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Value of Information Analysis for the Post-Earthquake Assessment of Existing Masonry Structures—Case Studies

Karlo Ožić *, Davor Skejić, Ivan Lukačević and Mislav Stepinac

Faculty of Civil Engineering, University of Zagreb, 10000 Zagreb, Croatia
* Correspondence: karlo.ozic@grad.unizg.hr

Abstract: In the last decades, the post-earthquake assessment and strengthening of existing structures are becoming one of the most critical fields of civil engineering. Most parts of Europe, as well as many existing buildings in Croatia, are built in masonry. For that reason, the main objective of this paper is to show the role of updating knowledge in the decision analysis process of existing masonry assessment. Collecting information through condition assessment can be performed on multiple levels with different precision and quality of the obtained data. Several alternative maintenance strategies and corresponding outcomes usually represent decision problems regarding the assessment of existing structures. Regarding existing buildings, decision analysis proved the benefits of updating knowledge in the building post-earthquake assessment process. As case studies, two existing masonry buildings were selected and different assessment procedures and decision scenarios were presented. The Value of Information (VoI) analysis showed that the applied method is feasible from the perspective of owners and users, as its implementation resulted in a reduction in the overall strengthening and maintenance costs.

Keywords: masonry; assessment; value of information; decision scenario; earthquake

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1. Introduction

Cultural heritage structures built in masonry represent an important part of the World Cultural Heritage. As they are still in use, they must be preserved to guarantee their functionality and conserved for their historical value [1,2]. In Croatia, as well as most parts of Europe, most of the so-called 'strategic' buildings of cultural significance and high historical importance are built in masonry. In addition, most of these buildings have exceeded their design working life. It is of great importance to have a decisive and effective assessment and maintenance plan with the greatest possible utility (health, safety, monetary, sustainability, functionality). To this purpose, the reduction of epistemic uncertainties can be achieved through various inspection techniques. Visual assessment, destructive, semi-destructive and non-destructive testing (NDT) methods and collecting the data with structural health monitoring (SHM) systems are essential parts of strengthening existing structures [3]. Although decision-making processes are widely accepted in various fields, in civil engineering, sustainable decision-making procedures are urgently needed [4]. In managing the performance of an existing structure, decision making is strongly associated with the condition assessment, encompassing comprehensive and qualitative measurements and properly collected data in a cost-effective way [5,6]. For our present purpose, the objective of such analysis is to identify a course of action that is in line with the decision maker's preferences. At the same time, consequences are expressed as numerical utilities. However, it should be mentioned that it is rarely, if ever, possible to find the best of all possible courses of action and that reasonable men 'satisfice' much more than they 'optimize' [7]. The utilization of information obtained from enhanced inspection, damage detection systems and monitoring has been an important topic in the past decades of structural reliability and risk research [8–10]. To this purpose, Value of Information (VoI) [11] analysis is introduced. It can be defined as quantification of the expected utility or benefit increase due to additional or predicted information.

The development has grown into a comprehensive research community, especially concerning the risk-based inspection of various types of infrastructure and deteriorating structural systems [12,13]. Knowing the VoI, decisions can be improved for the design, operation and life-cycle integrity management of structures and to enable more cost-efficient and reliable strategies for maintaining and developing the environment to benefit society [14–16]. The recently finished COST Action TU1402 [17] dealt with the benefits of condition inspection before it was carried out. This paper aims to study the role of various levels of post-earthquake condition assessment on the VoI analysis of existing masonry buildings. Subsequent decisions are analysed. The study focuses on existing heritage buildings to evaluate the advantages of assessment regarding the economy and safety of structures, as well as the preservation of cultural value. This paper discusses how pre-posterior decision analysis can help quantify the VoI gained from the condition assessment of masonry, which can help select appropriate post-earthquake assessment procedures and subsequent maintenance actions. As case studies, two masonry buildings in Zagreb, Croatia, are investigated in the context of VoI analysis. The first is a typical residential building, and the second is an educational one. Both buildings are under heritage protection. The calculations are based on the new Croatian guidelines and technical regulations issued after two significant earthquakes in Croatia [18,19]. A price analysis is performed following the documents mentioned above.

2. Post-Earthquake Assessment of Masonry Structures

The need for an assessment of an existing structure can be based upon a multitude of reasons. Among the most typical are given in [20]: if errors in the planning or construction period become known; on the occasion of a change in use of the building; in case of doubts about the structural reliability, caused by visible damage; due to inadequate serviceability and usability; because of exceptional incidents or accidental loads that might have damaged the structure; in the case of arising suspicion due to material-, construction- or system-inherent impairment of the structural safety; if a simple, initially unfounded suspicion needs to be eliminated; when the remaining lifetime, determined during a previous assessment, has expired. As already known, strengthening and reliability assessment of heritage buildings is always a more challenging process with more boundaries in the design and even more uncertainties regarding real building behaviour. Many different aspects must be considered (e.g., execution of the structure, nature of the original construction, the service life of the structure, design working life, deterioration, change in use, cultural value, etc.) [21] when reliability assessment is going to be performed.

