

HYBRID METHODOLOGY FOR RISK ASSESSMENT IN INDUSTRIALISED EXECUTION OF PRECAST CONCRETE ELEMENTS, WITH APPLICATIONS ON POST-EXECUTION INSPECTION AND POSSIBLE INTEGRATION OF DIGITAL TECHNOLOGIES

Dipl. Eng. PIRONEA Andreea Dora Bianca –Doctoral student Doctoral School of Industrial Engineering, National University of Science and Technology Polytechnic Bucharest, pironea.bianca@gmail.com

Dipl. Eng. IONESCU Vlad-Petruț – Doctoral student Doctoral School of Industrial Engineering, National University of Science and Technology Polytechnic Bucharest, vladionescu9921@outlook.com

Prof. Univ. Dr. Eng. RECE Laurențiu, habil Doctoral School of Industrial Engineering National University of Science and Technology Polytechnic Bucharest, Associate Professor Faculty of Mechanical and Robotic Engineering in Construction, Technical University of Civil Engineering Bucharest, recelaurentiu@gmail.com

Abstract

Hidden works in concrete structures, either by assembling prefabricated elements or by executing monolithic elements in situ from simple or reinforced concrete, generate a high level of uncertainty in assessing quality and behavior in the long term. Their inaccessibility after completion limits the possibility of identifying defects and traditional risk analysis methods, based solely on the probability-impact relationship, do not sufficiently capture the specificities of production, assembly and casting processes.

In this context, the paper proposes a technical risk assessment methodology integrating qualitative criteria with quantifiable parameters, such as detectability, accessibility and variability of execution, differentiated for industrialised and in-situ elements.

The methodology includes an adaptive tracking datasheet designed to adjust the level of risk to actual site conditions and assessor experience. This makes it possible to identify the particularities of prefabricates, manufacturing tolerances, handling defects, non-conformities at joints, as well as the risks associated with monolithic elements such as segregation, insufficient compaction or quality variations of fresh concrete. The model is complemented by a post-execution- monitoring system based on non-destructive methods and predictive maintenance principles, whereby identified risks are converted into time-tracked parameters.

The results highlight that the proposed approach leads to a more realistic prioritisation of risks and optimisation of the quality control processes of hidden works, helping to increase the reliability of concrete structures, whether made from prefabricated or in-situ moulded elements.

In light of the evolution of digital technologies in construction, possible directions to extend the methodology are also discussed, such as the use of image processing for automated identification of non-conformities, the application of machine learning models for risk classification, or the integration of monitoring sensors for critical structural elements. These

developments can help automate inspection steps and increase the objectivity and predictability of the assessment process, providing solid premises for improving quality control of hidden works in industrialised execution.

Keywords: quality control, risk valuation, industrialised execution, automated inspection, monitoring technique sheet, automatic defect classification

1. GENERAL CONSIDERATIONS ON THE QUALITY AND SAFETY OF PRECAST AND IN-SITU CONCRETE STRUCTURES

The safety of a construction works consists of the simultaneous fulfilment of the conditions required by the regulations in force and is ensured when all the listed basic requirements are complied with: “mechanical strength and stability; b) fire safety; c) hygiene, health and the environment; d) safety and accessibility in operation; e) protection against noise; f) energy saving and thermal insulation; g) sustainable use of natural resources. [11, 15]

These requirements shall be met regardless of whether the structure is made **of industrialised precast concrete** or of **elements made in situ** of simple or reinforced concrete. For prefabricates, safety depends both on the quality of the industrial production process and on how the elements are handled, transported and mounted. For in-situ moulding elements, safety is influenced by the variability of construction on the site, the quality of fresh concrete and the moulding and compacting conditions.

The safety of construction works, their reliability, their durability and their quality, in the broadest and deepest sense of the concept of quality and its management, are paramount requirements and ongoing concerns of all those involved, interested and responsible for the construction of safe, functional, maintainable constructions with the least possible risk to beneficiaries, investors or users. In particular, these concerns are heightened in the case of **hidden works**, where defects in the production or execution phases become difficult to identify at a later stage, in both prefabricated and monolithic elements.

The completion within a relatively short period of time of a large volume of buildings of high technical complexity, meeting and complying with all the required safety and quality requirements, including the conditions of maximum economic efficiency, results in the adoption of designs and construction methods which make it necessary to apply effective quality control of the works. This check must be carried out at all stages of the construction activity: feasibility, design, execution, commissioning, in-service and post-use monitoring and control.

In the case of **prefabricated elements**, quality control begins at the industrial production stage, where geometric tolerances, the quality of the raw materials, the burning method and the ripening conditions are established. Afterwards, control continues at the handling, transport and assembly stages, where non-conformities specific to industrialised elements may occur, such as local damage, positioning deviations or joints defects. For **elements executed in situ**, the control focuses on checking shuttering, reinforcement, fresh concrete quality, casting and compaction process, and hardening conditions.

According to the definition, 'quality control is the second management process of quality management and is intended to ensure stability, actual performance in line with planned performance and the possibility to act in case of deviations from planned objectives [5,16]. Quality control consists of a series of activities aimed at monitoring the stages of achievement of the objectives and minimising any non-compliances that may occur during their implementation. In general, depending on the objective to be achieved, quality control can be categorised as follows:

- a) Off-process control;
- b) Control during the execution of the process: pre-process control; in-process control; post-process control; final control; integrated control. [5]

To meet the required conditions and structural requirements, the safety of a construction works starts from the early stages of design, 'already at the loading assessment stage, static structure calculation, choice of materials, verification of sections, etc. [3,17]. This stage is essential both for prefabricated elements, where design needs to take account of handling and mounting, and for monolithic elements, where variability in execution can directly influence structural behaviour.

Regardless of the level of control applied, 'all structures are imperfect' [2].

Structural imperfections can be divided into two broad categories:

- process-generated imperfections (materials, geometry, sub-assemblies), in particular prefabricated elements;
- mounting imperfections (overall geometric imperfections, mechanical imperfections in the transmission of forces and in the drilling), encountered both in prefabrications and in elements executed in situ.

