

Article

Integrated Building Maintenance and Safety Framework: Educational and Public Facilities Case Study

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Abstract: The facility safety is a highly important issue in educational institutions and public facilities, where the safety and health of the occupants (students, educational and public service staff) is a high-order priority. The research hypothesizes that a synergy exists between the maintenance and safety of public facilities. Analytical–empirical research methods were aimed at the development of an integrated maintenance–safety framework. The framework was validated through inferential statistics and a case study. A correlation (R^2) of 0.74 between the level of maintenance and the safety level of 24 educational facilities was found using the Pearson correlation coefficient. The levels of maintenance and of safety observed were marginal. An innovative Integrated Safety–maintenance performance framework was developed for synergetic safety–maintenance monitoring, control and management. The framework proposes a cycle loop of safety–maintenance–performance audits of facilities as a key tool for advanced maintenance and safety management in public facilities. The framework was validated in a case study of public facility. The time history of maintenance performance and safety shows a high level of fitness ($R^2 = 0.8865$, p -Value < 0.05). These research findings stress that integrated safety and maintenance should be implemented as a unified procedure to enhance the advanced maintenance performance and safety climate in public facilities management.

Keywords: facilities management; maintenance; performance; risk; safety



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1. Introduction

Facility safety is highly important in educational institutions and public facilities in particular, where the safety and health of the occupants (students, educational and public service staff) is a high order of priority [1,2]. The safety of users of buildings and facilities is a highly important facility management issue. During the construction of the building, design methods and materials will be reviewed for different types of buildings and facilities to ensure the sustainability of the facilities, as well as the safety of users of the buildings and facilities [3–5]. In addition to the consideration of the construction process, the proactive management of maintenance and performance, as well as safety assessment of the facility during the maintenance phase, are required in order to effectively improve the safety mode of the building [6]. However, for the safety assessment of building facilities, there is currently no definite assessment methodology or indicator, nor a set of valid assessment models, for the implementation of these procedures [7]. To this end, this study summarizes the development of an integrated risk-informed methodology aimed at the integration between the maintenance and safety of facilities as a performance management tool for the fostering of the maintenance and safety of facilities, taking advantage of the synergy

between these disciplines. The research develops a model for evaluating and managing building safety and maintenance through this integrated methodology of maintenance and safety indicators.

The development of methods for safety assessments in educational institutions is a ubiquitous research topic, Al-Hemoud and Al-Asfoor [2] developed the Behavioral-Based Safety (BBS) that introduces safety using a behavioral safety approach. This theory follows Heinrich's [8] theory of the human factor in accident causation and stresses the training of individuals, safety control and inspection. DePasquale and Geller [9] examined the success of BBS models from the workers' perspective and found five predictive parameters of the success of the method: (a) effective training, (b) senior management trust, (c) effective safety control, (d) training of workers and (e) workers' commitment. Elementary and high school educational institution occupants are heterogenic groups with diverse patterns of safety behavior assimilation and, therefore, are more vulnerable to safety hazards [10–12]. Sabatino et al. [13] stressed that a methodology for the optimal maintenance of buildings must integrate into its considerations the consequences of a system failure or poor performance. Lai and Yik [14] studied the parameters of the optimal maintenance setup that will provide safety, efficiency and high user satisfaction within the building's occupants. Through a survey of 279 questionnaires in residential buildings in Hong Kong, the researchers analyzed five parameters of maintenance services: safety, cleanliness, break down and routine maintenance, aesthetics and overall satisfaction. This research did not consider the building performance as a key parameter of an optimal maintenance plan. Olanrewaju et al. [15] studied resource allocation priority settings in university facilities in Malaysia. The researchers found out that breakdown maintenance of visible components such as elevators, power supply and roofing failures are a high-order priority and should receive higher precedence in the allocation of routine maintenance resources. This review emphasizes the ultimate role of facility maintenance in ensuring the occupants' safety and satisfaction, as the latter is highly important and crucial in educational institutions and public facilities.

The research main objective is to investigate the correlation between maintenance and safety performance in educational and public facilities as a basis for the development of integrated maintenance and safety framework. Six research subgoals are defined as follows:

- a. Definition of the risk factors, according to the facility components, performance and users;
- b. Development of a methodology for the assessment of the safety risks in educational and public facilities;
- c. Assessment of the maintenance and safety performances in educational and public facilities;
- d. Development of an Integrated Safety–Maintenance management framework;
- e. Implementation of the framework and validation of the research hypotheses;
- f. Recommendations for further research and concluding remarks.

Subsequent from the research hypotheses, findings and conclusions, a new framework for integrated risk-informed maintenance and safety surveys and performance assessments is introduced as a part of the facility management. The framework is designated to take advantage of the synergy between safety and maintenance so as to enhance the maintenance, performance and safety of public facilities. This proposed framework will stimulate lower probabilities of safety hazards in the performances of public facilities; improve the sustainable performance of the facilities on a continuous basis and can fit into other types of facilities such as energy, healthcare, residential buildings and off-shore facilities. While previous research on the topic of safety and maintenance focused on the role of the human factor, in the synergy between maintenance and safety, e.g., Hobbs and Williamson [16] in the Aeronautics industry and Farrington-Darby et al. [17]. In the railway maintenance industry, this research develops a systemic and inherent synergy and introduces an integrated performance control of safety and maintenance management in public and educational facilities.

2. Literature Review

The literature review develops a research theme based on the definitions of the core topics of the research, review of the risk factors maintenance and safety indicators in facilities.

The core variables of this study, encompassing safety, maintenance, risk, acceptable risk and building performance, were defined on the basis of the literature, as follows in Table 1:

Table 1. Cross-comparative definitions of the core variables of the research.

Parameter	Definition	Cross-Comparative Definition
Safety	All preventive measures aimed at ensuring user well-being and facility-designated use.	Hollnagel [18] indicated that safety is accomplished through the prevention of hazards, unsafe events and the consequences of structural failures.
Maintenance	Activities carried out to maintain the durability and performance of the building in accordance with its designated use.	Three aspects of key facility maintenance: (1) actual service condition of the system, (2) failures affecting the service condition provided by the system and (3) actual preventive activities carried out to maintain acceptable designated service condition [19].
Risk	The probability and severity of an undesired event.	Aven [20] stated that the capability to express risk quantitatively and compare alternative mitigation strategies is at the heart of risk management.
Building performance	The concept in which the functions of buildings are defined by their outcomes rather than by prescription. Performance is determined by a building's success in achieving user satisfaction and meeting designated performance criteria.	The evaluation of the overall service condition of the building or of the building portfolio, according to the performance criteria of its components and systems defined by its designated use and current standards [19].
Acceptable risk	The level of risk deemed acceptable for an organization.	Hollnagel [21] stated that risk and safety are conceptually and practically linked—with higher safety meaning lower risk—and that the most effective way to achieve safety is through proactive mitigation actions.

