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Degradation Analysis and Preventive Maintenance Modelling and Assessment for Improved Resilience of Critical Infrastructures – Application to Torrent Checkdams

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Abstract

Natural threats have become more familiar, to the extent that requires ensuring the resilience of critical infrastructures. Critical infrastructures have always been complicated to study and assess, as they are all characterized by a collection of components that have numerous dependencies and interactions. Recently, several methods and frameworks have been put forward to assess and analyse comprehensively system's resilience. However, these methods have insufficiencies in identifying some hidden risks arising in a complex infrastructure. Therefore, it is essential to go beyond conventional methods and to develop risk strategies and decision-making techniques in order to overcome classical static assessment methods. This paper contributes to analyse the context of critical infrastructures with the ultimate objective of proposing new methods of choosing preventive maintenance strategies. It represents a modelling approach based on Petri nets to study the dynamic behaviour of the system when exposed to deterioration mechanisms and to support maintenance decision-making. The application is carried out on torrential checkdams in which the model results are presented and discussed in the paper.

Keywords: Critical infrastructures, degradation modelling, preventive maintenance, decision-making, Petri nets, checkdams.

1. Introduction

Recently, societies have become more and more reliant on infrastructures which constitute a network of man-made systems that delivers permanently and cooperatively major benefits, supplies, and services (e.g. electric power, telecommunication, transportation, water supply). Infrastructures are important for enhancing social environment and for economic prosperity. However, the complexity and interdependency of these infrastructures have turned them into a critical system-of-systems [1].

Critical infrastructures (CIs) are usually exposed to various types of threats (technical, natural, man-made attacks, etc.) which cause them damage. Consequently, the

destruction or weakness of CIs may foster the risk due to the resulted impact on the economy, safety, and society as a whole [2]. Hence, analysing their reliability and safety but also choosing the best maintenance strategy is very essential. The internal or external interdependencies of CIs might also trigger risk such as the risk of cascading failures [3]. In other words, an initial failure of a CI which has dependencies with other CIs can result in disastrous proportions across the whole system. This reveals that interdependency increases the complexity of the system of CIs [4]. Nevertheless, not all infrastructures are considered to be critical. They can be classified based on a criticality scale which is identified after assessing the impact of the infrastructure disruption [5].

Another kind of CIs is linked to protection works against natural phenomena. Protection structures in the mountainous regions (e.g. Alpine) seek to fight against natural hazards generated in these areas. Torrents, avalanches, landslides, and other mountainous natural phenomenon are mostly caused by a gravitational and rapid movement of complex mixtures of fluids and solids [6]. According to the intensity of each natural phenomenon, several damages may arise. The impact can be expressed by the extent of the area that has been destructed, number of people affected, materials and assets disrupted (buildings, roads, infrastructures, etc.), financial damages, and the recovery rate of the resulted deterioration.

Due to the fact that torrential protection works (checkdams, sedimentation dams, levees, etc.) aim in preventing or mitigating the risk and thus protect people and assets from the imposed danger resulting from the natural phenomena, deep attention has been given to them. Unfortunately, protection works age, deteriorate, and may be damaged overtime when exposed to hazards. Their deterioration will influence their level of performance and thus will affect the possibility of reducing risk as much as it should be reduced. Moreover, these structures are interdependent in which a failure of a certain component (one structure) of the system (series of protection works) can lead to the perturbation of other components within the same system. Also, certain type of failure in one component may trigger another type of failure in the same component. All of the previous aspects lead to the conclusion that protection works are complex structures and can be considered as CIs. Checkdams are the most used torrential protection works in France. They represent around 14,000 civil engineering protection works in the French state forests [7].

To better understand the ability of protection structures in preventing damage, mitigating losses, and to be restored after an event requires mainly resilience analysis [8]. The term resilience refers to the ability of a system to withstand and adapt unfavourable events and its capacity to be recovered after being influenced due to such situations. Resilience analysis will give a comprehensive knowledge regarding the performance of these structures during and after the occurrence of hazards. Researchers have suggested several methods for quantifying resilience. Some researchers have concentrated on modelling the restoration of critical structures especially for bridge [9] and railway track [10] asset management hoping to improve their resilience.

Due to the fact that the system can be repaired following different maintenance strategies, decision-aiding models can help to choose the most preferable strategy.

These models analyse the behavior of the system over its lifetime period while being deteriorated or repaired. Such decision-aiding models can be implemented and assessed using Petri nets modelling tools and Monte Carlo simulation, which allow choosing between several maintenance strategies based on degraded-state conditions.