In order to minimise structural imperfections in manufacture and assembly, their level shall be limited by quality standards and tolerance standards and their effect shall be taken into account in the design by means of safety coefficients and special calculation procedures. In the case of prefabricates, these procedures include additional checks on joints, anchorage areas and handling behaviour,

while for monolithic elements attention is paid to the variability of construction and influence of site conditions.

2. RISKS ASSOCIATED WITH THE PRODUCTION AND POST-EXECUTION STAGES

According to theoretical research, the concept of risk is the possibility of reaching a hazard, which means a possible danger.

In the case of construction works, hazard means a material factor or certain physical, biological, chemical or environmental conditions which may cause an adverse effect on the quality and safety of the construction works.

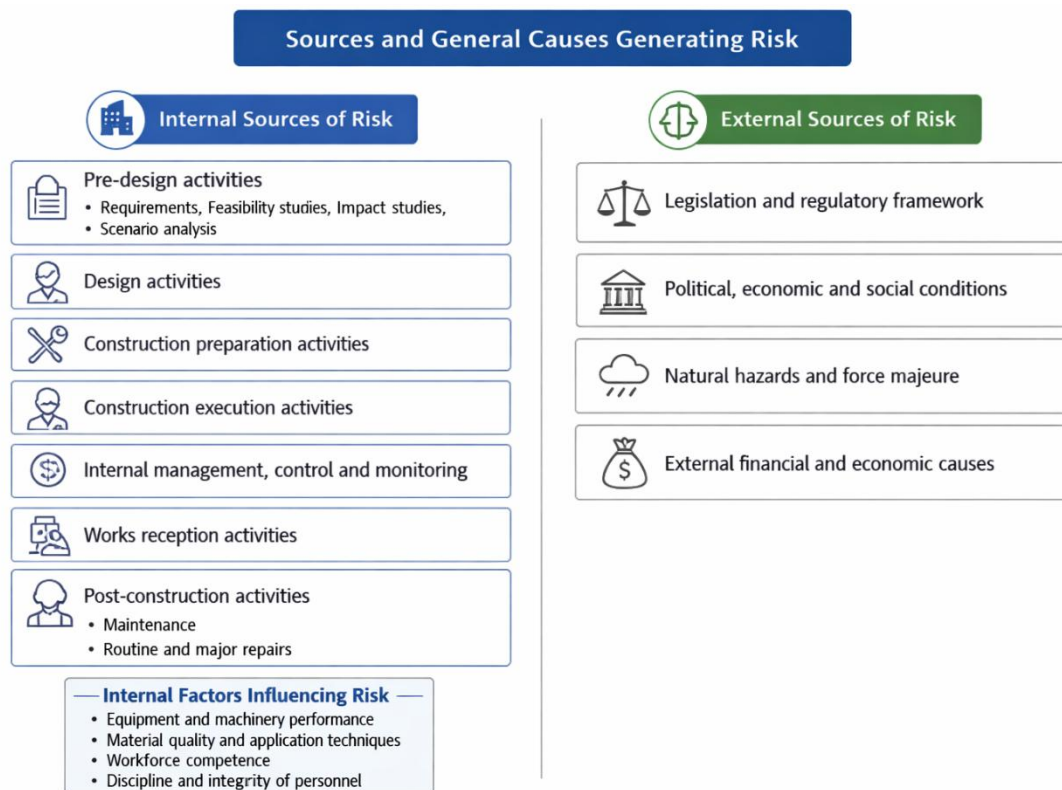


Figure 2-1 Sources and general causes that may give rise to risks to the quality and safety of a construction project

For prefabricated elements, the risks are associated with:

- internal defects in concrete (segregation, gaps, residual stresses);
- geometrical deviations from manufacturing tolerances;
- damage during handling and transport;
- non-compliances at joints with elements carried out in situ.

3. CONCEPT OF “HIDDEN WORKS” AND RELATED RISK ANALYSIS METHODS

The construction sector faces major challenges in ensuring the level of quality imposed by regulations and specifications, especially in the case of elements that become inaccessible after execution.

Hidden works define those works carried out, parts of the construction works or parts thereof which, after they have been carried out and completed, can no longer be viewed, controlled or assessed except by means of special, costly and often destructive intervention measures.

According to the theoretical documentation, these types of works ‘are those works which are executed, part of or complementary to a building which, once executed and completed, can no longer be viewed, controlled or assessed except by means of costly, sometimes destructive, intervention measures’ [7].

In the context of the **industrialisation of construction**, hidden works acquire an additional dimension, as they include both **precast concrete elements** and **in-situ bonding and completion areas**. These become critical points in the risk assessment, as defects in the production, transport or assembly phases may remain undetected after the works have been completed. In the case of prefabricates, hidden risks may arise from **manufacturing imperfections, outdated geometric tolerances, internal cracks, non-conformities at joints, or loosening of anchorages**, all of which have a direct impact on long-term structural behaviour.

The potential dangers of hidden works are difficult to monitor and manage, especially with the passage of time from execution. Assessments, assessments and investigations of the adverse effects of these hazards become costly and sometimes inconclusive. In the case of industrialised structures, the difficulty increases due to the **modular nature** of the elements **and the dependence between prefabricated and in-situ moulded components**, where execution defects can be masked by finishes or shields.

Classical risk assessment methods are limited as they do not integrate critical factors such as **fault detectability, accessibility to interventions, or the degree of industrialisation of the execution process**. In this context, the paper proposes an innovative approach based on **hybrid methods** of analysis, combining qualitative and quantitative assessment with digital post-execution monitoring tools, applicable to both prefabricated and mono-points. Risk analysis is an important part of risk management and by definition “risk analysis is a method for assessing the likelihood of an undesirable event occurring.” [12].

There are several methods and techniques of risk analysis applicable in different areas of activity and at different phases of the project. Forms of analysis ranging from simple qualitative methods to complex and sophisticated quantitative methods may be used.

‘Qualitative analysis is based on the use of nominal or descriptive scales to describe the likelihood and consequences of risks. This is particularly useful for an initial view or review (radiography) of the risks or when a rapid estimation is required.

Semi-quantitative analysis extends qualitative analysis by assigning numerical values to descriptive scales. Quantitative risk factors derive from these numbers used.