The definitions stem from the performance concept and are supported by cross-referencing from the literature.

2.1. Risk Factors

Risk assessment and management is a key driver of building performance and maintenance management [15,17]. Using the fatigue design factor, Straub and Faber [22] developed a risk-based inspection strategy for planning an optimal inspection regime for structural components. Khalil et al. [23] developed integrated indicators of a building performance and user risk through the analytical hierarchy process method. Their methodology yielded a building performance risk rating tool (BPRT). They identified five critical risk indicators: (1) structural stability, (2) fire protection services, (3) building-related pathology, (4) emergency exits and (5) electrical services. The BPRT was implemented in the maintenance of higher education buildings in Malaysia. Khan et al. [24] introduced a risk-based maintenance methodology composed of three modules: (1) risk estimation, (2) risk evaluation and (3) maintenance planning. They used a heating, ventilation and air-conditioning (HVAC) system as a case study of risk-based maintenance to validate their methodology. The case study contributed to the successful reduction of risk in an HVAC system from an unacceptable level to an acceptable level.

Backlund and Hannu [25] compared three strategies of systems risk assessment to identify a maintenance strategy that minimizes maintenance costs as a part of the deregulation of the Swedish hydro power plants sector. The researchers identified several key maintenance-related tasks for accurately assessing risk: (1) exposure time, (2) frequency estimation, (3) consequence estimation, (4) qualitative and quantitative methods for reliability

and frequency estimation, (5) teamwork, (6) performance analysis and (7) uncertainty and sensitivity analysis. Khan and Haddara [26] developed effective risk-based maintenance for HVAC systems by using a scenario analysis, probabilistic failure analysis, risk estimation and evaluation and maintenance planning.

De Silva et al. [27] identified 10 maintenance-related risk factors for buildings: (1) architecture and design risks; (2) structural and detailing risks; (3) service integration risks; (4) accessibility risks; (5) maintenance requirement risks; (6) material and spare parts risks; (7) constructability risks; (8) maintenance process quality risks; (9) characteristics, environment and exposure risks and (10) user requirement and change-related risks. De Silva et al. [27] emphasized the integration of various characteristics of the exposure of the building environment to hazards. Addressing such exposure requires the integration of risk management, safety and maintenance. Ruparathna et al. [28] developed a risk-based scenario planning approach that incorporates predicted changes in technology, costs and organizational strategies for the selection of maintenance strategies. Their methodology minimizes financial risk. Their study also stressed the integration between risk and maintenance planning.

Chiu et al. [29] used the concept of the reliability of a series system to develop a theory of the deterioration risk of Reinforced Concrete structures exposed to chloride attacks. They determined an optimal maintenance plan using probabilistic effect assessment models that considered the effects of maintenance strategies on the failure and spalling probability of a structure and could be used to estimate life cycle costs and performances. Their study emphasized the need to integrate safety and maintenance in a comprehensive framework.

2.2. Maintenance

Despite being part of the last stage of the facilities life cycle, the maintenance and management of buildings should be considered throughout the design stage. Such considerations should include the intensity of the facility use, facility attributes, facility maintenance methods, facility maintenance costs, facility vulnerabilities, the total number of facilities and the facility maintenance period [30–32]. That is, the impact of the building material configuration on the building facilities (including durability and replaceability) must be considered in the building design. If these factors are considered in detail in the design stage, a building can be maintained and managed at low cost [33].

The quality of buildings and their facilities is often poor because of a lack of proper building maintenance and management, even with high maintenance costs [34–36]. In addition, once passive management is adopted, various types of building defects, including structural or nonstructural cracking and concrete fragments spalling, can cause severe damage. Therefore, many studies have proposed building maintenance and management methods that fall into one of three categories: corrosive, preventive or predictive maintenance. Among these, corrosive maintenance is passive and involves repairing equipment after it is damaged, whereas the other two types of maintenance are active [30]. An optimization framework was developed to consider the interdependencies among different units of HVAC equipment and interdependencies among maintenance, operation and equipment durability to deduce predictive and preventive maintenance.

Saqib, Faruoqui and Lodi [37] identified 77 factors and classified them into seven categories, including project management-related factors, procurement-related factors, client-related factors and business-related factors. They revealed that the 10 CSFs (Critical Success Factors) of a project are decision-making effectiveness, project manager experience, contractor cash flow, contractor experience, owner or owner representative decision timeliness, site management, supervision, planning effort, project management experience and client decision-making ability. They determined that the five CSF groups that most influence project success are contractor-related factors, project manager-related factors, procurement-related factors, design team-related factors and project management-related factors. Au Yong et al. [38,39] validated the importance and role of safety for setting the priority of maintenance activities.

2.3. Safety Indicators

Safety indicators are the core and key tool for the control and management of safety in the facilities life cycle. Ho et al. [40] developed a system composed of a building health and hygiene index (BHHI) and a building safety and conditions index (BSCI) for the improvement of tall residential building performance, hygiene and safety in Hong Kong. They surveyed 140 tall residential buildings and used their survey results to develop an assessment method based on a hierarchy of indicators: (1) architectural design, (2) building services design, (3) the surrounding environment, (4) operations and maintenance and (5) management. They concluded that management systems account for 82% of the variance in the BHHI and 45% of the variance in the BSCI. Their results emphasized the importance of building management systems for the safety and health of building users, particularly in densely populated areas. Hopkins [41] stressed that process safety indicators should measure the effectiveness of the risk control system and that these indicators must be included in an incentive payment scheme. Nevertheless, Hopkins emphasized that careful attention is required to avoid managing the management process rather than actual safety. Following Hopkins, Harms-Ringdahl [42] determined that the core safety indicators can be static or dynamic and should reflect the organizational safety process, as well as the outcomes. Ryczyński et al. [43] proposed that, to strengthen structural safety and durability, special attention must be paid to the causes of cracks, as well as to planning and conducting appropriate repairs. In addition, many building safety accidents are caused by faulty designs. Therefore, risk assessment in the design stage is crucial in risk management [44].

This review of the concepts of risk factors, maintenance and safety indicators reveals a gap in the integration between risk, maintenance and safety for synergetic and integrated maintenance and the safety management of facilities and indicates the research gap. The latter derived the principal purpose of the research: the development of an integrated maintenance–safety framework, as well as the subgoals, to examine the correlation between safety and maintenance in educational and public facilities.

The research hypotheses were derived from the research gap and literature as follows:

- a. A correlation exists between the maintenance performance of the educational facility and its safety, i.e., the higher the maintenance performance of the facility, the higher the safety of the facility is.
- b. There exists a correlation between the density of occupants (occupancy) and the performance and safety of educational and public facilities.