In the field of structural engineering, especially when dealing with existing structures, there are many uncertainties, epistemic and aleatory. Epistemic uncertainties are related to the lack of knowledge regarding the phenomena that dictate how a system should behave, ultimately affecting the outcome of an event, while aleatory uncertainty can be defined as the internal randomness of phenomena [22]. In order to reduce them to a satisfactory level, structural engineers should try to obtain as much information as possible to still have, in economic terms, optimal construction. The assessment of heritage structures is a cyclic process. As a rule, it often requires the application of sophisticated methods (pushover, time-history analysis, NDT methods, SHM systems) beyond the scope of conventional design practice and codes [23–25]. Both structural behaviour and cultural value affect the decision process and must be chosen carefully. Approaching structural assessment of cultural heritage, engineers should not act overly cautiously as it can lead to unnecessary structural interventions, which consequently leads to significant alteration or loss of heritage-defining elements. Finally, it affects the authenticity and historical significance of the cultural identity [26].

Using destructive tests should be only considered as the last resort, in cases when the information cannot be obtained using other means or to calibrate NDTs, preferably in less-conspicuous areas and without affecting character-defining elements [27]. For example, flat-jack testing gives valuable and necessary data on the modulus of elasticity and shear properties of masonry. However, sometimes it is not feasible due to the destructive nature of the test and its influence on heritage-protected elements [28]. In recent decades, the application of technological advances and tools in civil and infrastructure engineering has yielded many results [29]. They are important factors in ensuring the safety of engineering structures, reducing the probability of accidental structural failure and improving the life-cycle costs of the structures. The most common method of post-earthquake assessment of historical masonry structures is a combination of visual on-site inspection and preferably non-destructive tests. An experienced engineer's on-site visual inspection can provide basic information about the overall state of a structure's integrity and stability, as well as identify weak and critical zones and elements. Currently, there are several guidelines for the assessment of existing structures, not particularly for masonry structures, but for all existing and heritage structures. Based on existing guidelines and a literature search [21–23,26–28] for the assessment of existing structures, the flowchart for condition assessment is presented in Figure 1.

A common feature of the available assessment procedures is that they start with a preliminary assessment, based on visual inspection and review of available documentation. Based on the result of the preliminary inspection, a decision is made on whether more detailed assessments are required or not. Nevertheless, it might not be straightforward how the decision should be made. According to the authors, there is an urgent need for bringing together the different approaches to a broadly accepted, coherent and harmonised set of rules for existing structures in general and for heritage buildings in particular. Besides the aforementioned generic guidelines, a rich literature exists which can help in the assessment [30–33], maintenance and decision-making [34–37].

2.1. Knowledge Levels According to EN 1998-3

The most distinguishing feature in the post-earthquake assessment of existing buildings is the number of epistemic uncertainties which add up to the aleatory ones. Thus, it is important to have effective procedures to account for as many uncertainties as possible in the final assessment. As a function of the information obtained to overcome current incomplete knowledge for the assessment and retrofitting of buildings, as seen in Figure 2 [38], mostly in relation to geometry, structural details and material properties, knowledge levels (KL) are defined in the current Eurocode (EN-1998-3 [37]). When enough information is gathered to satisfy a certain knowledge level, it leads to a value of the corresponding Confidence Factor (CF). Proceeding, the value of CF is applied to one particular parameter, assumed by the code to be the most critical in affecting the building's response. In some cases, it leads to some limitations on the method of analysis that must be used. In EN 1998-3, there are three defined knowledge levels, KL1, KL2 and KL3, where KL3 corresponds to the highest achievable knowledge. Values of CFs defined by the code are associated with each knowledge level: CF (KL1) = 1.35, CF (KL2) = 1.2, CF (KL3) = 1.0. Commonly, the KL to be reached is arbitrarily chosen by the engineer or the decision maker. Figure 2 [38] shows the cumulative distribution of CF when the three previously mentioned knowledge levels have been achieved, where the grey area indicates a reduction in unsafe assessment for each knowledge level. In Figure 2, Θ represents the ratio between the outcome of the assessment and the real capacity of the building. The real behaviour of the building is described as $\Theta = 1$. In particular: (1) a reduction in the dispersion of results and a progressive convergence to the real behaviour is expected, moving from KL1 to KL3; (2) more conservative outcomes must therefore occur in case the of lower knowledge levels; (3) unsafe assessments must be limited to an 'acceptably small' fraction of cases [38].