Quantitative analysis uses numerical ration scales for probability and consequences rather than descriptive scales.’ [9].

In the case of industrialised works, these methods may be adapted by introducing **additional parameters**, such as:

- degree of industrialisation of the element (percentage of prefabrication);
- level of post-installation accessibility;
- non-destructive detection of hidden defects;
- the reliability of the manufacturing and assembly process;
- interdependence between prefabricated and in-situ moulded elements.

By integrating these factors, risk analysis becomes more realistic and applicable in the context of modern construction, providing a solid basis for the development of a **hybrid methodology for assessing and monitoring** hidden works, adapted to both industrialised and traditional systems.

3.1. Estimated risk analysis method

On the basis of the qualitative risk analysis method, using the probability-impact matrices, a new method was designed and proposed by prof. univ. dr.eng. Lidia Niculita University Professor, Technical University of Construction, Bucharest, which incorporates notes from qualitative and quantitative methods, the method referred to as the *estimated risk diagram method or the probability-impact diagram*. This new risk analysis method was first published in 2018 in the process of ERAZ’s fourth conference entitled ‘Knowledge based sustainable economic development’. [7]

This risk analysis method is a combination of the qualitative analysis method using the probability-impact matrices and the method of quantitative analysis of the expected value.

Also, according to theoretical research, one of the possible methods to identify the risks associated with hidden works is the ‘*estimated risk diagram method*’ by which it is defined that ‘the most important risk characteristics are the probability of occurrence and the impact on the quality of the end result’ [8]. The probability-impact diagram, can be seen as a probability-impact matrix with an infinite number of lines and an infinite number of columns, and the quantification of the expected value of risk resulted from the cordon product the fields of the point representing the risk in the diagram field, i.e. the product of the probability of the risk (abscissa of the risk point) and the impact of the risk (ordinate of the risk point).

In the case of *the expected value method*, the expected value VA_A of risk A , i.e. the occurrence of the undesirable event A , is obtained by the calculation relationship:

$$VA_A = P_A * I_A \quad (1)$$

where P_A is the probability of the occurrence and materialisation of risk A and I_A is the value of the impact of the occurrence of risk A .

In the case of the Estimated Risk Map method, the Estimated Risk Value results from the product of the X_A abscissa of the point in the A risk diagram and its Y_A order:

$$VA_A = X_A * Y_A \quad (2)$$

In order for a risk to be represented in the risk diagram, it is necessary to quantitatively estimate both the probability of the risk event occurring and the amount of its impact.

For the probability of the risk represented on the abscissa of the diagram, a scale of 0 to 1 shall be used. Extreme values, with 0 representing the probability of the risk event occurring and 1 representing the certain probability of the event occurring.

For the impact of the risk, a percentage scale is used, with values ranging from 0 % (which defines a zero impact) to 100 % (which defines the highest possible impact for that risk).

The probability of the risk for any given case is analysed, estimated and quantified by the rule by processing data and information in the field and category of work related to the risk analysed, experience gained and based on literature consultations (charts, treaties, journal articles, scientific communications, previous technical expertise, etc.).

The impact of the risk shall be assessed and quantified on the basis of impact studies, by means of studies on the costs of the effects produced and the

costs necessary to restore the situation prior to the occurrence of the effects of the undesirable event. The representation of a risk A , which has the probability P_A and the impact I_A , is shown in Figure 3-1.

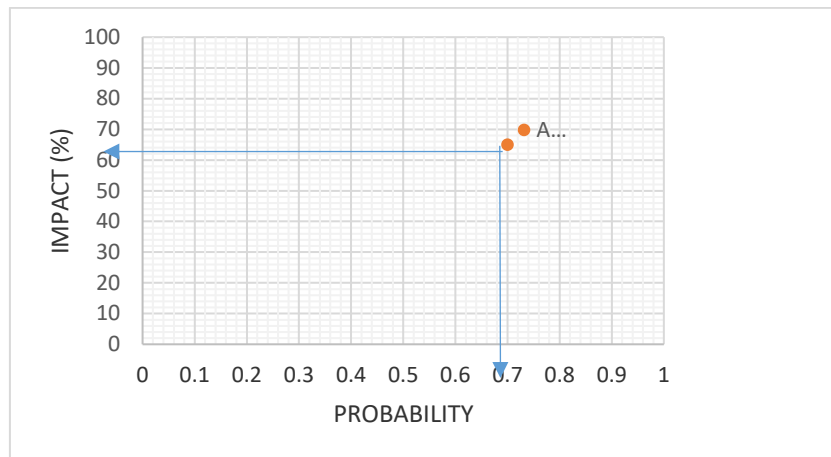


Figure 3-1 Probability-impact risk profile: A – point A relating to risk A; P_A – probability of risk A; I_B – impact of risk A.

On the basis of the facilities provided by the probability-impact risk chart, it is possible to analyse, compare and rank the estimated risks for a category of works hidden or assimilated to them, which may affect the quality and safety of a construction work. Thus, for each of the new risk diagrams presented above, relating to the new categories of works, the risks can be analysed, compared and prioritised.

Table 3-1 Risk levels

RISK LEVEL (by probability – impact)	IMPACT VALUE (%)	PROBABILITY VALUE (–)	DEFINED RISK LEVEL
Very high probability / Very high impact	80 – 100	0,8 – 1,0	VERY HIGH RISK 
High probability / High impact	60 – 80	0,6 – 0,8	HIGH RISK 
Medium probability / Medium impact	40 – 60	0,4 – 0,6	MEDIUM RISK 
Low probability / Low impact	20 – 40	0,2 – 0,4	LOW RISK 
Very low probability / Very low impact	0 – 20	0 – 0,2	VERY LOW RISK 

The risk classification and prioritisation shall be based on the risk levels set out in Table 3-1, which shall be determined taking into account the estimated

value of the risks resulting from the product from the estimated values of the risk probabilities and the impact of the risks.

4. RATIONALE FOR THE PROPOSED METHODOLOGY

Currently, according to the regulations, there is a way to implement additional measures on the quality of construction works, using coefficients by design. According to national regulations, this mechanism is defined by “three reliability classes RC1, RC2 and RC3 associated with the three consequence classes CC1, CC2 and CC3” [14], with the consequence classes classified according to the importance categories of the construction, the possible consequences due to failures or defects associated with the strength structure.