3. Integrated Risk-Informed Safety–Maintenance Framework

An integrated risk-informed safety–maintenance framework was developed within the scope of the research. The framework is composed of the performance model (monitoring the adequacy of the building to its designated performance), maintenance model (monitoring preventive and breakdown maintenance) through the MI and safety model (monitoring and control of the safety of the building's systems) through the BRI. The framework is implemented using three phases: safety monitoring and control using the BRI, building performance monitoring and building maintenance monitoring using the MI. Synthesis between the safety, maintenance and performance indicators yields control loop remarks and outputs for the implementation of corrective safety maintenance activities and corrective condition-based maintenance that stimulates the synergy between safety and maintenance performance over the life cycle of the building (Figure 1). The framework is implemented with a structured object class demonstrated in Figure 2; it is composed of structural stability, structural integrity, preventive maintenance, breakdown maintenance and a performance evaluation of the components (Figure 3, referring to the exterior envelope). Similar schemes are implemented for the interior finishing; electrical system; water and sewage system; HVAC (Heating, Ventilation and Air Conditioning); fire extinguishing; elevators; Information and Communication Systems (ICT) and peripheral infrastructures.

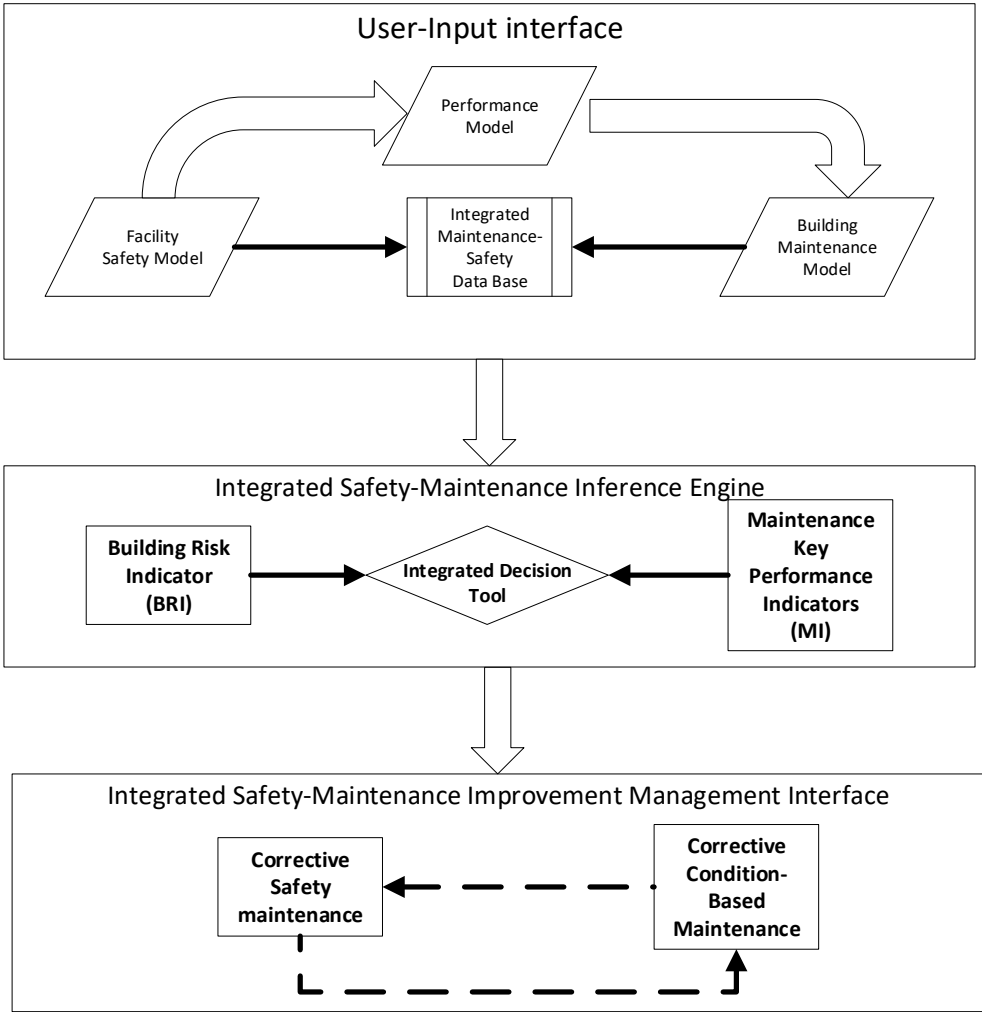


Figure 1. Integrate the risk-informed safety-maintenance implementation framework.

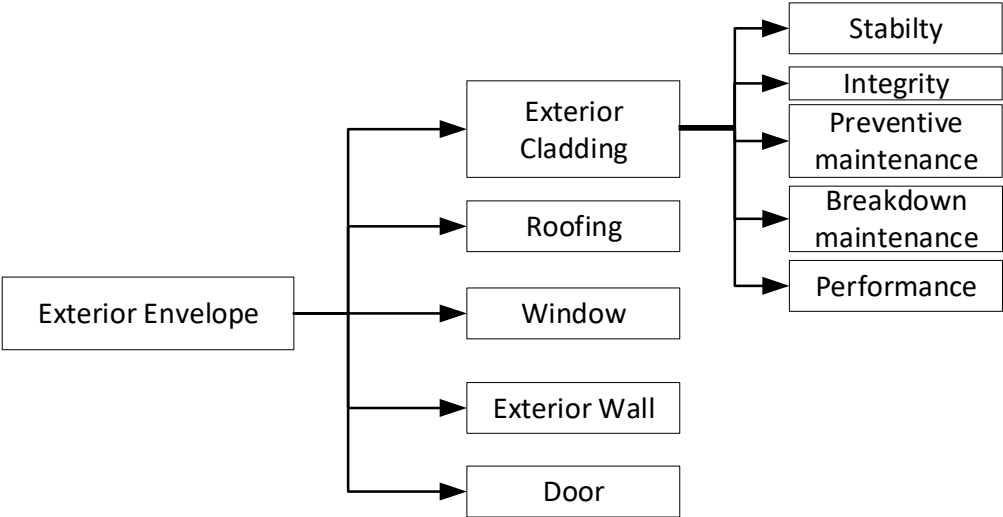


Figure 2. Structure of object classes for parameters of the integrated safety-maintenance in the user-Interface.

