Investigating the Functional Vulnerability of an Industrial Building in Seismic Risk Management

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ABSTRACT

The seismic protection level of a structure depends on its functional purpose and relative importance in accordance with the protection objectives established by the authorities. Critical infrastructure, such as hospitals and industrial facilities, must remain operational following a major seismic event, adhering to the performance-based design criteria. While the moderate seismic activity may pose a negligible structural risk, it can critically compromise the service functionality due to non-structural component failures (e.g., mechanical, electrical, or plumbing systems), potentially disrupting the essential operations. For critical facilities, such as hospitals, power plants, or industrial complexes, post-earthquake operational continuity requires both structural robustness, ensuring the life-safety and collapse prevention under earthquake scenarios, and functional reliability, maintaining the operational capacity of the technical systems through seismic qualification and fragility mitigation. This paradigm aligns with the advancements in functional recovery frameworks, which emphasize not only the survivability, but also a fast return-to-service. However, challenges remain in standardizing the vulnerability assessment methodologies for non-structural components, particularly in regions with heterogeneous construction practices, such as Northern Algeria. Within the framework of seismic risk prevention, this study implements a Rapid Visual Screening (RVS) based methodology initially developed for the seismic vulnerability assessment of hospital buildings, to investigate its application in the industrial context using a cement plant as a case study.

Keywords-vulnerability; seismic risk; industrial buildings; non-structural component; rapid visual screening; multicriteria analysis

I. INTRODUCTION

The increasing frequency and severity of the seismic events have highlighted the critical need for robust vulnerability assessment methodologies, particularly for strategically vital infrastructure (e.g., hospitals, power plants, and industrial facilities) [1–5]. Such infrastructure must not only resist the structural collapse during earthquakes, but also maintain functional continuity to ensure the post-disaster serviceability [6, 7]. While traditional seismic risk assessments have focused primarily on the structural integrity, research highlights that the non-structural components (e.g., mechanical, electrical, and plumbing systems) often dictate operational resilience [8, 9]. Failures in these systems, even in cases where the building structure remains intact, can lead to catastrophic service disruptions, particularly in essential facilities which communities rely on for emergency response and recovery [10]. The operational disruptions systematically generate catastrophic consequences for the critical service providers (e.g., hospitals, industrial facilities), while inducing severe economic losses for the industrial facilities due to the production shutdown during the seismic events [11]. For industrial facilities specifically, the requirement to maintain operations immediately post-earthquake compels operators to implement preventive measures ensuring that the non-structural elements–through their behavior or failure–do not directly or indirectly disrupt the operational continuity or business recovery [10]. The operational continuity after seismic events depends on maintaining critical systems (e.g., electrical power, water supply) and preserving the structural integrity.

Advancements in the vulnerability assessment methods have improved large-scale vulnerability mapping, yet challenges remain in accurately assessing the functional vulnerability–the susceptibility of critical systems to seismic-induced operational failure [12]. The RVS Method is a well-known approach for evaluating the reliability of the mechanical and electrical components in the context of earthquakes, based on American codes [13–15]. While the RVS method relies on historical seismic data, it fails to address the integration of new components, prompting the search for an alternative method that combines intrinsic component characteristics with on-site installation conditions to provide a more comprehensive evaluation framework [15]. A study on hospital vulnerability assessment [16] addresses this gap, integrating on-site new components by adopting a refined multi-criteria vulnerability assessment framework, taking into account both structural and non-structural performance metrics. Building upon the specialized method developed in [16], this study investigates its adaptation in the industrial context using a cement plant production unit as a case study.

II. ADOPTED VULNERABILITY ASSESSMENT METHOD

The specialized method adopted in this work focuses on evaluating the vulnerability of individual components within a system, which is essential for assessing the overall system's vulnerability to seismic events. The methodology is structured into three main steps, as shown in Figure 1.

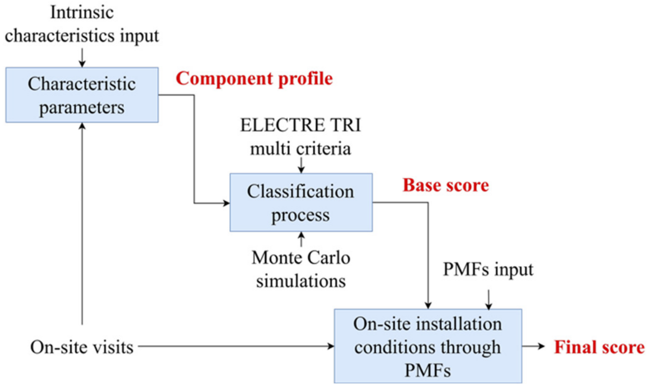

Fig. 1. Process for determining the base score and final score of a component (adapted from [16]).