As regards the additional quality assurance mechanism defined by the consequence classes characteristic of the execution phase, there are three inspection levels IL1, IL2 and IL3, which correspond to the three reliability classes where only for the high consequence level, i.e. IL3, an extension of inspections was requested, i.e. inspections carried out by third parties, while for IL2 and IL1 the inspection during execution is characterised by a simplified grade, carried out according to their own organisational procedures.

The analysis of the application of the probability-impact risk diagram method revealed the need to design and develop an alternative, broader and operationally oriented method that allows, in addition to identifying and assessing the risks associated with works that become hidden, to base decisions on the possibility of subsequent intervention (post-execution).

The main element of the proposed innovative methodology is the definition **of the novel element called Technical sheet for risk assessment and monitoring in industrialised and in-situ execution of simple and reinforced concrete elements**, designed as a risk assessment and monitoring tool across the entire workflow applicable to both prefabricates or in-situ elements (production-execution-operation), with a focus on two key dimensions for hidden works:

- (i) the likelihood of occurrence of a non-compliance and its impact during the execution phase;
- (ii) ability to identify and intervene after execution, when the element is already hidden and the construction is in operation.

As regards the component **of the technical sheet for risk assessment and monitoring in the industrialised and in-situ execution of simple and reinforced concrete elements**, it is composed of:

Step I – Identifying and prioritising the risks associated with the different phases of implementation

The first stage in drawing up the technical tracking sheet consists of analysing all stages of execution and defining the vulnerabilities (risks) associated with each stage of each type of element, whether structural or non-structural, industrialised by prefabrication or realised in-situ, thus resulting in a numerical value of the initial risk related to the execution stage.

At the same time, for each vulnerability, the type of verification/inspection required and the purpose of the verification (ensuring quality and compliance parameters) are established.

1) initial execution risk R_e defined as the product of probability and impact:

$$R_e = P \times I \quad (3)$$

where:

- P = the estimated probability of occurrence of vulnerability;
- I = impact on fundamental requirements.

In the case of the *estimated risk analysis*, the probability (P) is expressed corresponding to the estimated occurrence frequency and is normalised over the interval $[0, 1]$ for the calculation. The principle remains the same for the first step of the monitoring datasheet. As regards the impact (I) of the *estimated risk analysis method*, is expressed as a percentage, corresponding to the estimated frequency of occurrence of the vulnerability. This indicator **captures the risk in the execution phase, either industrialised or in-situ**, before the work becomes ‘hidden’. Similarly, the risk classes for R_e were defined by 5 classification levels, in accordance with the estimated risk analysis method set out in Table 3-1.

Technical sheet for risk assessment and monitoring in industrialised and in-situ execution of simple and reinforced concrete elements										
Step I – Identification and ranking of risks by execution phase										
Crt No.	Phase (technological flow)	Vulnerability = Risk	Type of structural element	Verification method	Verification scope	Probability of occurrence	Impact	Estimated value of risk R_e	Risk class R_e	OBS.
						[0,1]	[0,100 %]	$R_e = P \times I$		

Figure 4-1 Extract from the technical sheet – Phase I – Identification and prioritisation of risks associated with the different phases of execution

Step II – Structural element application and integration of subsequent intervention

In the second stage, the vulnerability analysis continued to be carried out separately for each type of structural element, either induced by prefabrication or carried out in-situ (foundations, columns, beams, walls, tiles), and the factsheet explicitly includes information on:

- the possibility of subsequent (in service) identification and possible investigative methods;
- the degree of access for the intervention (under real operating conditions);
- intervention options to restore quality criteria to the design level.

Therefore, the fiche does not remain an exclusive tool to control execution, but becomes a life cycle risk management tool geared towards intervention decisions.

Technical sheet for risk assessment and monitoring in industrialised and in-situ execution of simple and reinforced concrete elements			
Phase II – Integration of the follow-up intervention			
Preventive measures (execution phase)	Subsequent in-situ verification methods (in service phase)	Possible interventions (post- execution)	OBS.

Figure 4-2 Extract from the technical sheet – Step II – Application to structural elements and integration of subsequent intervention

Step III – Hierarchy of risks by indicator: post-execution risk

To obtain a classification relevant for hidden works, the methodology uses two levels of quantification:

- 1) the risk at the execution stage resulting from the estimated risk analysis method, with precision as the impact value, is **normalised over** the interval [0, 1] for the calculation.
- 2) the post-execution- risk R_{p_e} through the technical sheet introduces the innovative elements of the method, namely: detectability, accessibility, experience.

After execution, the risk becomes critical not only in terms of severity, but also in terms of:

- the defect may be difficult to detect,
- access for intervention can be difficult.
- the evaluation may depend on the evaluator's experience.

This introduces two additional components, both on 4 levels (1-4):

- Detectability (**D**): 1 = readily detectable, 4 = barely detectable
- Accessibility (**A**): 1 = easy access, 4 = very difficult

and an evaluator's coefficient of experience k_e :

Assessor level	k_e		k_e		k_e
Junior	0.8	Medium	1.0	Senior	1.2

For direct comparability with R_e , I propose a normalised- post-execution indicator:

$$R_{p_e} = k_e \times (P \times I) \times \frac{(D+A)}{8} \quad (4)$$

interpreting:

- $P \times I$ keeps the basis of the execution risk but also the **Impact** values become normalised in the $[0, 1]$ probability-like **range**;
- $(D+A)$ penalises situations where detection and intervention are difficult, dividing by 8 normalises (because $D + A \in [0.25, 1]$);
- k_e adjust according to experience (prudent in evaluations).

Similarly, the risk classes for R_{p_e} are defined in five risk categories as illustrated in Figure 4-1.

The probability of vulnerabilities occurring is expressed as a percentage and normalised over the range $[0, 1]$, and the impact is defined by the severity of the consequences on the fundamental requirements. The initial execution risk R_e is determined as the product of the probability and the impact. For works that become hidden, the post-execution- risk R_{p_e} is obtained by penalising the initial risk with a factor integrating detectability, accessibility and assessor experience, allowing for a realistic ranking of risks during construction operation.