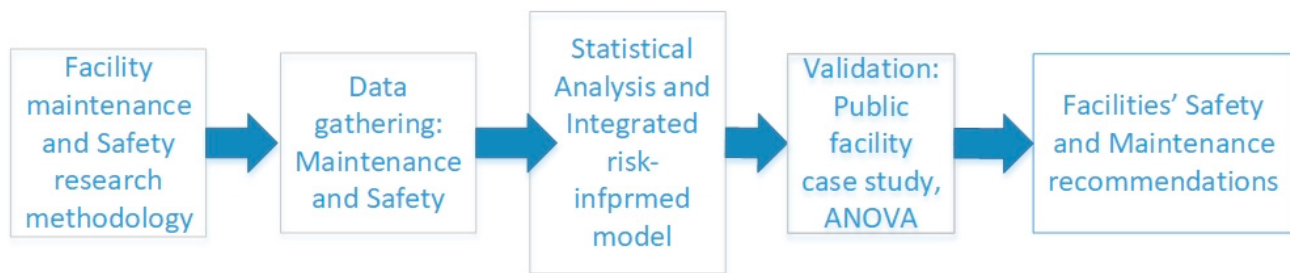


Figure 3. Research phases and methodology.

The proposed framework develops a novel risk-informed methodology for the integrated safety–maintenance management of public and educational facilities. The framework builds upon an integrated tool for combined safety–maintenance monitoring of facilities. The framework takes advantage of the synergy between maintenance and safety and leverages the synergy to introduce enhanced high-performance, safe and cost-effective maintenance of facilities.

4. Research Method

The research employed analytical–empirical methods aimed at the development of an integrated maintenance–safety framework and validation of the framework through inferential statistics and a case study. The research followed the definitions of ISO/DIS 45001 [45] and the guidelines of ISO 14001 and OSH 2001: Guidelines on Occupational Safety and Health Management Systems. The research phases and method are described in Figure 3. It followed five steps [19,46,47]: (1) data gathering methodology for safety and maintenance assessment and control in educational and public facilities, (2) field survey of maintenance and safety in educational facilities, (3) inferential statistical analysis and the development of an integrated risk-informed safety–maintenance framework, (4) implementation and validation of the framework in a public facility case study and assessment of the research hypothesis using regression analysis and F-statistics and (5) conclusion and recommendations for further research. The framework is a theoretical and practical framework, and the theory is validated in a field survey in Section 3 and implemented for practical validation in Section 4.

The research employed four tools of data gathering and analysis:

- a. Field survey of 24 educational institutions facilities, with at least 200 students each carried out by the researchers. The survey examined the maintenance activities according to: (1) breakdown maintenance, (2) routine maintenance (performance based) and (3) preventive maintenance [46,47]. The institutions were sampled according to their size, data was gathered by a trained surveyor and the information was collected from the city database and from the site survey. The data collected included: floor area (sq.m.), number of students, density of students (students/sq.m.), BRI score and MI score.
- b. Gathering of the data of safety hazards in the institutions in all disciplines of the buildings' systems; the data was gathered through interviews with the facilities' maintenance managers using the BRI (Building Risk Indicator) described below;
- c. Assessment of the maintenance performance and safety of the facilities using a 25-point rating scale of the severity and probability of failures; assessments were carried out by the researchers through walk out and detailed site surveys in the facilities;
- d. Case study and validation of the proposed framework in a public facility using the safety (BRI) and maintenance performance (MI—Maintenance Indicator) models.

The research used 25-point rating scale for the assessment of the safety and maintenance performance of the facilities. The safety assessment and the maintenance performance scales are presented in Tables 2 and 3, respectively, and the deterioration and safety assessment criteria are described in Appendix A. The scales follow the outline developed by

Ni et al. [48] for safety assessment and were further developed for deterioration assessment. The deterioration categories definitions based on the 5-point rating scale introduced in Shohet [19,46]. The safety assessment categories examine the safety consequences, and the 25-point scale represents the risk potential as a multiplication of the severity (consequences) of hazards by the likelihood (probability). These definitions were further developed in this study to 24 categories of core safety components and systems as follows: Infrastructures, Yard organization, Ground leveling, Walking trails, Fence, Gates, Parking, Sports facilities, Preventive measures, Fire Protection, Escape Preparations, Nuisance, Windows and bars, Doors, Railings, Stairs and stairways, Structure, Electric Panels, Lighting, and Emergency lighting and electric wirings. These categories were selected from the review of the literature and are the guide for the safety of educational institutions in the literature review as key maintenance performance and safety performance indicators [11,12,49]. A Building Risk Indicator (BRI) of 0–4 indicates low risk, i.e., safe facility (within this category, between 0 and 2 represents exceptionally safe and between 2 and 4 safe). Building Risk Indicator of 5–12 indicates moderate to marginal and unacceptable risk; within this category, 5–8 represents moderate and unacceptable risk, and a BRI of 8–12 represents marginal-severe risk. The BRI of 12–25 indicates risk at highly severe and up to critical level (this category requires immediate repair of the faults and closure of the institution due to regulatory restrictions). The Building Risk Indicator refers to architectural design, building services schemes safety, the surrounding environment safety, operations and maintenance safety and to safety management activities as derived from Ho et al. [41]. In a similar manner, a maintenance indicator (MI) of 0–4 indicates a durable and well-maintained facility, and within this category, a maintenance indicator between 0 and 2 represents a high durability, and maintenance indicator of 2–4 indicates light deterioration due to aging of the component. A maintenance indicator of 5–12 indicates moderate deterioration (5–8) and marginal maintenance performance (8–12), and between 13–25 indicates highly deteriorated system and lack of maintenance.

Table 2. Grading scale of safety risks of educational buildings systems.

Severity \ Probability	Rare 1 0–10%	Low 2 11–40%	Moderate 3 41–60%	High 4 61–90%	Frequent 5 91–100%
Critical 5	5	10	15	20	25
Severe 4	4	8	12	16	20
Moderate 3	3	6	9	12	15
Minor 2	2	4	6	8	10
Negligible 1	1	2	3	4	5
Legend			High Risk		
			Moderate Risk		
			Low Risk		

This stage laid the ground of the risk informed framework with safety risk and maintenance assessment criteria. These will be used to examine the correlation between the two core variables and as tools for implementing the framework.

Table 3. Grading scale of maintenance of educational buildings systems.

Severity \ Probability	Rare 1 0–10%	Low 2 11–40%	Moderate 3 41–60%	High 4 61–90%	Frequent 5 91–100%
Critical 5	5	10	15	20	25
Severe 4	4	8	12	16	20
Moderate 3	3	6	9	12	15
Minor 2	2	4	6	8	10
Negligible 1	1	2	3	4	5
Legend			High Risk		
			Moderate Risk		
			Low Risk		

5. Results

The field survey encompassed 24 educational institutes out of 80 in the city of Beer Sheva, composing 30% of the educational facilities population of the city. The survey included background data of the buildings, such as floor area and number of users, as well as assessment of the facilities' maintenance and safety according to the maintenance indicator (MI) and Building Risk Indicator (BRI) defined in the research methodology. The field survey was carried out using a questionnaire and in situ data gathering using a form with detailed scales of safety and maintenance rating criteria. Appendix A presents an example of the rating criteria for exterior cladding safety and maintenance performance. Table 4 summarizes the sample population characteristic background data.