First, a component profile is created by inputting fifteen key characteristics, grouped into five criteria based on the analysis of post-earthquake mission reports, technical manuals, and component datasheets from the Visual Screening Method [17–20]: mass, constitution, dynamic behavior, functional sensitivity, and installation mode. These criteria capture both physical and operational aspects of the component, such as its weight, fragility, moving parts, sensitivity to vibrations, and connection to the structural system. Second, an intrinsic base score is calculated using the ELECTRE-TRI Multi Criteria Decision Analysis method [21], designed to classify a set of alternatives into predefined ordered categories, which classifies the components in this case into vulnerability categories (from Non-Vulnerable to Highly Vulnerable). To objectively determine criteria's weights, the study employed the Analytic Hierarchy Process (AHP) [22], which relies on pairwise comparisons, where analysts assess the relative importance of each criterion against the others. These comparisons populate a decision matrix, which undergoes mathematical transformations to derive normalized eigenvector components, representing criteria weights and quantifying the contribution of each criterion to the overall decision framework. The pairwise criteria comparison matrix used in AHP and the relative weight of the five criteria are displayed in Tables I and II, respectively. Next, two distinct classification outcomes are considered, an optimistic and pessimistic ranking, which may either converge or diverge in their assessment. A predefined transition matrix converts these ordinal classifications into quantitative vulnerability scores spanning a continuous scale from 0 to 6, as presented in Table III. Monte Carlo simulations are then employed to account for the uncertainties in the data, ensuring the robustness of the results [23]. The component vulnerability classification demonstrates significant sensitivity to two primary factors. First, the ELECTRE-TRI's technical parameters substantially influence the outcomes, including threshold values (preference p, indifference q, veto v, and cutting level λ), reference actions, and criteria weights. To account for the technical parameter uncertainty, the method established bounded intervals for each threshold while preserving the fundamental relationship $q<p<v$. These intervals are carefully constrained to maintain the separation between the reference profiles, as presented in Table IV. The analysis considers:

- Indifference threshold q: 3 discrete values (2, 3, 4)
- Preference threshold p: 3 values (5, 6, 7)
- Veto threshold v: 5 values (8-12)
- Cutting level λ: 5 values (0.65-0.80 in 0.05 increments)

The second factor is the operator-assigned component profile, as analysts typically rely solely on the perceptual assessments of the observable component characteristics rather than on the quantitative measurements, which introduces variability. To account for the uncertainty during the parameter entry, the method introduced a confidence assessment system where the users classify their inputs as "Sure," "Fairly sure," or "Unsure." The qualitative inputs are modeled using triangular distributions scaled to confidence levels: "Sure" corresponds to a narrow ±5% range, "Fairly sure" to a ±25% range, and "Unsure" to a broad ±50% range. In the final step, the base score is adjusted to reflect the on-site conditions through Performance Modification Factors (PMFs), which involve factors like anchoring quality, attachment systems, stability, and environmental interactions, providing a clear indication of the component's overall vulnerability. The final score, in this case, is evaluated according to a standardized rating scale illustrated in Table V.

TABLE I. PAIRWISE CRITERIA COMPARISON MATRIX [16]

Criteria	Mass	Constitution	Dynamic	Functional sensitivity	Installation mode
Mass	1	3	3	1/3	1/3
Constitution	1/3	1	1	1/5	1/5
Dynamic	1/3	1	1	1/3	1/4
Functional sensitivity	3	5	3	1	2
Installation mode	3	5	4	1/2	1

TABLE II. RELATIVE WEIGHTS OF FIVE CRITERIA (INTER-CRITERIA PARAMETERS) [16]

Criteria	Mass	Constitution	Dynamic	Functional sensitivity	Installation mode
Relative weights	16	7	8	38	31

TABLE III. BASIC SCORE ASSIGNMENT MATRIX [16]

		Optimist			
		Non-vulnerable	Slightly vulnerable	Vulnerable	Highly vulnerable
Pessimist	Non-vulnerable	0	X	X	X
	Non-vulnerable	1	2	X	X
	Non-vulnerable	2	3	4	X
	Non-vulnerable	X	4	5	6

X denotes "No available option. "

TABLE IV. INTRA-CRITERIA PARAMETERS [16]

Nom	Mass	Constitution	Dynamic	Functional sensitivity	Installation mode
Preference threshold (*p*)	6	6	6	6	6
Indifference threshold (*q*)	3	3	3	3	3
Veto threshold (*v*)	9	9	9	9	9

TABLE V. RATING SCALE FOR THE FINAL SCORE (S) OF COMPONENT VULNERABILITY [16]

Scale	$S<3$	$3<S<6$	$6<S<10$	$S>10$
Vulnerability class	Non-vulnerable	Slightly vulnerable	Vulnerable	Highly vulnerable

III. VULNERABILITY ASSESSMENT PROCESS

The method was tested in the El-Ma Labiod cement plant in Algeria. The plant is composed of several operational sections:

- Crushing workshops (limestone, clay, and additions)
- Storage halls
- Grinding workshops (raw grinding, cement grinding)
- Furnace supply workshop
- Preheating tower
- Firing workshop
- Shipping (bagging) workshop
- Dust collection filter (bag filter)

A. *Critical Systems Identification*

Given the industrial work scale and system complexity, the analysis is restricted to those systems that are identified as possessing the highest criticality, namely:

- Furnace supply
- Material recovery and preheating
- Material preparation
- Firing
- Furnace protective system

Among these, the furnace supply system has been selected as a representative case to provide clarity and illustrative insights of the adopted approach, while also highlighting its critical role within the overall operational framework. The results for the remaining four systems are summarized in later sections. Table VI displays the different subsystems and components used in the furnace supply system.