This paper is organised as follows: Section 2 introduces the methodology used to implement the desired model; Section 3 presents the modelling approach which models the behaviour of the system from one state to another; Section 4 considers a case study applied on check dams after identifying the possible failure modes and maintenance strategies; Finally, section 5 provides results coming from the simulation of the model.

2. Methodology Used: Stochastic Petri Nets (SPNs)

Petri nets (PNs) are dynamic models used in modelling the behaviour of a system (e.g. failure, repair, etc.) and in dependability calculations [11]. They present a graphical and mathematical tool for modelling complex systems and their evolution over time. Carl Adam Petri was the German who invented the graphics and the rules of PNs in the 1962 to be used in automation systems [12]. PNs allow analysing the dynamic behaviour of the system by modelling the transitions between its different states. Following their invention, PNs were developed by going far from traditional analytical approaches and using Monte Carlo simulation instead. In addition, the use of stochastic transitions has proven its efficiency for dependability (reliability, availability, and maintainability) analysis and for system safety [13].

Recently, SPNs are used to model complex systems, mainly the deterioration of critical infrastructures, such as railway networks [14]. SPNs are particularly well suited to model the evolution of the system while changing from one state to another and are able to compute the time spent by the system in each state and the number of each type of intervention that was carried out based on Monte Carlo simulation [15]. They can therefore extend and complement existing methods providing static effectiveness assessment [16].

PNs are a collection of four main elements. Places represent a condition and reflect the state of the system and are symbolized by circles. Transitions are symbolized by rectangles and correspond to events that cause a change of state in the system. The state of the system is characterized by marking places with tokens. Arcs are arrows that connect a place to a transition or a transition to a place only. They are associated with multiplicities which are responsible for the operation of the PN. If an arc does not indicate any multiplicity, the value will be one by default.

Once the PN model is constructed and the lifetime period t_f of the system is identified, Monte-Carlo simulation starts and the tokens will keep on moving around the model until t_f is reached. The movement of tokens is governed by the following rules:

1. When the number of tokens in each input place of a transition is at least equal to the multiplicity of the arcs connecting each, the transition is enabled and will be fired after a specified transition firing time.
2. When a transition is fired, a number of tokens equal to the multiplicity of the arc is removed from the input places, and added to the output places.

An additional characteristic of PNs is the inhibitor arc. This arc is represented by a dotted arrow and can be only directed from a place to a transition. Its aim is to inhibit the firing of the transition which it is connected to when its multiplicity is equal to the number of tokens located in its input place.

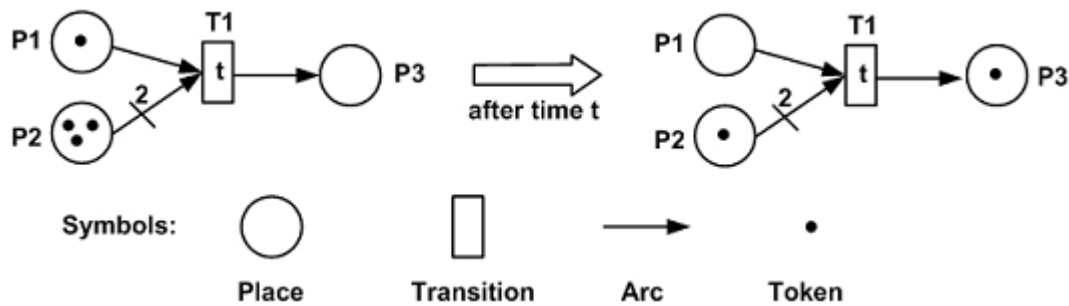


Figure 1: Simple PN showing the transition firing process.

A simple PN is illustrated in Figure 1. P1 and P2 are both marked with a number of tokens satisfying the rule of enabling a transition. Therefore, T1 is enabled. After time t , T1 is fired in which 1 token (multiplicity = 1) is removed from P1, 2 tokens (multiplicity = 2) is removed from P2, and 1 token (multiplicity = 1) is added to the output place P3.

3. SPN Modelling and Assessment Framework for a Deteriorating Structure

In this section, a general modelling framework using SPN is presented. The aim is to represent the evolution of the state of a CI when exposed to degradation mechanisms or to maintenance operations and then to support decision-making by comparing different maintenance strategies.