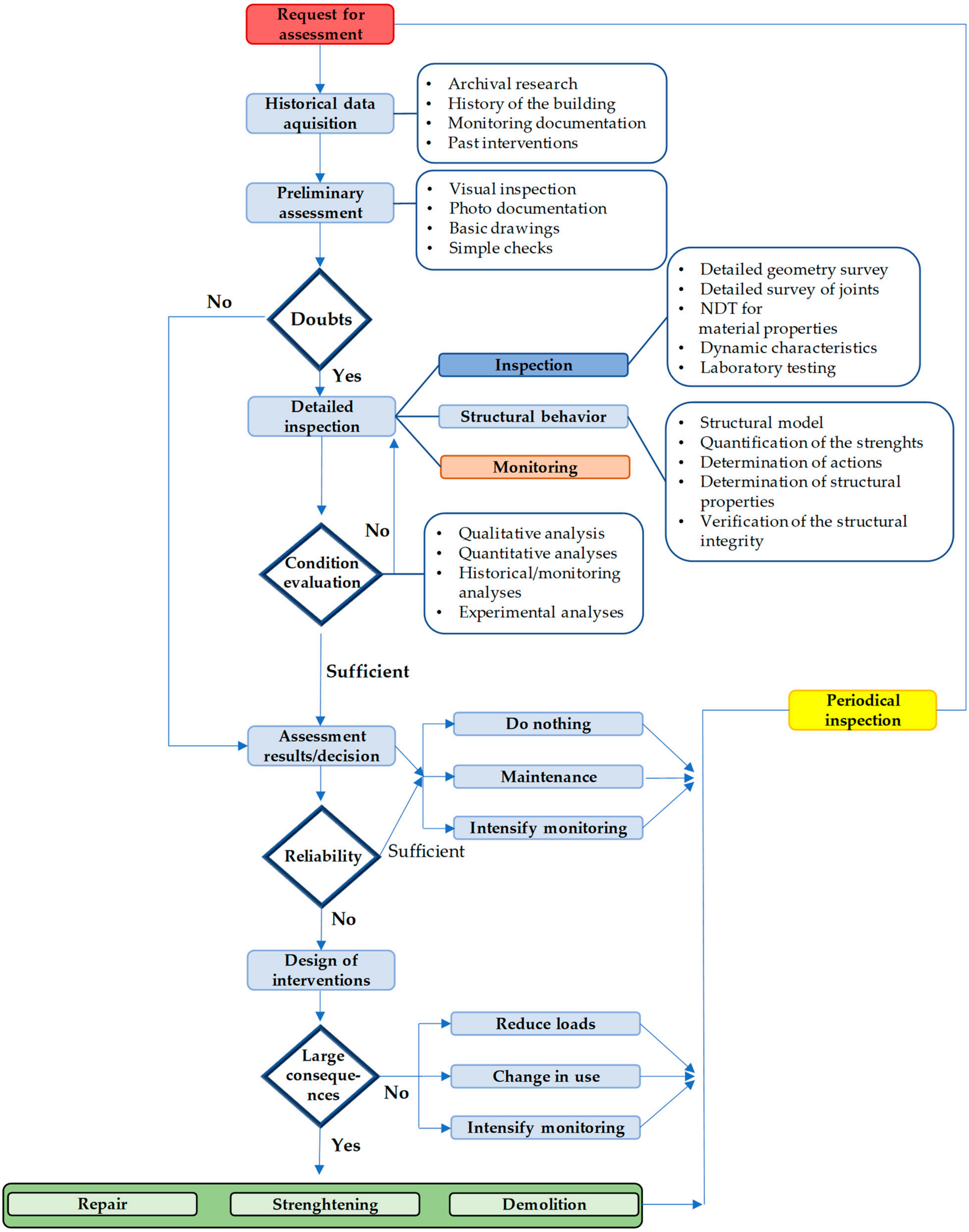

Figure 1. Flowchart of the post-earthquake assessment of masonry buildings.