TABLE VI. LIST OF SUBSYSTEMS AND COMPONENTS STUDIED IN THE FURNACE SUPPLY SYSTEM

System	Subsystems	Components	No.
Furnace supply system	Airlift Transport	Conduit	1
		Bottle	1
		Pressure booster	1
	Hovercraft Transport 2	Transport sheath	1
		Fan (with motor)	1
	Quantity control	Flow meter (Schenck)	2
		Schenck motor	1
		Buffer hopper	1
	Mechanical transport	Bucket elevator	2
		Elevator motor	1
	Hovercraft Transport 1	Transport sheath	2
		Fan (with motor)	2
	Electrical power supply	Transformer	1
		Air conditioner	1
		Capacitor battery	1
		Capacitor	1
		Cell	1
		Electrical cabinet	1

B. *Assigning Scores to the Components*

First, the component profile is deduced from the entry form. The component Cell has been selected as a representative case for clarity purpose. Table VII depicts the entry form for the component Cell in the electrical power subsystem, as shown in Figure 2. The mass criteria score is calculated based on a combination tree system, whereas the score of all other criteria is calculated based on a sum of the point system. The combination tree evaluation system is portrayed in Figure 3. The Cell component presented a heavy mass with bad horizontal distribution and good vertical distribution, which gives a value of $C_1 = 35$. This scoring reflects the interplay between the weight of the mass and its distribution properties, emphasizing the importance of the horizontal and vertical alignment in the assessment. The scores of the other criteria are presented in the component profile (Table VII).

TABLE VII. COMPONENT ENTRY FORM (CELL): INTRINSIC CHARACTERISTICS OF THE COMPONENT

No.	**Settings**	**Answers from the documentation or the visit**				**Profile to classify (criteria)**	**Certainty level**
P_{1-1}	Estimated mass	Light ☐	Little heavy ☐	Heavy ☒		(1) Mass **35**	Sure ☐ Fairly sure ☒ Unsure ☐
P_{1-2}	Estimation of the horizontal distribution of mass	Good ☐		Bad ☒			
P_{1-3}	Estimation of the vertical distribution of mass	Good ☒		Bad ☐			
P_{2-1}	Does it contain brittle organs?	Yes (20) ☐		No (0) ☒		(2) Constitution **0**	Sure ☒ Fairly sure ☐ Unsure ☐
P_{2-2}	Automatic closing system	Yes (20) ☐	No (0) ☒	Not applicable (0) ☐			
P_{2-3}	Does it contain pressure-bearing components?	Yes (10) ☐		No (0) ☒			
P_{3-1}	Are there moving masses?	Yes (25) ☐	No (0) ☒	Don't know (10) ☐		(3) Dynamic **25**	Sure ☐ Fairly sure ☒ Unsure ☐
P_{3-2}	Is there an anti-vibration system?	Not useful (0) ☐	Yes (10) ☐	No (25) ☒	Don't know (15) ☐		
P_{4-1}	Are any functions sensitive to movement?	Yes (10) ☐	No (0) ☐	Don't know (5) ☒		(4) Functional sensitivity **35**	Sure ☐ Fairly sure ☒ Unsure ☐
P_{4-2}	Are any functions sensitive to vibration?	Yes (20) ☐	No (0) ☐	Don't know (10) ☒			
P_{4-3}	Are certain functions sensitive to shock?	Yes (10) ☒	No (0) ☐	Don't know (5) ☐			
P_{4-4}	Is it equipped with a restart mode after a safety shutdown?	Yes (0) ☐	No (10) ☒	Don't know (5) ☐	Not applicable (0) ☐		
P_{5-1}	What is the intended component installation mode?	Fixed (0) ☐	Posed (10) ☒	Rolling (15) ☐	Suspended (20) ☐	(5) Installation mode **20**	Sure ☐ Fairly sure ☐ Unsure ☒
P_{5-2}	What is the intrinsic quality of the attachment system?	Good (0) ☐	Bad (10) ☐	Not applicable (0) ☒			
P_{5-3}	What connections are planned with the rest of the system?	Isolated (0) ☐	Flexible connection (10) ☒	Rigid connection (20) ☐			

Fig. 2. Cell from the electric power system.