3.1 Degradation, inspection, and maintenance processes

The modelling of the degradation process is illustrated in Figure 2 [17]. P1-P4 represents the four degraded states which are linked by stochastic transitions T1-T3 associated with exponential distribution firing times assumed and judged by an expert. In order to detect the state of the system, inspection must be carried out periodically. At $t=0$, a token is added to P1 (initial state) and to P5 waiting for T5 to fire so that the token moves to P6 where inspection takes place. In this study, inspection is scheduled every year. After the firing of one of the immediate transitions T6-T8, the condition of the system is revealed where a token appears in one of the

places P7-P9. In this case, the respective maintenance operation begins and after a specific time needed for repair, T9, T10, or T11 fires depending on the condition revealed and the system returns back to its initial state waiting for another inspection.

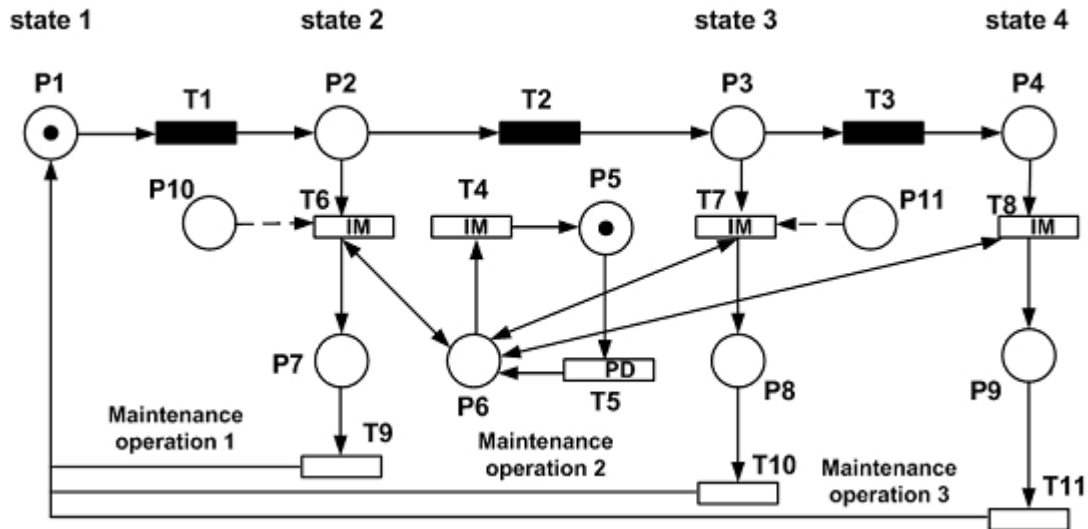


Figure 2. A basic PN model showing the degradation, inspection, and maintenance processes [17].

3.2 Decision-making support

In order to make a decision and choose between the different possible maintenance operations, inhibitor arcs should be added to the model. The presence of a token in P10 or in P11 inhibits respectively maintenance operation 1 or maintenance operation 2 from being carried out over the lifetime period of the system.

After implementing each strategy, the results provided after Monte Carlo simulation reveals the time spent by the system in each state (sojourn time) and the number of maintenance operations performed within the lifetime period of the system. These outputs allow comparing between the different maintenance strategies in terms of time and cost.

4. Application to Checkdams

Checkdams, like any other protection structures, are constructed to perform certain functions. Their major functions involve bed stabilization, bed elevation and slope reduction, retention of sediment deposits, flow centring, and prevention of longitudinal erosion. However, due to their age, wear and tear, and the intensity of the phenomenon that they must resist, different kinds of pathologies may appear affecting their performance level. The assessment of the efficacy of protection structures to reduce risk is based on three components: structural, functional, and economical efficacy [16]. To limit their degradation, these structures should be inspected and maintained regularly. Besides, in order to choose a suitable maintenance strategy, it is

important to have a comprehensive knowledge on the types of failures that checkdams may be subjected to.

It is also essential to differentiate between functional and structural failures. This is due to the fact that the structure may be stable from a structural point of view but is not fulfilling a certain function. On the other hand, the structure may have some bad structural properties but is still fulfilling its functions. Structural failures are linked to the external (e.g. sliding, overturning, etc.) and internal (e.g. reinforcement, material strength, etc.) stability of the structure. Functional failures includes the phenomena of lateral bypass in which the dam is no more able to release the flow from its hydraulic section and the phenomena of scouring where intense clear water flow removes the soil under the base of the dam's foundation.

The present study aims to prove the ability of SPN models in choosing between different maintenance strategies to be applied on checkdams highlighting on some aspects such as time, cost, and efficiency. The application presented below aims to study the stability of a checkdam when exposed to scouring. Figure 3, represents the different possible functional (FS) and structural (SS) states of the dam depending on the increase level of scouring under the foundation.