Technical sheet for risk assessment and monitoring in industrialised and in-situ execution of simple and reinforced concrete elements								
Phase III – Post-Execution Risk Hierarchy								
Probability of occurrence	Impact	Detectability D	Accessibility A	Difficult Intervention Penalty Factor F _p	Coef. Assessor experience k _e	Execution risk R _{p_e}	Risk class R _{p_e}	OBS.
[0,1]	[0,1]	[1; 4]	[1; 4]	F _p = (D + A)/8	[0.8/1.0/1.2]	R _{p_e} = k _e × R _e × F _p		

Figure 4-3 Extract from the technical sheet – Step III- a – Hierarchisation of risks by indicator: post- execution risk

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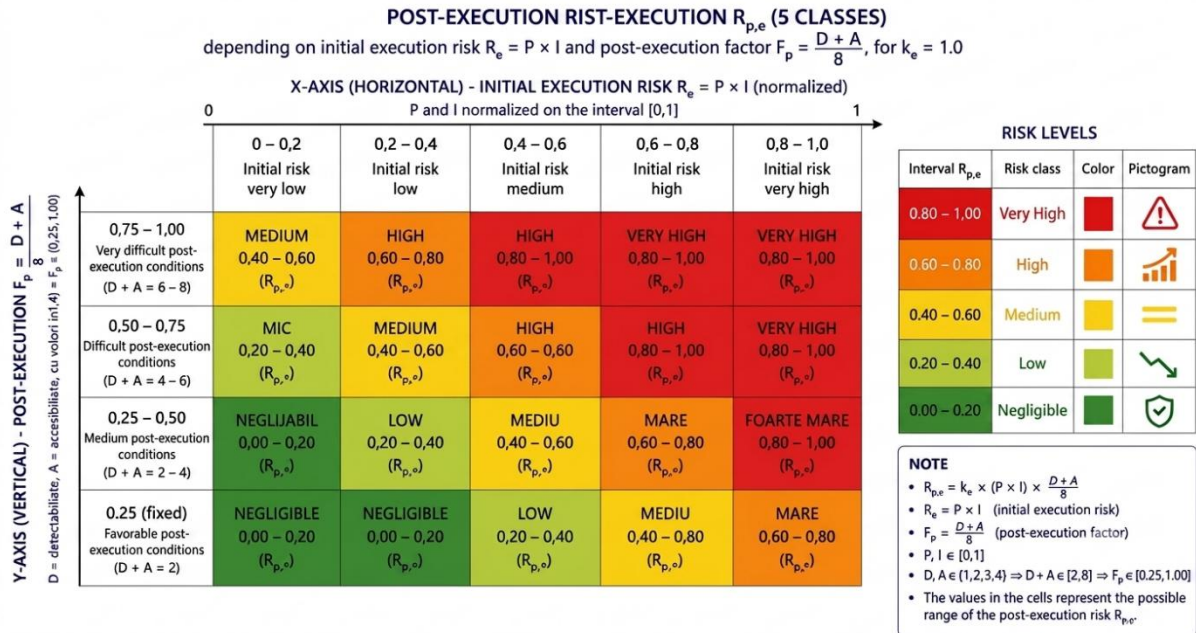


Figure 4-4 Probability-impact matrix used for post-execution risk assessment

Figure IV-5 illustrates the post- execution risk matrix $R_{p,e}$ (5 classes) by initial execution risk $R_e = P \times I_n$ and post- execution factor $F_p = (D + A)/8$, for $k_e = 1.0$. Colour coding: very mast-red, mast-orange, medium-yellow, small green light, neglected green.

Matrix interpretation:

- X: buckets for R_e (Original execution risk), both normalised values P, $I_n \in [0,1]$
- Y: tapes for $F_p = (D + A)/8$ (post- execution factor – detectability + accessibility) with values $\in [0,25;1]$
- In cells: risk class + resulting amount $R_{p,e}$
- Note: the matrix is generated for $k_e = 1.0$ (medium evaluator). For Junior/Senior, the values shall be multiplied by 0.8/1.2.

Step IV – ‘Post- Control Loop’ – updated based on $R_{p,e}$

The methodology is complemented by the **Post- Control Loop** concept, which makes the fiche a dynamic tool in operation:

- periodic inspections (class adapted frequency $R_{p,e}$) – The frequency of periodic inspections is adapted to the post-execution risk class $R_{p,e}$ according to the principle of risk-based monitoring. Items assigned to higher risk classes require reduced intervals between inspections and

advanced investigation methods, while low-risk items may be subject to simplified checks at longer intervals.

- digital log of defects/interventions,
- periodic analysis of R_{p_e} (defining a possible risk score evolution),
- corrective measures according to trend (increase/decrease).

Technical sheet for risk assessment and monitoring in industrialised and in-situ execution of simple and reinforced concrete elements				
Step IV – Post-control Loop – updated based on R_{p_e}				
Periodical Inspection	Intervention log	Corrective measures – dynamic risk	Evaluator	Observations

Figure 4-5 Extract from technical sheet – Phase IV a – ‘Post Control Loop’ – updated based on $R_{(p_e)}$

Although the indicators used in the risk assessment are expressed on different scales, the comparability of the results is achieved by referring them to the risk classes defined in the methodology (negligible, small, medium, high and very high) and not by directly comparing absolute numerical values.

The proposed methodology can be further enhanced through the integration of digital technologies consistent with the principles of Industry 4.0. Digitalization has been identified as a significant factor influencing productivity and organizational performance by enabling interconnected digital systems and more efficient data processing [1].

In this context, the inspection and post-control phases of precast concrete elements could benefit from automated image acquisition, computer vision techniques, and machine learning algorithms capable of detecting non-conformities and classifying risks based on historical performance data.

There is also potential to use image processing to identify superficial non-conformities, as well as machine learning models to classify risks based on historical data and indicators extracted from images.

For critical structural elements, the methodology may be extended to integrate monitoring sensors and use simplified numerical models to assess the consequences of defects on structural behavior.