By assigning the level of certainty, it is possible to obtain the performance profile and achieve a detailed assignment of the component (Cell) by the ELECTRE-TRI and Monte-Carlo simulation-based process. The performance profile of the component (Cell) is illustrated in Figure 4. Three reference profiles (Reference 1–Reference 3) partition the (0–50) criterion range into four classes (0-10: Non-Vulnerable, 10-25: Slightly Vulnerable, 25-40: Vulnerable and 40-50: Highly Vulnerable).

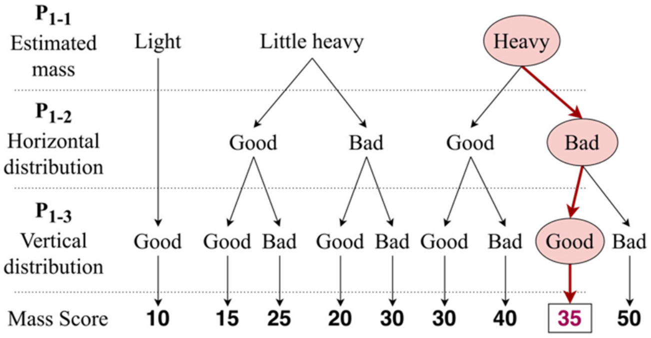

Fig. 3. Mass criteria attribution.

The two criteria "mass and functional sensitivity" have the greatest impact on the vulnerability of the component (Vulnerable), lower impact for the criteria "dynamic and installation mode", and no impact for the "constitution" criteria. The results of the classification analysis demonstrated that the component Cell is categorized as Slightly Vulnerable when assessed using the optimistic evaluation procedure, and as Vulnerable under the pessimistic evaluation procedure, as shown in Figure 5.

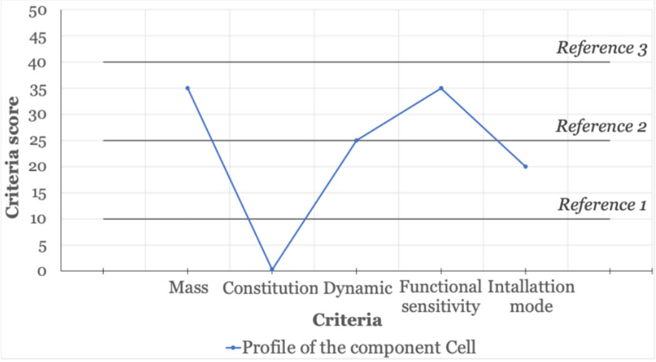

Fig. 4. Performance profile of the component (cell).

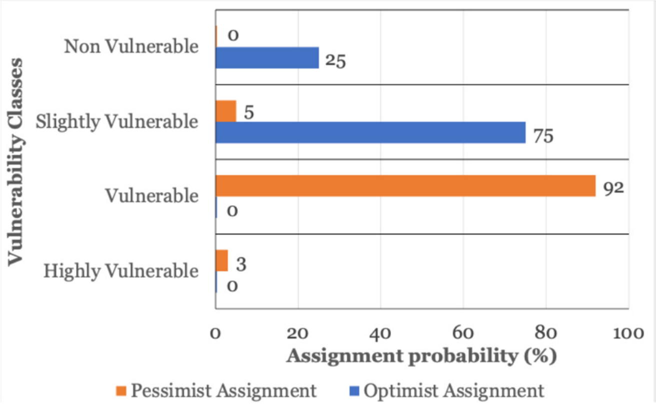

Fig. 5. Detailed results of component assignment (cell).

C. Sensitivity Analysis of AHP Weights and Profile Scores

The vulnerability classification of the component is particularly sensitive to the AHP relative weight variation and to the profile attributed to the component (criterion profile score variation). The relative weight and criterion profile score of the two criteria, mass and functional sensitivity, which had the most impact on the component vulnerability, has been varied to investigate their effect on the assignment results, and are summarized in Tables VIII and IX. The sensitivity analysis results are presented in Figures 6 and 7. For the attributed relative weight w_2, it is observed that ±20% variations in the criterion relative weight values lead to significant changes in the pessimist assignment results from Vulnerable to Slightly Vulnerable, while the optimistic assignment has not changed, even when the Slightly Vulnerable assignment probability has been slightly decreased by 12%, as shown in Figure 6. In the case of the relative weight w_3, the optimist and pessimist vulnerability assignments remained unchanged. However, a 5% higher probability for the "Vulnerable" assignment in pessimist ranking has been observed, and a slight decrease in the probability assignment "Slightly Vulnerable" for optimist ranking by 19% bringing it closer to the "Vulnerable" threshold. The effect of the criteria profile score is demonstrated through the sensitivity analysis in Figure 7. While increasing the attributed score of the two criteria, mass and functional sensitivity, the optimist ranking remained unchanged showing a slight decline in the probability assignment "Slightly Vulnerable" of about 25%, whereas, a significant change in the pessimist vulnerability assignments has been observed from "Vulnerable" to "Highly Vulnerable". Also, the decrease in the attributed score of the two criteria presented a significant effect, changing both the pessimist and optimist vulnerability assignments to "Slightly Vulnerable" and "Non Vulnerable," respectively.