Table 4. Parameters of educational institutes' samples.

Variable	Total	Mean
Floor area (sq.m.)	98,270	4095
Number of students	14,381	599
Density (Number of students/100 sq.m.)	-	15.94
Mean Maintenance score (MI)	-	5.88
Mean Safety Score (BRI)	-	5.42

The mean maintenance indicator (MI) and Building Risk Indicator (BRI) were found to be 5.88 and 5.42, respectively, indicating moderate/marginal maintenance performance and safety risks. The main safety and maintenance faults found are sports grounds, gates, emergency lights and electricity end fixtures. Examination of the correlation between the density of students and the maintenance, as well as the safety performance of the institutions found no systematic ratio, and led to rejection of the second research hypothesis.

5.1. Safety

The highest mean scores of safety risk indicators for the different sections found to be: windows and bars (8.2), static and dynamic nuisances (7.5), wirings (7.0), hallways (6.9), doors and railings (6.7) (Figure 4). Figures 5 and 6 demonstrate examples of typical safety hazards in sports ground and exterior cladding, respectively: lack of safety fixtures and poor maintenance of sport ground (Figure 5a,b, respectively) and deteriorated and poorly maintained exterior stone (Figure 6a,b, respectively).

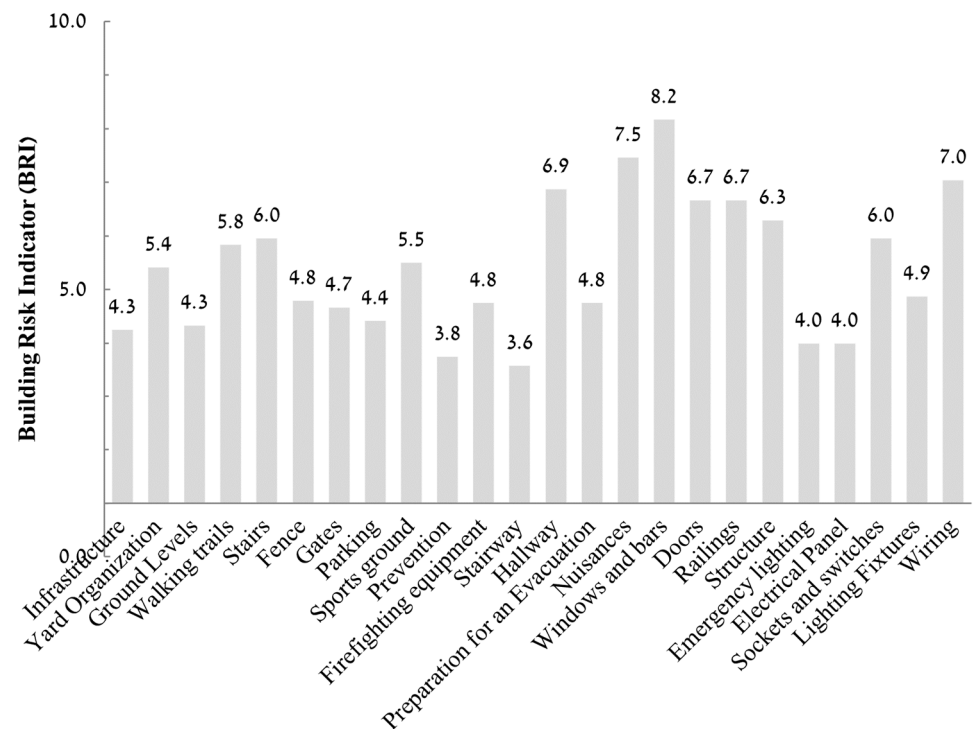


Figure 4. Mean Building Risk Indicator (BRI) in educational facilities sample according to building systems.



(a)



(b)

Figure 5. Sports—(a) unprotected basket column and (b) poorly maintained basketball surface.

5.2. Maintenance

The following systems found with the highest maintenance score (i.e., most deteriorated): (1) emergency lighting (7.3); (2) static and dynamic nuisances (7.3); (3) electric sockets and switches (7.0); (4) railings (6.9) and (5) gates, preparation for escape and sports grounds (6.8) (Figure 7). The findings demonstrate that electric components, static and dynamic nuisances are the most deteriorated components. Considering $MI < 5$ as a threshold of high maintenance, it is evident that most of the systems do not meet this performance criterion.



Figure 6. (a) Deteriorated exterior stone cladding. (b) Cracked stone claddings.

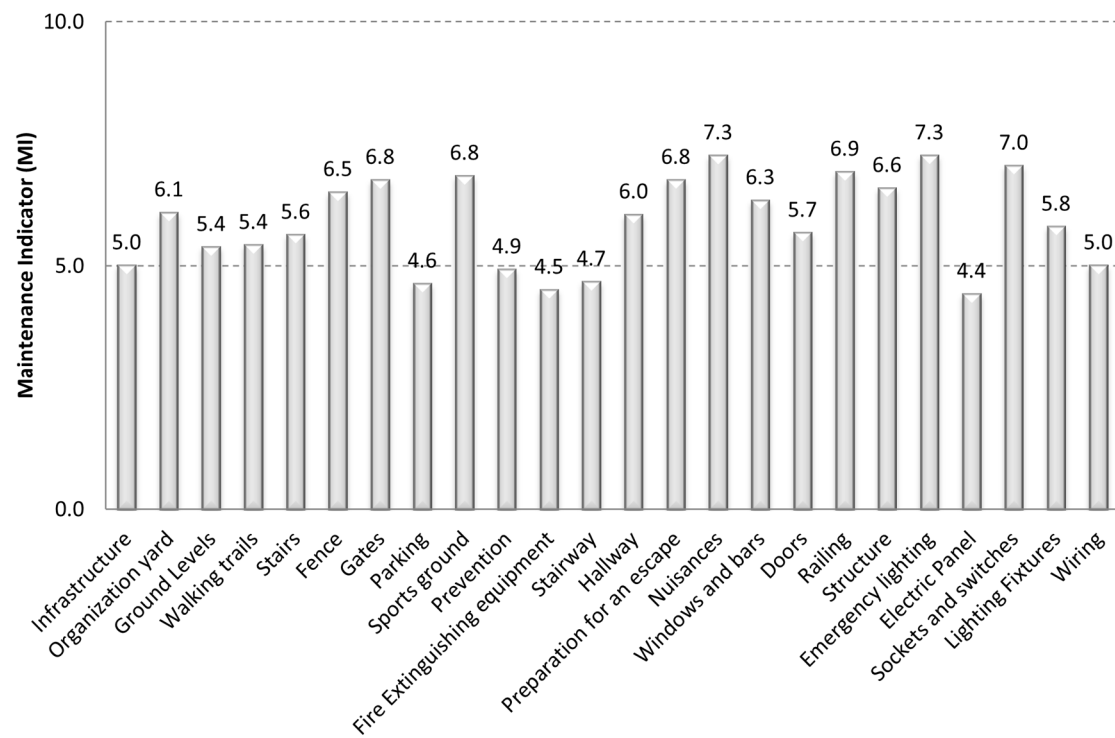


Figure 7. Mean maintenance indicator (MI) for different building and infrastructure systems—Educational Institutions.

