experience of maintenance professionals. Additionally, future research can address further aspects of elevator maintainability, for example, a detailed engineering study of the defects and maintenance practices for elevators in healthcare facilities. This may alert designers early in the process to the impact of design decisions on future maintenance.

Author Contributions: Conceptualization, H.A., K.A.-G. and G.A.; methodology, H.A. and K.A.-G.; software, H.A.; validation, H.A., K.A.-G., A.A. and G.A.; formal analysis, H.A.; investigation, H.A.; resources, H.A.; data curation, H.A.; writing—original draft preparation, H.A.; writing—review and editing, H.A. and K.A.-G.; visualization, H.A. and K.A.-G.; supervision, K.A.-G.; project administration, H.A.; funding acquisition, H.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Deanship of Scientific Research (DSR), King Saud University (KSU).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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