D. Factors Aggravating Vulnerability Scores

The aggravating factor effect due to the implementation state of the component is also considered in the component score calculation. The method incorporates two distinct scenarios for evaluating the obsolescence factor using a bathtub curve. The score is considered intact reflecting a moderate failure rate when the component's service life D_u remains below half of its nominal lifespan D_n: $D_u < \frac{D_n}{2}$. The failure rate experiences a significant increase when the component surpasses half of its nominal lifespan $FAV_1 = \left(\frac{2D_u}{D_n}\right) - 1$. The effect of the component positioning in the building was accounted for using a discrete law based on the floor level where the component is located (n), relative to the total levels in the building (N) expressed as: n/N. The result of the other *FAVs* is presented in Table X. The cumulative *FAVs* are then integrated into the base score to derive the component's final score (S), which is evaluated according to the standardized rating scale shown in Table V. Therefore, the component is considered "slightly vulnerable" (S = 4.5). While this study focuses on seismic vulnerability metrics, future applications could integrate OSHA/NIOSH safety guidelines besides *FAV* to create dual-purpose assessments that address both the seismic resilience and worker protection. Safety-critical components (e.g., elevated conduits, pressurized vessels) could receive additional vulnerability weighting based on OSHA (Electrical Safety) [24] and NIOSH guidelines [25] for:

- Fall protection requirements (components >1.8m height)
- Lockout/Tagout (LOTO) complexity
- Hazardous material exposure (e.g., kiln dust inhalation risks)

Integrating the OSHA/NIOSH compliance data could enhance the RVS efficiency by leveraging the existing safety inspections to identify the seismic vulnerabilities (e.g., unbraced shelving flagged). However, the formal safety audits were beyond this study's scope.

TABLE VIII. ATTRIBUTED RELATIVE WEIGHT VARIATION

Relative weights	Mass	Constitution	Dynamic	Functional sensitivity	Installation mode
w_1	16	7	8	38	31
w_2	20	7	8	30	31
w_3	13	7	8	45	31

TABLE IX. ATTRIBUTED CRITERIA SCORE VARIATION

Criterion profile score	Mass	Constitution	Dynamic	Functional sensitivity	Installation mode
P_1	35	0	25	35	20
P_2	50	0	25	45	20
P_3	15	0	25	20	20

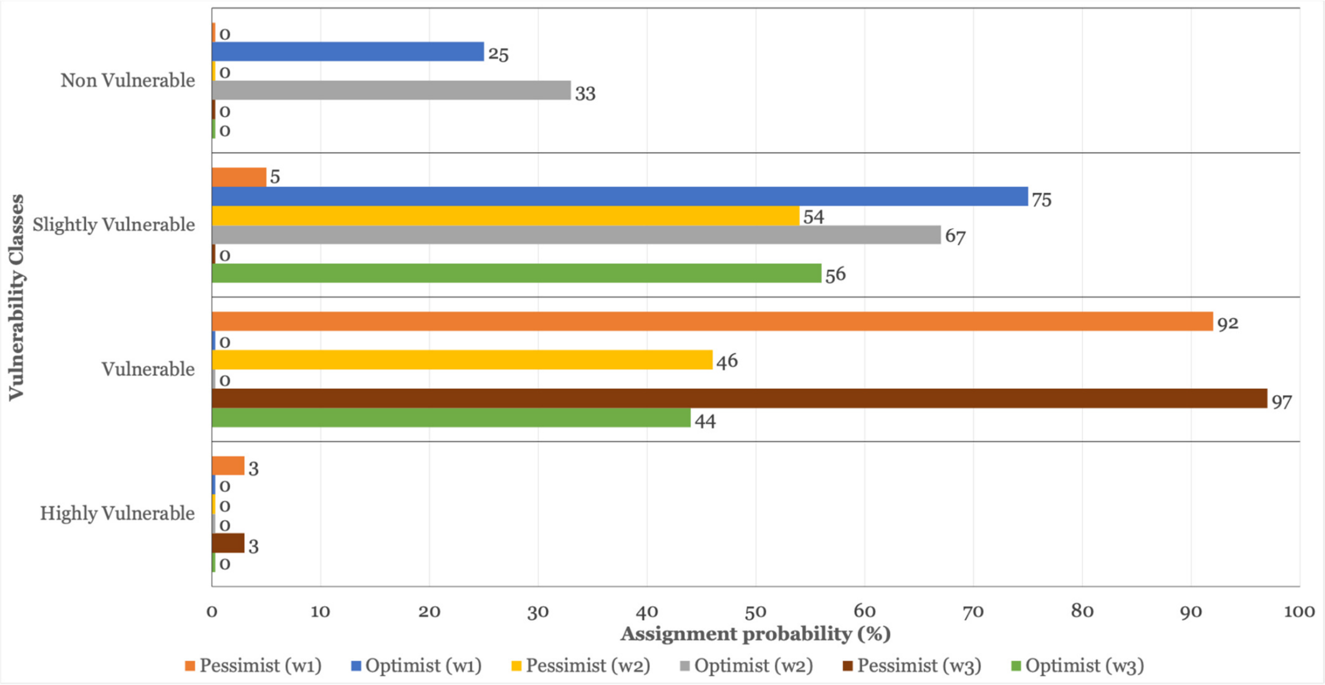

Fig. 6. Sensitivity of component assignment (Cell) to AHP criterion weight variation.