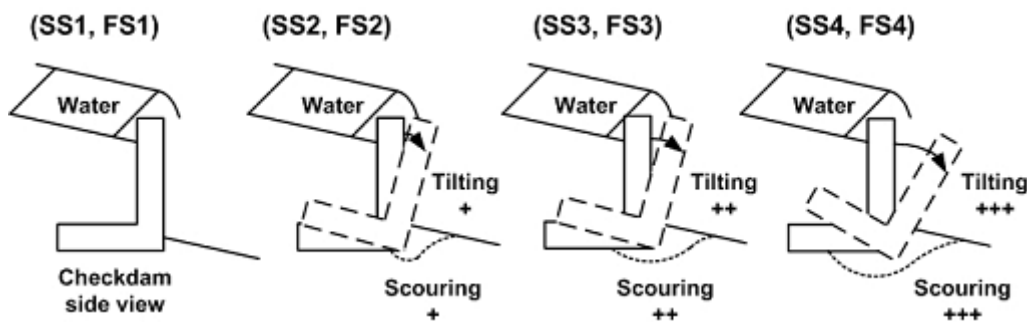


Figure 3. State-degradation due to scouring under the foundation of a checkdam.

In this paper, the functional and structural degradations are modelled separately without taking into account the dependencies and interactions between both failures.

4.1 Evaluation of functional degradation states

In this section, the SPN model describes the behaviour of the checkdam when exposed to functional failure. The different functional states are presented assuming that the system is stable from a structural point of view. Four stability states were defined as shown in Figure 4. Regarding maintenance operations: minor maintenance can be applied when the slight deterioration can be easily repaired (SS1, FS2), major maintenance is needed in order to repair the serious degradation level that the structure has reached (SS1, FS3), and corrective maintenance is required when the structure completely fails and should be replaced (SS1, FS4).

Thus the structural state is fixed to SS1 and four functional states are defined FS1, FS2, FS3, and FS4 corresponding to an increased level in scouring. When the system is not in its initial state, minor, major, or corrective (replacement) maintenance operations are to be carried out.

In addition, the system can only be maintained by three minor operations and two major operations before replacing the system with a new one. This is illustrated by the presence of P12 and P13 (Figure 4) linked with inhibitor arcs with respective multiplicities 3 and 2. Meaning that when 3 tokens appear in P12, minor operations are inhibited and when 2 tokens appear in P13, major operations are inhibited. However, after each replacement, P12 and P13 should be emptied from tokens in order to enable again minor and major operations. This function is included within the properties of T11 (reset transition) in which upon firing, it removes all the tokens in P12 and P13.

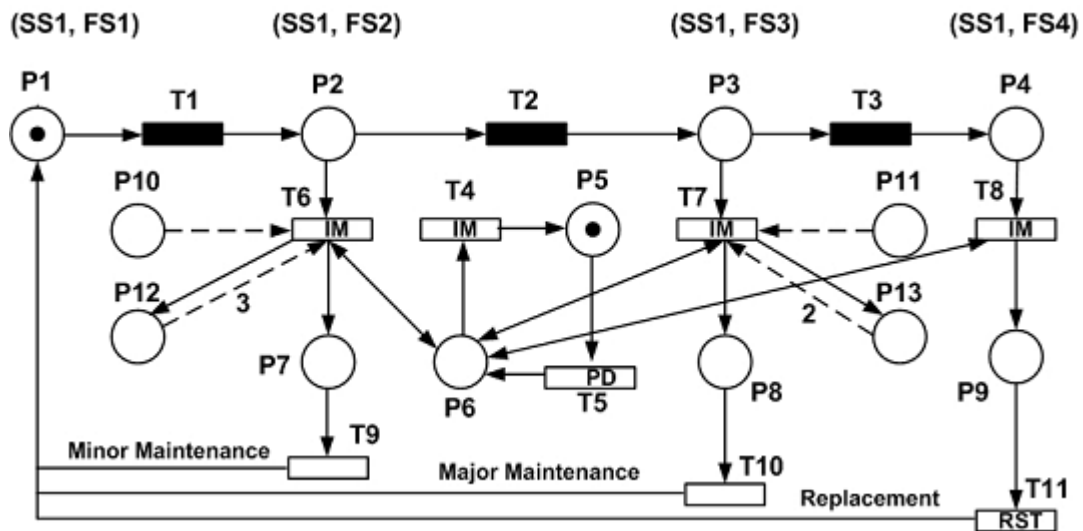


Figure 4. SPN model showing the functional degradation, inspection, and maintenance processes (improved and adapted version of [17]).