5.3. Synergy between Maintenance and Safety

The synergy between maintenance and safety was examined using the Pearson correlation for two variables sample with 22 DOF (Degrees Of Freedom) and at a significance level of 0.01. The critical value for positive correlation is 0.472. Components with Pearson coefficient higher than 0.472 defined as components with strong synergy and those with the Pearson's coefficient lower than 0.472 defined as components with low or no synergy. Figure 8 depicts the distribution of the maintenance indicator (MI) and building risk indicator (BRI) for the 24 systems investigated. The distribution indicates fair link between the safety and maintenance of structure, railings, static and dynamic nuisance, hallways, fire protection, parking, stairs, walking trails, yard organization and infrastructures. The Pearson coefficient for the overall maintenance coefficient found to be 0.7408 indicating that a variance in the maintenance performance explains 74.08% of the variance in safety

(BRI). Table 5 depicts the details of the Pearson's coefficients between the BRI and MI for 24 variables examined within the study. One can deduce that the safety of electric panels and emergency lighting fully explained by the maintenance of these components, 90% of the variance in electric end fixtures, 78% of the variance in parking safety, 49% of the variance in sports facilities and 48% in Fire Protection safety are explained by the conduct of adequate maintenance activities. The findings provide solid evidence of the synergy between safety and maintenance and indicate that 74% of the variance in maintenance is explained by the variance in safety of the facility. Figures 5 and 6 demonstrate a couple of examples of the impact of lack of maintenance of a sports facility (6) and exterior stone cladding (5) on the safety of the facility. It stems from the study that other root causes such as: (1) service regime, (2) design parameters, and (3) safety control and assurance affect the rest of the variance in the facilities' safety risk.

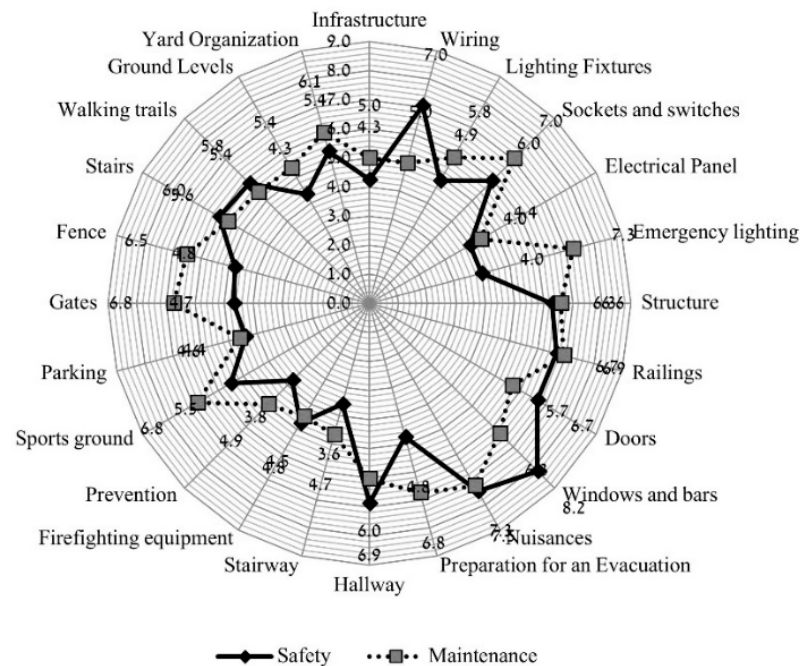


Figure 8. Mean Safety Indicators Vs. Mean Maintenance Indicators—Educational Institutions.

Table 5. Pearson coefficient for the facilities' components and systems.

Component	R	R ²	% of Explained Variance
Infrastructures	0.310	0.10	9.61
Yard organization	0.603	0.36	36.36
Ground leveling	0.422	0.18	17.81
Walking Trails	0.649	0.42	42.12
Stairs	0.114	0.01	1.30
Fence	0.538	0.29	28.94
Gates	0.318	0.10	10.11
Parking	0.886	0.78	78.50
Sports Facilities	0.702	0.49	49.28
Prevention	0.331	0.11	10.96
Fire Protection	0.697	0.49	48.58
Stairways	0.734	0.54	53.88
Hallways	0.444	0.20	19.71

Table 5. Cont.

Component	R	R ²	% of Explained Variance
Escape Preparation	0.576	0.33	33.18
Nuisance	0.056	0.00	0.31
Windows and Bars	0.117	0.01	1.37
Doors	0.426	0.18	18.15
Railing	0.475	0.23	22.56
Structure	0.666	0.44	44.36
Emergency Lighting	1	1	100
Electric Panels	1	1	100
Electric Fixtures and Switches	0.952	0.91	90.63
Lighting fixtures	0.334	0.11	11.16
Wirings	0.291	0.08	8.47

Figures 4–8 indicate marginal maintenance and safety performance in the educational facilities sample. It stems from the mean scores of MI and BRI of most of the components at levels higher than 5.74% of the variance in Risk were explained by the execution of maintenance. These findings are demonstrated by Figures 5 and 6. In the next phase of the research a case study of the proposed framework was implemented in public facility to assess the validity of the framework.

5.4. Case-Study—Public Building Integrated Maintenance and Safety

The case study is a public building (courthouse) located in the north of Israel. Its floor area is 26,000 sq.m. of office floors, 3000 sq.m. of parking floors and 4000 sq.m. of gardens and paved access paths. It was constructed in 1999, and its average occupancy is: 340 employees and 3000 visitors per working day (250 days/year). The service regime in the building is standard [50,51]. The integrated risk-informed safety–maintenance framework was implemented in the building between 2010 and 2021 using the safety and maintenance indicators through integrated maintenance–safety audits. An overview of the building, its exterior envelope and electromechanical systems conditions as per 2021 are presented herein. Figures 9–12 illustrate the overview of the building, its exterior envelope, roofing and peripheral infrastructures.



Figure 9. Overview of the building.



Figure 10. Exterior envelope (Maintenance Indicator = 2.5).



Figure 11. Roofing and installations (Maintenance Indicator = 2.5).

The building went under an integrated maintenance–safety performance model according to the framework put forward in this research. The maintenance and safety indicators of the building along the case study implementation period are presented in Figure 13. A high level of fitness between the safety and maintenance performance indicators is observed. Furthermore, consistent improvement in maintenance and safety is observed along the period of implementation. The maintenance and the safety performance of the building as of 2021 (22 years after construction) is remarkably high (2.673 and 2.43 for the maintenance and safety indicators, respectively). The latter indicates a safe working environment, effective safety climate and high-performance building environment.