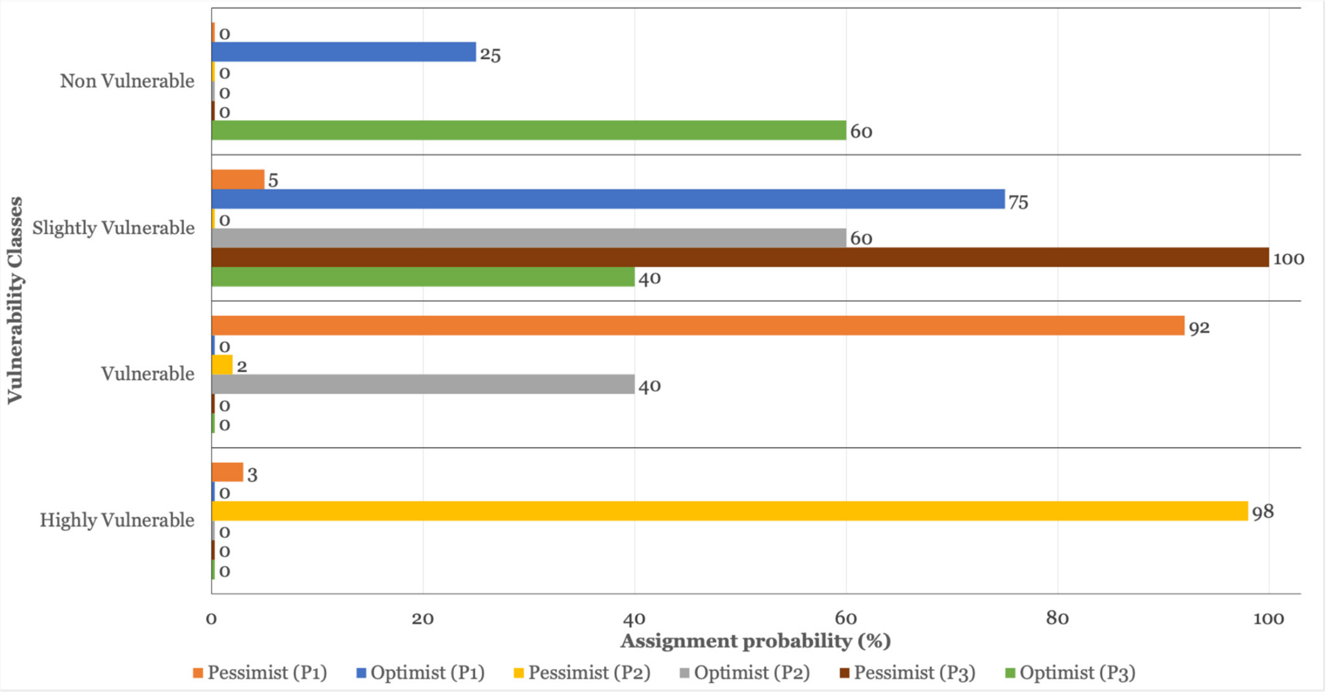

Fig. 7. Sensitivity of component assignment (Cell) to criterion score variation.

TABLE X. COMPONENT ENTRY FORM (CELL): COMPONENT SET-UP

FAV No.	Factors aggravating vulnerability	Answers from the visit			FAV
FAV_1	Nominal life D_n and age in place	D_n = 15 years, age = 5 years			0
FAV_2	Component floor number	n = Ground floor			0
FAV_3	What is the quality of the anchoring to the support?	Good (0) ☐	Bad (0.5) ☐	Doesn't exist (1) ☒	1
FAV_4	What is the nature of the support attachment system?	Rigid (1) ☐	Flexible (0.5) ☐	Not applicable (0) ☒	0
FAV_5	The stability of the component installed	Good (0) ☐	Medium (0.5) ☒	Bad (1) ☐	0.5
FAV_6	Is there any abnormal use of the component?	Yes (1) ☐		No (0) ☒	0
FAV_7	Is the component subjected to potentially dangerous interactions?	Yes (1) ☐	Maybe (0.5) ☐	No (0) ☒	0
Final score of component = Base Score + $\sum FAV$ = 3 + 1.5 = 4.5				$\sum FAV$	1.5