The input data needed to run this model are the firing delay times associated with each transition. In this study, no historical data are available, therefore these data are assumed and assessed by experts in the field of checkdams and presented in Table I and Table II.

Four different strategies are identified. In strategy 1, reparation is done as soon as the condition revealed after inspection does not correspond to the new state. In strategy 2, a token is added to P10 which inhibits minor operations. In strategy 3, a token is added to P11, thus major operations are inhibited. In strategy 4, P10 and P11 are marked with tokens meaning that only corrective maintenance can be carried out.

Table I: Failure rates of degraded-states transitions. **Table II:** Constant transitions firing times.

Transition	Exponential Failure rate λ (years ⁻¹)
T1	0.5
T2	0.1
T3	0.033

Transition	Firing time (years)
T4 T6 T7 T8	0
T5	1
T9	0.013
T10	0.022
T11	0.041

4.1 Evaluation of structural degradation states

In this section, the SPN model describes the behaviour of the checkdam when exposed to structural failure. The different structural states are presented assuming that the system is fixed to a functional state FS3 where scouring already exists. Four structural states are defined SS1, SS2, SS3, and SS4. The structural state of the dam degrades in which the dam will start to tilt until it finally overturns when scouring reaches a critical level. Scouring level can be used as an indicator to describe the behaviour of the checkdam from structural point of view. The four different stability states are represented in Figure 5.

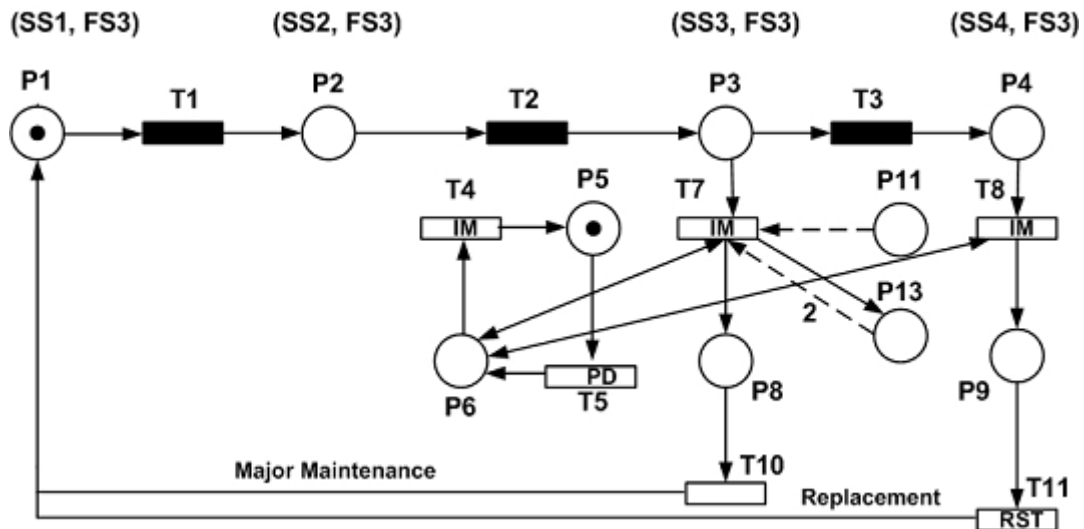


Figure 5. SPN model showing the structural degradation, inspection, and maintenance processes (improved and adapted version of [17]).

Regarding maintenance operations: major maintenance can be applied by reinforcing the checkdam to avoid its failure by overturning after reaching state (SS3, FS3) and corrective maintenance is required when the structure completely fails and should be replaced (SS4, FS3). In state (SS2, FS3), the checkdam is subjected to mild tilting in which no need for a maintenance operation to be carried out at this stage. Moreover, Figure 5 reveals that only two major operations can be carried out before the

replacement of the system. The firing delay times corresponding to structural deterioration are estimated by an expert and given in Table III and Table IV.

Table III: Failure rates of degraded-states transitions. **Table IV:** Constant transitions firing times.

Transition	Exponential Failure rate λ (years ⁻¹)
T1	0.5
T2	0.25
T3	0.5

Transition	Firing time (years)
T4 T7 T8	0
T5	1
T10	0.082
T11	0.33

For structural degradation, two maintenance strategies are suggested. In strategy 1, repair is done when the system reaches state (SS3, FS3). In strategy 2, P11 is marked with a token in which only corrective maintenance can be carried out.