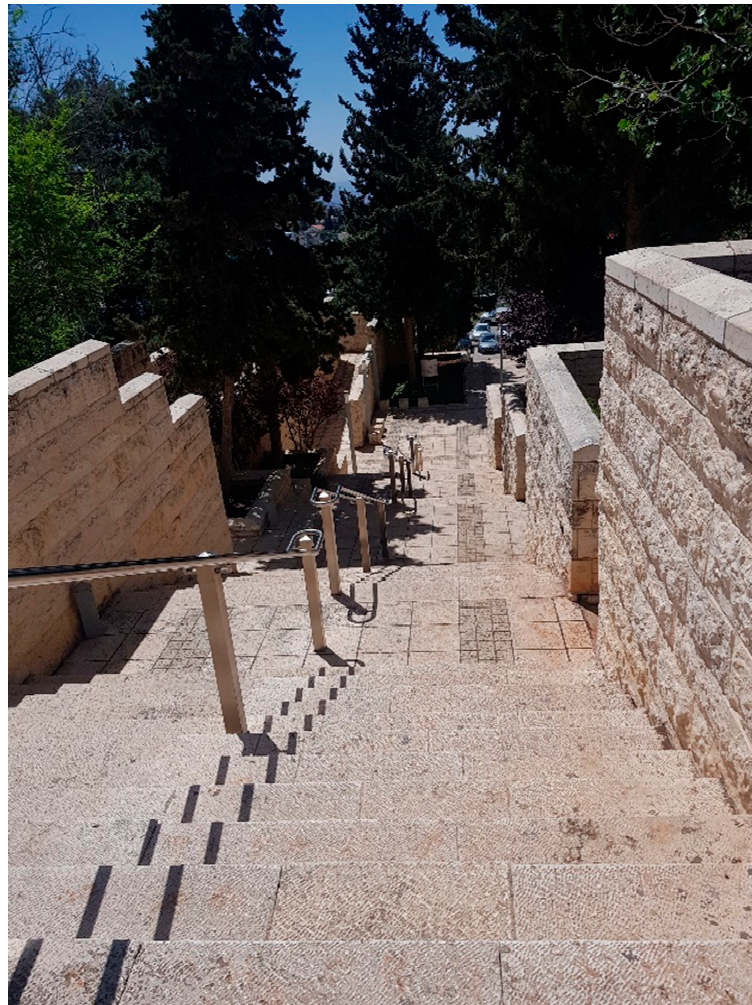


Figure 12. Stairs and drainage infrastructures around the building (Maintenance Indicator = 2.75).

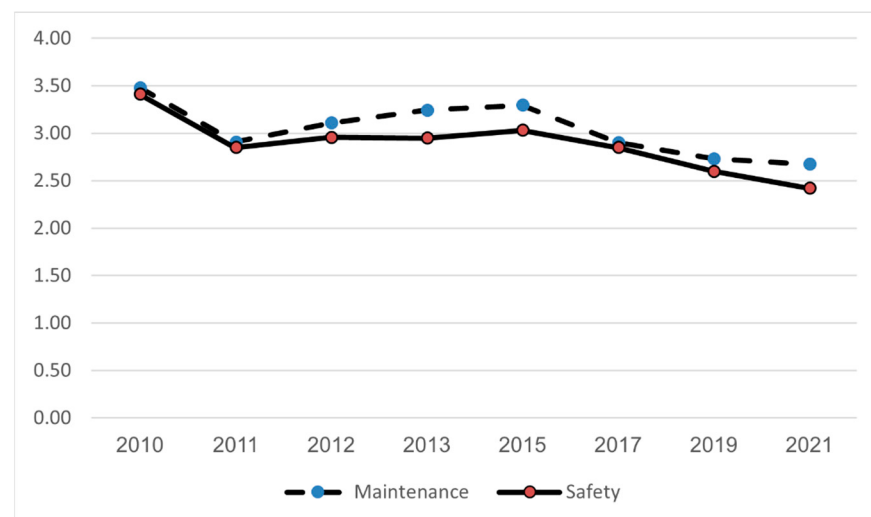


Figure 13. Maintenance and safety indicators in public building case study 2010–2021.

Analysis of variance of the correlation between the maintenance and safety indicators in the case study found a correlation (R^2) of 0.8865 and the p -Value < 0.000478 for significance level of 0.05 (Figure 14). The regression analysis equation is: $Y = 0.9135 \cdot X + 0.4081$ (where Y is the maintenance indicator and X is the safety indicator). The case study strongly validates the

safety–maintenance synergy hypothesis resulting from the integrated safety and maintenance performance model proposed in this research. 88.65% of the variance in maintenance performance was explained by the variance in the safety of the facility. The case study demonstrates a strong synergy between the implementation of safety and maintenance models, and that this synergy enhances simultaneous and continuous improvement of the safety, maintenance and performance of buildings. The findings were found to be significant at high level of significance (p Value = 0.00047). These findings support the practical implication of the framework for facility managers.

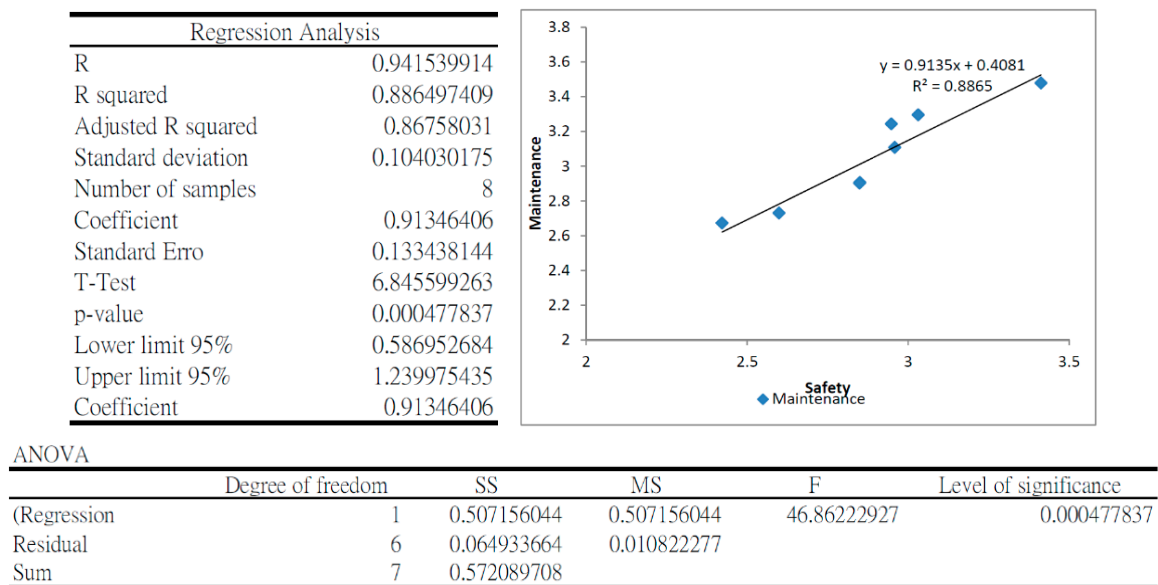


Figure 14. Regression model and analysis.