E. Assigning Scores to the System

The system score calculation depends on the type of the logic gate encountered. It follows an ascending approach, beginning with the elementary components at the lowest level and progressing through each logical gate sequentially until reaching the final gate of the subsystem or system, as illustrated in Figure 8. The system score is then deduced as the maximum score of the subsystems as indicated by:

$$S_{sys} = Max(S_{sub1}; S_{sub2}; S_{sub3}; \dots; S_{subn}) \quad (1)$$

In the case of a dependence gate, the score assigned to the subsystem is determined by the highest score among its constituent components (2). Whereas, the score of a redundant system or subsystem is determined by the lowest score among its constituent components, in conjunction with the quantity of the redundant elements present:

$$S = S_{max} \quad (2)$$

$$S = S_{min} - 0.5(N - 1) \quad (3)$$

The final system score is then derived by integrating the site effect factor FAV_8, which quantifies the vulnerability associated with the foundation soil type. This factor is applied as a global variable at the system level within the building structure. The incorporation of this factor is based on the classification of the soil types as defined by the Eurocode 8 standard [26]. The values proposed in this method are correlated from the maximum values (plateaus) of the response spectrum, as shown in Table XI. The foundation soil where the cement plant is implanted is type B, according to the Eurocode 8 classification. Incorporating the site effect factor FAV_8 into the system scoring, the final score for the furnace supply system was determined, resulting in a classification of Slightly Vulnerable system based on the scale provided in Table V. The final score as well as the vulnerability class are also determined for the four other systems and summarized in Table XII. The method has established a threshold beyond which a vulnerability reduction strategy is required, which involves conducting a more detailed analysis of vulnerable systems, strengthening or replacing the vulnerable components, and modifying the system functionality, such as adding redundant components. The threshold varies from 0 to 14 as indicated in Table XIII.

TABLE XI. SOIL TYPE FAV CORRELATED FROM MAXIMUM SPECTRUM VALUE IN ACCORDANCE WITH EUROCODE 8 (SITE EFFECT) [16]

Soil type	A	B	C	D	E
Max. spectrum value	2.5	3.4	3.7	4	4.5
Proposed FAV_8	0	0.25	0.5	0.75	1

TABLE XII. FINAL SCORE AND VULNERABILITY CLASS OF THE FIVE IDENTIFIED SYSTEMS

System	Score	Classes
Furnace supply	5.0	Slightly Vulnerable
Material recovery and preheating	5.0	Slightly Vulnerable
Material preparation	5.0	Slightly Vulnerable
Firing	6.5	Vulnerable
Furnace protective system	4.0	Slightly Vulnerable

TABLE XIII. DECISION MAKING ACCORDING TO THE ESTABLISHED THRESHOLD [16]

Threshold	$0<S<7$	$7<S<14$
Decision	No intervention required	Intervention required

From the vulnerability classification results in Table XII, none of the systems required an intervention, as all scores remained below the established threshold, $S<7$.

F. Time Estimation for Visual Screening

To ensure the practical implementation, time estimates for visual screening were also derived based on the component complexity and site conditions. The time estimates for visual screening are presented in Table XIV. As it is observed, the screening durations account for the component type (electrical, mechanical, structural), accessibility (elevation, confined spaces), and safety protocols (e.g., lockout-tagout for electrical systems).

The furnace supply system (score: 5) required 3.5-4.0 h due to the time-intensive inspections of elevated conduits and pressurized vessels, while the material recovery and preheating system (score: 5) took less time (2.5–3.0 h) despite its dusty environment and conveyor networks, as its components were predominantly ground-level and required fewer safety protocols. The vulnerability scores alone are insufficient predictors of the screening duration, as evidenced by the 2:1 time ratio between the similarly-scored systems (furnace supply versus material recovery). The screening durations depend on both the vulnerability levels and operational environment factors and were clearly dominated by the accessibility and safety demands.