5. Results

The SPN models are constructed using GRIF-Workshop developed by TOTAL. The simulation of the previous models is based on Monte-Carlo simulation. After each simulation, the mean sojourn time in each state and the number of maintenance operations carried out during the lifetime period of the system will be given. The model is simulated over a period of 100 years. It is noticed that convergence in results occurs after 200 simulations. Tables V - VIII provide all the results obtained after the simulation of the different strategies applied for functional and structural degradation over a period of 100 years.

Table VI reveals the effect of each maintenance strategy on the mean sojourn time. It is noticed that the longest sojourn time in the initial state (21 years) occurs by performing strategy 1. This is due to the fact that the system is repaired as soon as it degrades further from the initial state. For strategy 2, minor operations are inhibited, thus the system will remain in a degraded state for a long time. This is the reason behind the decrease in the sojourn time in the initial state (11 years) when applying strategy 2.

Table V: Average expected number of interventions - functional degradation.

Strategy	Minor Maintenance	Major Maintenance	Corrective Maintenance
1	6	3	1
2	0	4	1
3	7	0	2
4	0	0	3

Table VI: Average expected sojourn time (years) – functional degradation.

Strategy	(SS1, FS1)	(SS1, FS2)	(SS1, FS3)	(SS1, FS4)
1	21	46	32	0
2	11	53	35	1
3	20	24	55	1
4	6	28	65	1

Table VII: Average expected number of interventions – structural degradation.

Strategy	Major Maintenance	Corrective Maintenance
1	8	5
2	0	11

Table VIII: Average expected sojourn time (years) – structural degradation.

Strategy	(SS1, FS3)	(SS2, FS3)	(SS3, FS3)	(SS4, FS3)
1	30	56	11	2
2	25	46	22	6

In Table VIII, it is also clear that when major maintenance is inhibited, the sojourn time of the system in the initial state (SS1, FS3) will be less than that when maintenance is applied directly if the system degrades to state (SS3, FS3). The results obtained in Table V and Table VII, allow comparing the different strategies in terms of cost. It is assumed that for functional degradation, the cost of minor maintenance, major maintenance and corrective maintenance are 5 000 €, 15 000 €, and 45 000 € respectively. For structural degradation, it is assumed that the cost of major maintenance and corrective maintenance are 60 000 € and 150 000 € respectively.

Knowing the cost of each type of operation and using the data in Table V and Table VII, the total cost of each strategy can be computed. The results are given in Table IX and Table X. It can be seen that for functional degradation, strategy 4 is the most expensive because of the huge number of corrective maintenance to be done (3 replacements). Strategy 2 has the lowest cost since the system is allowed to deteriorate before being maintained with minor operations.

Table IX: Total maintenance cost (€) for each strategy – functional degradation.

Strategy	Minor Maintenance	Major Maintenance	Corrective Maintenance	Total Cost
1	30 000	45 000	45 000	120 000
2	0	60 000	45 000	105 000
3	35 000	0	90 000	125 000
4	0	0	135 000	135 000

Table X: Total maintenance cost (€) for each strategy – structural degradation.

Strategy	Major Maintenance	Corrective Maintenance	Total Cost
1	480 000	750 000	1 230 000
2	0	1 650 000	1 650 000

Similarly, for structural degradation, strategy 2 is more expensive than strategy 1 due to the large number of corrective maintenance operations.

6. Conclusion

This paper addresses the development of a decision-aiding method regarding resilience and maintenance of CIs. The main objective is to go beyond traditional safety and reliability techniques for efficacy and resilience assessment. Based on the results, SPN approach, combining Monte Carlo simulation and state-based modelling technique has proved to be favourable and can be an appropriate tool to be used later for 1) analysing the interdependencies among CIs and 2) choosing the best operating strategies. The limitations in this study include modelling the system without taking into account the dynamic interactions between the different failure modes that may occur on the structure and how an event may foster the occurrence of another event (accident sequence). Calculations are based on expert assumptions and further works are needed to improve and determine modelling hypothesis (e.g. failure rates). Furthermore, acquiring reliable results in the domain of resilience and preventive maintenance is not easy due to a number of barriers such as information imperfection and the absence of real historical data. This study will be developed by taking into consideration interdependencies which increase the risk of failure. The strong reliance on CIs points out that it is a priority to assure their safety and availability.

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