The methodology can also be applied to industrialised patented products, such as applied metal structures, where hidden risks are associated with welds, anti-corrosion treatments and anchoring in the underlying structure. [13]

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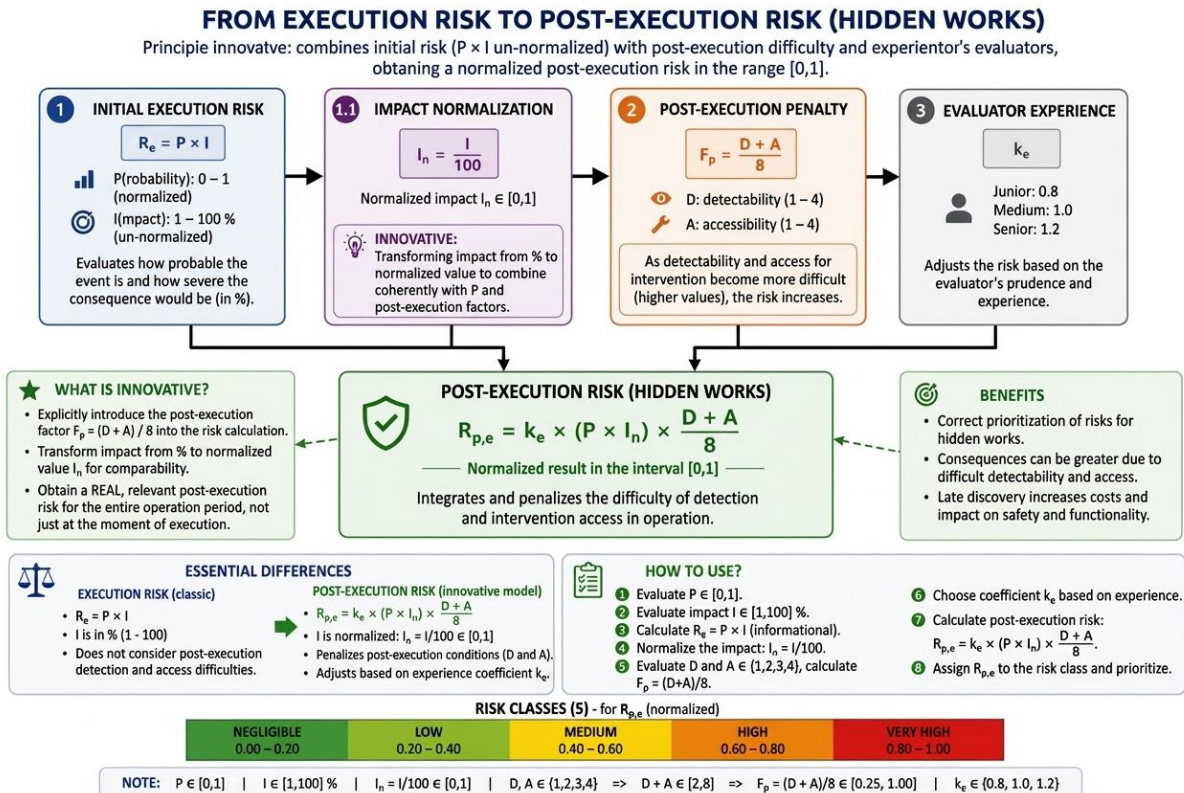


Figure 4-6 Comparative transition scheme from initial execution risk R_e to post execution risk $R_{(p_e)}$, by integrating detectability, accessibility and evaluator experience

5. CASE STUDY – application of the risk assessment and prioritisation methodology based on the use of the technical sheet in order to optimise the quality of industrialised and in-situ elements made of simple and reinforced concrete

Following the analysis of the ‘estimated risk diagram method’, it was considered necessary to design and develop a new, simplified method aimed at analysing structural elements, defined as works that become hidden and assessing the risks associated with them.

In order to identify the risks of high occurrence, the methodology involved their analysis across the entire output stream, namely: the execution phase, the verification/inspection modalities, the type of structural element, the possibility of subsequent identification during the construction phase, the identification methods, the impact and possible consequences on the whole construction, as well as the intervention mode to restore the quality characteristics to the required level-

Risk analysis by type of structural element is methodologically justified, as the likelihood and impact of vulnerabilities differ significantly between foundations, poles, beams, walls and tiles, both for prefabricated and in-situ elements. This differentiation allows for a realistic initial risk assessment (R_e) and a correct post-execution risk (RPE) ranking, in line with the principles of the proposed hybrid method.

The technical sheet for risk assessment and monitoring in industrialised and in-situ execution of simple and reinforced concrete elements constitutes an operational risk assessment tool used to identify, monitor and analyse critical steps in the industrialised process of production, execution and post-execution inspection of precast plain and reinforced concrete elements.

FISA was complemented by identifying the vulnerabilities associated with each phase of the technology flow and assessing their impact on the structural elements analysed. The four technological steps defined are:

- AI. Before pouring concrete
- IB During pouring
- IC After casting
- ID During use

The analysis was carried out for the main structural components, foundations, poles, beams, walls and tiles, taking into account both the execution phase and the possibility of subsequent interventions during the exploitation period.

In the first step, potential risks resulting from non-compliances or execution deficiencies, such as lack of quality documents or poor condition of shuttering, were identified.

The estimated value of the initial risk R_e was determined by reporting the probability of occurrence at the level of the estimated impact. Step I is illustrated in Figure 5-1.

Subsequently, the preventive measures applicable during the execution phase were introduced, as well as the possibilities for post-execution verification and intervention. At this stage, the aim was to assess the extent to which the risks identified could be controlled or mitigated during the operation of the construction works.

Detectability and accessibility indicators were introduced to assess post-execution risk, reflecting the difficulty of identifying defects and the complexity of access for possible subsequent interventions.

The values entered in the sheet were based on the author's objective technical estimates, drawn up following analysis of the technical documentation, performance requirements, quality control principles and professional experience

in the field of construction. Estimates of probability, impact, detectability and accessibility were not arbitrary values but were established by linking the technical characteristics of each structural element to the actual possibilities of verification, monitoring and operational intervention, all of which are illustrated in Figure 5-2.

The assignment to risk classes made it possible to rank the identified vulnerabilities and to highlight situations where preventive measures and the accessibility of subsequent interventions contributed to significantly reducing the residual risk.