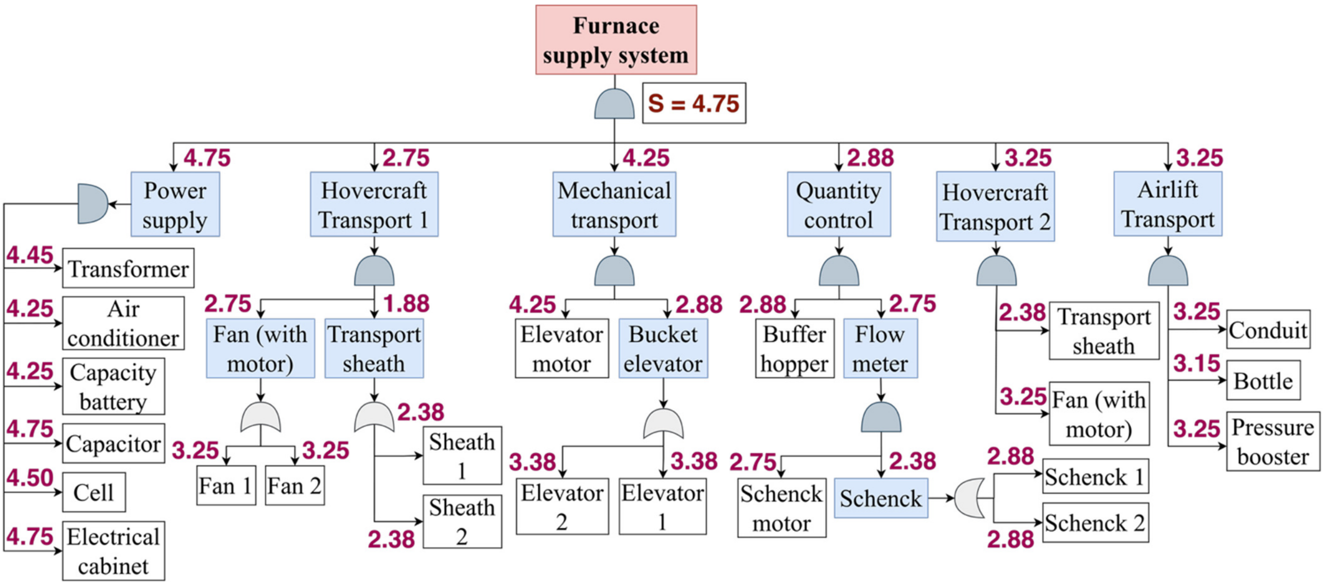

Fig. 8. Furnace supply system components and subsystem scores.

TABLE XIV. TIME ESTIMAES FOR VISUAL SCREENING PER SYSTEM

System	Estimated versus time (h)	Key variables
Furnace supply	3.5-4.0	High component count, elevated equipment
Material recovery and preheating	2.5-3.0	Conveyor complexity, dusty environment
Material preparation	3.0-3.5	Heavy machinery (grinders), vibration-sensitive components
Firing	4.0-4.5	High-risk burners, thermal checks, safety protocols
Furnace protective system	2.0-2.5	Lockout-tagout protocols, capacitor bank hazards

IV. CONCLUSION

The current study successfully adapted a hospital-based seismic vulnerability assessment framework to an industrial context, demonstrating its versatility in evaluating complex systems, like cement plants. The study contributes to the first application of this framework to a cement plant—an industrial setting previously underexplored in seismic vulnerability studies, demonstrating the framework's scalability to complex, high-risk environments and its adaptability beyond its original hospital-based design. The study results bridge a key methodological gap and constitute a significant advancement over prior applications limited to hospitals or conventional buildings. From the case-study, the following conclusions can be drawn:

- Non-structural components, particularly electrical and mechanical systems, were found to pose higher risks than the structural elements.
- The firing system emerged as the most critical subsystem, primarily due to its high operational sensitivity and complex mechanical interactions. Also, the heavy equipment with poor mass distribution contributed most to the risk scores.
- The ELECTRE-TRI and Monte Carlo methods proved effective in handling multicriteria decision-making under uncertainty and confirmed the robustness of the scoring system, with the results showing <10% variation for high confidence inputs.
- A 20% Analytic Hierarchy Process (AHP) weight variation in w_2 shifted the pessimist classification from "Vulnerable" to "Slightly Vulnerable," while the optimist results remained stable. The w_3 set maintained the classifications but showed probability shifts (5% more "Vulnerable" in the pessimist and 19% less "Slightly Vulnerable" in the optimist rankings). This reveals pessimist assessments with greater sensitivity to the parameter variations, although the optimist rankings offer more stable screening, highlighting the need for a careful calibration of the criteria weights in high-stake scenarios.
- Increasing the mass and functional sensitivity scores caused a 25% drop in the optimist "Slightly Vulnerable" classifications and shifted the pessimist ratings from "Vulnerable" to "Highly Vulnerable," highlighting these criteria's critical impact. In contrast, the decreasing scores

downgraded both the assessments to "Non-Vulnerable" (optimist) and "Slightly Vulnerable" (pessimist), showing a risk reduction potential, but also a possible vulnerability underestimation, if the scores are improperly calibrated. Also, the stability of the optimistic ranking, despite the score fluctuations, indicates its utility for preliminary screenings where the rapid, less conservative evaluations are sufficient.

- The proposed visual screening protocol provided practical time estimates (2-4.5 h per system), enabling the prioritization of high-risk subsystems, like the furnace supply (3.5-4.0 h) and firing systems (4.0-4.5 h).

The study also provides the following recommendations:

- Future *FAV* refinements should incorporate both zone-of-influence concepts for large equipment (addressing modal mass distribution) and height-to width ratios with type-specific coefficients differentiating the static (silos) from the dynamic (transporters) systems.
- Human factors (e.g., evacuation risks) exacerbate the functional vulnerability, making their formal integration with system requiring further research.
- Future applications should integrate cost-benefit analysis using local retrofit cost data to develop priority matrices for industrial facilities.
- Harmonizing the framework with OSHA/NIOSH safety standards (crosswalk table mapping standards to Performance Modification Factors (PMFs) adjustments, safety inspection checklist for rapid seismic screening) and FEMA P-58 could unify the seismic and occupational risk assessments.

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