6. Discussion

Maintenance and safety of facilities are two close disciplines that share common tools and principles [18–20]. While facilities maintenance is a discipline that carries out preventive, performance-based and breakdown maintenance activities aimed at maintaining the building performance, value and its designated use at high standards, safety discipline uses audits and control tools to maintain acceptable level of risk and maintain the facility safety performance and the wellbeing of the facility occupants.

An integrated theoretical and practical multi-layered risk informed safety–maintenance framework is introduced. The model follows four layers: (1) risk assessment, (2) corrective safety maintenance, (3) maintenance performance assessment and (4) risk-informed preventive maintenance and safety activities. Frangopol et al. [52] introduced the integration of risk, sustainability and resilience into the service life planning of structural bridge systems and components. The model integrates risk and life-cycle loss assessment with multi-objective optimization of bridge and bridge network management. This research emphasizes that a parallel model for educational and other public facilities attains the potential for optimum life cycle costs, as well as meeting the safety and performance constraints.

The preliminary phases of the study revealed that the conduct of high-quality maintenance activities explains 74% of the safety risks variations in educational facilities. The density of the occupants (service regime) does not significantly affect the level of safety risks. The outcomes of the research are similar to preceding research by Arunraj and Maiti [53] in the chemical industry, Geng et al. [54] in virtual maintenance in improving the maintenance safety design and by Khalil et al. [23] in high education facilities. A case study in public facility for a period of 11 years yielded a consistent and continuous improvement of safety and performance of the facility and showed a correlation coefficient of 0.8665 between the safety and the maintenance performance of the facility. The research proposes a novel integrated safety–maintenance management model, and provides solid, validated evidence

regarding the synergy between safety and maintenance. The proposed framework may be implemented in various types of facilities such as critical facilities, energy, healthcare and off-shore facilities.

7. Conclusions

The research introduces the topic of synergy and integrated risk-informed safety–maintenance in facilities management. An integrated safety–maintenance model for public facilities was developed and implemented in a case study in the last phase of the research. The following conclusions summarize the research findings:

- a. Safety performance in educational institutions was found to be highly dependent on the variance in maintenance performance; this conclusion was deduced from the high Pearson coefficient between the Building Risk Indicator and the Maintenance Indicator;
- b. It was found that maintenance activities strongly affect the safety of electric system components (electric panels, lighting, end-fixtures and switches); infrastructures (parking lots, sports facilities, walking trails, and yard organization), fire protection and structural components (stairways, walls, roofs and columns). This conclusion deduced from the partial Pearson coefficients of the facilities' systems between the safety and the maintenance performance for these systems;
- c. The study indicates that systematic maintenance of the critical facilities' components such as electric system components, structural components, fire protection and infrastructures implemented with robust, integrated safety–maintenance procedures. This conclusion stems from the inherent dependency between these systems safety and maintenance performance as depicted by the Pearson coefficients discussed above.
- d. Annual safety audits of the systems seem to be insufficient in light of the study findings, higher frequencies of maintenance, and safety audits with intervals of between 3 and 6 months are suggested. This conclusion drawn from the marginal performance of maintenance indicator (MI) and safety (BRI) in the sample population, which accomplished in annual safety and performance audits regime.
- e. An integrated safety–maintenance performance framework was introduced for synergetic safety–maintenance monitoring, control and management. The framework proposes a cycle loop of safety–maintenance–performance of facilities as a key tool for advanced and effective maintenance and safety management with intervals between 3 and 6 months in public facilities.
- f. The framework was validated in a case study of public facility along a period of 11 years. The time history of maintenance performance and safety shows a high level of fitness ($R^2 = 0.8865$ $p < 0.05$). The latter finding supports the practical implication of the framework for facility management applications.
- g. This research findings stresses that integrated safety and maintenance should be implemented as a unified and integrated procedure and that this procedure will enhance advanced maintenance performance and safety.

The research develops and provides a robust framework for risk-informed integrated safety–maintenance management framework for educational and public facilities. The theory has been validated in educational and public facilities.

A methodology for the implementation of the framework has been put forward and lay the ground for integrated safety–maintenance methodology. The case study provided solid evidence of sustainable development of the performance of the facility under the implementation of the framework. Future research is recommended to elaborate the framework for automation withing the IFC schema and implement the principles through AI and machine learning tools.

8. Limitations of the Research

The research was carried out on a limited sample of educational public facilities. Extending the research sample could improve the reliability and validity of the research.

Further case studies can elaborate the significance and applicability of the methodology in critical facilities; healthcare and infrastructures such as water, communications, etc.

The research did not refer to the cost-effectiveness of the proposed framework. This should include labor, equipment and spare parts and overheads costs. Analysis of the cost-effectiveness could shed light on the sustainability of the methodology and provide economic and organizational drivers to implement the methodology.

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Appendix A. Static and Dynamic Nuisance Maintenance and Safety Grading Criteria

Table A1. Maintenance grading criteria (MI).

1	2	3	4	5
Cladding is complete and undamaged. No cladding elements have fallen off. Some capillary cracking may be present.	Capillary cracks have developed on portions of the cladding. Single cladding elements have fallen off.	Cracks 0.5 mm wide cover less than 5% of the total cladding area. Up to 3 % of cladding elements have fallen off	Cracks wider than 1 mm have developed on 5% or more of the cladding area. Portions of stone cladding have fallen off.	Significant portions of the cladding have peeled or fallen off. Cracks wider than 5 mm have developed

Table A2. Safety grading criteria (BRI).

1	2	3	4	5
Interior Claddings: Complete, stable, no signs of erosion, degradation, No mechanical deflections, cladding is planar Exterior cladding: Cladding is complete, no minor cracking, no mechanical deformations exterior element properly fixed to claddings.	No erosions, but minor sporadic cracks or spalling in interior cladding, Exterior cladding: Cladding is complete, nor fractures, minor cracks and spalling.	Detachment of up to 3% of cladding, erosion and deterioration of cladding due to intensive use. Fixtures attached to cladding are loosely fixed.	Exterior cladding cracking of up to 5 mm. development of spalling and detachments. Fixtured detached from cladding.	Significant part of cladding have peeled or fallen off. Significant spalling, cladding detached. Cracks wider than 5 mm have developed. Cladding is unstable.

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