Technical sheet for risk assessment and monitoring in industrialised and in-situ execution of simple and reinforced concrete elements										
Step I – Identification and ranking of risks by execution phase										
Crt No.	Phase (technological flow)	Vulnerability = Risk	Type of structural element	Verification method	Verification scope	Probability of occurrence	Impact	Estimated value of risk R_e	Risk class R_e	OBS.
						[0,1]	[0,100 %]	$R_e = P \times I$		
1	AI	Lack of quality documents	foundations	examination by visual inspection	compliance with the quality requirements for construction materials	0.9	50%	0.45	Medium	
2	AI		stalls			0.9	50%	0.45	Medium	
3	AI		beams			0.9	50%	0.45	Medium	
4	AI		walls			0.9	50%	0.45	Medium	
5	AI		boards			0.9	50%	0.45	Medium	
6	AI	Shredding status (moisture)	foundations	examination by visual inspection	compliance with technical design and tender specifications	0.5	80%	0.40	Low	
7	AI		stalls			0.7	80%	0.56	Medium	
8	AI		beams			0.7	80%	0.56	Medium	
9	AI		walls			0.7	80%	0.56	Medium	
10	AI		boards			0.7	80%	0.56	Medium	

Figure 5-1 Extrast from the content of the fiche, step I, AI technology phase.
Before pouring concrete for the second of the identified and analysed vulnerabilities

Technical sheet for risk assessment and monitoring in industrialised and in-situ execution of simple and reinforced concrete elements								
Phase III – Post-Execution Risk Hierarchy								
Probability of occurrence	Impact	Detectability D	Accessibility A	Difficult Intervention Penalty Factor F_p	Coef. Assessor experience k_e	Execution risk R_{p_e}	Risk class R_{p_e}	OBS.
[0,1]	[0,1]	[1; 4]	[1; 4]	$F_p = (D + A)/8$	[0.8/1.0/1.2]	$R_{p_e} = k_e \times R_e \times F_p$		
0.8	0.4	1	1	0.25	1	0.08	Negligible	
0.8	0.4	1	1	0.25	1	0.08	Negligible	
0.8	0.4	1	1	0.25	1	0.08	Negligible	
0.8	0.4	1	1	0.25	1	0.08	Negligible	
0.8	0.4	1	1	0.25	1	0.08	Negligible	
0.7	0.5	2	2	0.5	1	0.17	Negligible	
0.7	0.6	2	3	0.625	1	0.26	Low	
0.8	0.6	2	3	0.625	1	0.30	Low	
0.8	0.6	2	3	0.625	1	0.30	Low	
0.5	0.6	2	2	0.5	1	0.15	Negligible	

Figure 5-2 Extract from the content of the fiche, step III for the AI technological phase. Before pouring concrete for the second of the identified and analysed vulnerabilities

In view of an even clearer picture of the functioning of the new methodology, two of the discussions associated with the *IB execution phase*

during pouring of simple and reinforced concrete elements were also analysed. Thus Figure 5-3 and Figure 5-4 represent the risk analysis in Steps I and III of the tracking sheet.

Technical sheet for risk assessment and monitoring in industrialised and in-situ execution of simple and reinforced concrete elements										
Step I – Identification and ranking of risks by execution phase										
Crt No.	Phase (technological flow)	Vulnerability = Risk	Type of structural element	Verification method	Verification scope	Probability of occurrence	Impact	Estimated value of risk R_e	Risk class R_e	OBS.
						[0,1]	[0,100 %]	$R_e = P \times I$		
126	IB	Inappropriate concrete pouring	foundations	examination by visual inspection	in order to obtain the requirements of strength and stability	0,61	80%	0,49	Medium	
127	IB		stalls			0,8	80%	0,64	High	
128	IB		beams			0,8	85%	0,68	High	
129	IB		walls			0,8	70%	0,56	Medium	
130	IB		boards			0,5	70%	0,35	Low	
131	IB	Excess water	foundations	examination by visual inspection	in order to obtain the requirements of strength and stability	0,8	99%	0,79	High	
132	IB		stalls			0,8	80%	0,64	High	
133	IB		beams			0,8	80%	0,64	High	
134	IB		walls			0,8	80%	0,64	High	
135	IB		boards			0,7	76%	0,53	Medium	

Figure 5-3 Extract from the content of the sheet, Phase I, for the technological phase IB During pouring, for the second of the vulnerabilities identified and analysed

Technical sheet for risk assessment and monitoring in industrialised and in-situ execution of simple and reinforced concrete elements									
Phase III – Post-Execution Risk Hierarchy									
Probability of occurrence	pact	Detectability D	Accessibility A	Difficult Intervention Penalty Factor F_p	Coef. Assessor experience k_e	Execution risk R_{p_e}	Risk class R_{p_e}	OBS.	
	[,1]	[1; 4]	[1; 4]	$F_p = (D + A)/8$	[0.8/1.0/1.2]	$R_{p_e} = k_e \times R_e \times F_p$			
0,61	0,9	4	2	0,75	1	0,41	Medium		
0,7	0,8	3	3	0,75	1	0,42	Medium		
0,8	0,8	4	3	0,875	1	0,56	Medium		
0,8	0,7	3	3	0,75	1	0,42	Medium		
0,3	0,7	4	4	1	1	0,21	Low		
0,95	0,9	4	4	1	1	0,86	Very high		
0,95	0,8	4	3	0,875	1	0,67	High		
0,95	0,8	4	3	0,875	1	0,67	High		
0,95	0,8	4	2	0,75	1	0,57	Medium		
0,95	0,8	4	2	0,75	1	0,57	Medium		

Figure 5-4 Extract from sheet content, step III for technology phase IB During concrete pouring for the second of the identified and analysed vulnerabilities

The differences in risk levels achieved in the two steps analysed, the estimated risk in the execution phase R_e and the post-execution risk R_{p_e} , highlighted the influence of preventive measures, monitoring possibilities and subsequent intervention conditions on the identified vulnerabilities.

A lower post-execution risk compared to the initial risk indicated that:

- the defect or vulnerability could be identified relatively easily in operation;
- effective methods of subsequent verification were in place;
- access to the structural element allowed for corrective interventions;
- the preventive measures applied in implementation mitigated the potential consequences of non-compliance.

In these situations, while the initial risk could be categorised as ‘medium’ or ‘low’, the subsequent control and remediation capacity significantly reduced the residual risk, leading to its downgrading, e.g. ‘negligible’.

Conversely, situations where the differences between the two levels of risk were reduced or where the post-execution risk remained relatively high indicated the existence of associated difficulties:

- fault detection;
- access to structural elements after completion of implementation;
- the complexity of the remedial interventions;
- the impossibility of continuous monitoring of certain areas.

These cases suggested that these vulnerabilities required more rigorous control already at the implementation stage, as the possibilities for subsequent correction were limited or costly.

Therefore, the differences between the two risk levels were an indicator of the effectiveness of the prevention and maintenance strategies integrated into the design and execution process. A significant reduction in post-execution risk revealed a good capacity to manage vulnerabilities throughout the construction lifecycle, while maintaining a high risk signalled the need for additional measures to control, monitor or redesign technical solutions.

6. CONCLUSIONS AND FUTURE DIRECTIONS

6.1. General conclusions

The proposed methodology expands the classic risk assessment model of the execution phase by introducing factors specific to the post-execution period, particularly relevant for hidden works and elements difficult to access after commissioning.

In the initial stage of execution, the risk is assessed on the basis of the probability of occurrence of the defect and its associated impact. The probability is expressed on a normalised scale between 0 and 1, while the impact is expressed as a percentage, in the range of 1-100 %.

For coherent integration of post-implementation parameters, the impact is then transformed into a normalised value between 0 and 1. This step is one of the

innovative elements of the methodology, as it allows direct comparability between parameters and integration into a uniform assessment model.

The model additionally introduces detectability and accessibility factors, used to reflect the difficulty of identifying defects and intervening on elements after the execution has been completed. As follows:

- defects that are difficult to detect increase the level of risk;
- elements difficult to access for inspection or intervention are further penalised;
- the final assessment shall reflect actual operating and maintenance conditions.

The methodology also introduces the influence of the evaluator's experience by adjusting the level of risk according to the level of professional expertise. In this way, the template includes the prudence component specific to the technical assessment process.

The essential difference with classic models is that the analysis is not limited to the time of execution, but also incorporates the subsequent behaviour of the elements in service. The model thus converts the theoretical execution risk into a post execution risk applicable to the actual conditions of construction.

The application of this methodology results in:

- realistically prioritising risks for hidden works;
- identification of critical operational elements;
- optimising inspection and maintenance processes;
- reducing the costs of defects discovered late;
- increase the level of safety and functionality for industrialised and prefabricated buildings.

6.2. Summary of results obtained

Analysing the results of the two methods, namely the 'estimated risk diagram method', characterised by 2 components, i.e. probability and impact, to which numerical values and the tracking data sheet method were assigned, where the two methodologies, i.e. possible subsequent identifications/inspections and possible consequences, failure to meet fundamental requirements, established that 90 % of the vulnerabilities analysed in both situations turned into risk factors requiring additional attention and a personalised monitoring regime.

Also, another novelty feature of this methodology is the possible definition of additional inspection measures during execution by defining and personalising

new subdivisions or inspection levels during the execution of works that become hidden.

The new inspection levels can be defined taking into account the risks associated with the works that become hidden characteristics of each structural element, i.e. the severity of the consequences and the negative impact on the quality of the construction properties, as well as the degree of difficulty with the intervention methods.

By analysing the results determined by completing the technical tracking sheet, the key document of the methodology presented in the content of this theoretical research, the risks classified at higher levels, i.e. high and medium risks, associated with the vulnerabilities identified, may define and determine new inspection levels in addition to those existing with regard to execution in accordance with national regulations.

The role of these new levels of inspection is to reduce the occurrence of possible risks due to the improper execution of works that become hidden, in this case the execution of concrete elements, and to minimise the consequences due to the occurrence of risks.

6.3. Original research contributions and directions for further development

The paper proposes a hybrid methodology that integrates expert assessment with quantifiable technical parameters and introduces the concept of adaptive risk according to the accessibility and detectability of hidden works.

The methodology allows for the future development of a digital tool for continuous risk monitoring, transforming quality control from a static process into dynamic and predictive and efficient.

At the same time, another innovative element of the tracking datasheet method allows for continuous monitoring of the risks posed by hidden works through the introduction of the ‘post-control Loop’ concept.

This concept allows for:

- periodic inspections
- digital Fault Log
- evolving risk score

Going further, the Tracking Data Sheet method can also be developed in terms of possible risk-based maintenance strategies. At the same time, the following categories of information can be defined:

- Preventive maintenance = medium risk

- Predictive maintenance = data-driven (e.g.: sensors)
- Corrective intervention = critical risk

The paper proposes a hybrid approach for assessing the risks associated with industrialised execution of precast concrete elements, combining qualitative analysis with quantitative indicators integrated into- a uniform monitoring framework.

The methodology aims at identifying vulnerabilities specific to each stage of the technology flow and structuring them in- a technical sheet allowing for a consistent risk assessment throughout the execution cycle.

Considering the evolution of technologies used in construction, the possibilities of expanding the methodology by integrating modern digital tools such as image processing for identifying non-conformities, the use of machine learning models for risk categorisation, or the deployment of sensor-based monitoring systems for critical structural elements are also discussed. The processing of pictures captured on site or 3D models can contribute to the early identification of superficial and geometric non-conformities, reducing reliance on purely visual assessment and providing measurable indicators, directly integrated into the assessment process. For critical structural elements, monitoring through embedded sensors represents a high potential direction. Linking in-situ measurement data to the information obtained at the visual inspection stage can transform the datasheet into- a dynamic tool, capable of capturing the actual evolution of the element over time and signalling deviations from expected behaviour.

By combining these directions, i.e. digitalisation, automation, monitoring and mechanical analysis, the methodology can evolve into a complete tool, adapted to the current requirements of industrialised execution and capable of supporting a more efficient, reproducible and predictive quality control process. These directorates can help automate inspection phases and increase the objectivity and predictability of the evaluation process, providing strong prerequisites for further developments in quality control in industrialised execution.

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