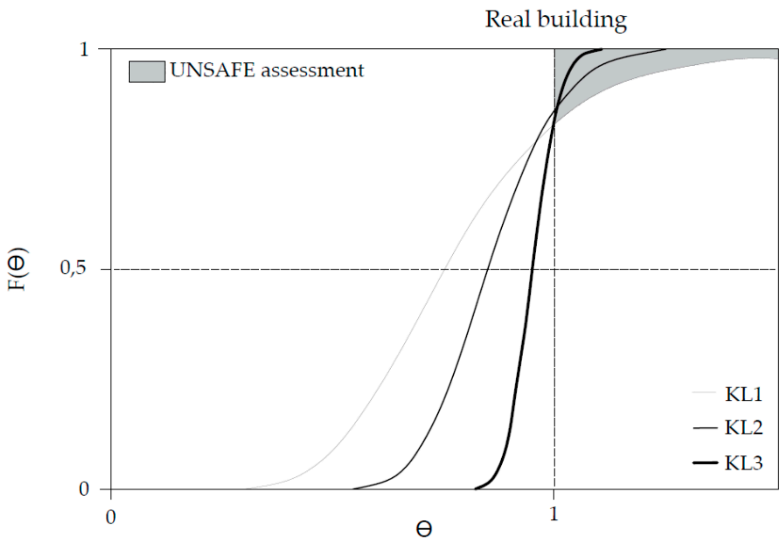

Figure 2. Dispersion of results of knowledge levels (modification from [38]).

Generally, the application of the CF differs in relation to the type of analysis: in the global post-earthquake assessment, the factor is applied as a reduction in the material strength while, in the local analysis, the factor is directly applied as a reduction in the peak ground acceleration that leads to the formation of the collapse mechanism [39].

It can be said that the philosophy behind the definition of CFs is in part similar to that of partial safety factors, which are applied to loads and mechanical properties in the design of new structures.

With the aim of obtaining a certain KL in heritage buildings, significant variability often causes an increase in the 'minimum' number of tests, in opposition to what is proposed in standards.

The general aim in the case of cultural heritage buildings is the need to minimize the invasiveness of experimental in situ tests. Since heritage buildings have a rich history in which they have been subjected to many transformations/renovations, they are often characterized by a significant variability in materials and masonry types.

If the engineer chooses to be satisfied with a lower KL it guarantees a more conservative result, although more retrofitting interventions could be required even if not strictly necessary. This results in two conflicting sides of the conservation principle/minimizing the costs and invasiveness. In light of the above, it is of great importance that the assessment result is as close as possible to the real behaviour to satisfy the idea of 'minimum intervention'.

2.2. Decision-Making Procedure

Decision making in structural engineering can be considered as a 'game' in which the goal is to maximize the expected utility by making the 'best' decisions [40]. The utility is related to the preferences over the set of possible outcomes and the decision maker. For example, the structural engineer in charge can be seen as an agent acting according to a certain utility function representing the preferences of an organization and/or society. The utility is typically expressed in monetary costs. It includes the benefits that arise from the functionality of the structure, cost of maintenance and repair actions, risks of failure and disruptions of service, etc. Since decision-making procedures tend to rank decision alternatives proportionally to their expected utility, it is only logical that additional information from available data should be considered beneficial.

Decision making can also be viewed as a problem-solving activity completed by a result regarded to be optimal or at least satisfactory. Therefore, it is a process that can be more or less rational or irrational and can be based on explicit or tacit knowledge and beliefs [41]. The decision-making process can be described as the analysis of a finite set of alternatives described in terms of evaluative criteria. Then the task might be to rank these alternatives in terms of how attractive they are to the decision maker(s) when all the criteria are considered simultaneously [42]. It states that rational behaviour can be described as maximizing the expectation of a utility function. From there, the concept of VoI, derived from the Bayesian decision theory, presents the theoretical foundation for quantifying the potential benefits of additional information.

A self-explanatory way of describing VoI is to compare an act-then-learn approach with a learn-then-act approach. In this way, the decisions can be analysed using game theory [43]. To play and ultimately win the game, the decision maker can 'purchase' either information about the system or physical changes in it [44]. Both options require resources to be committed and therefore decrease the utility; however, they might increase the chances of 'winning', e.g., maximizing the benefits and minimizing the losses due to maintenance. A rational approach to decision making is provided by Bayesian decision analysis. It states that rational behaviour can be described as maximizing the expectation of a utility function. It enables the decision maker to quantify the expected benefits of various assessments prior to making a decision on which option to choose and thus put a price tag on them. Thus, the decision maker can decide how much it is worth to pay for different types of assessments. Furthermore, it even allows the calculation of alternate benefits on the various levels of successive assessment procedures.

One of the major problems of decision analysis, especially for existing structures, is a large number of uncertainties. Uncertainties from all known sources should be evaluated and accounted for in a model. Besides the aforementioned classification of uncertainties as epistemic or aleatory, a different classification can be found in [45]. They are divided into intrinsic physical or mechanical uncertainty, statistical uncertainty and model uncertainties [45]. Of course, there are also a number of other uncertainties, such as visual assessment uncertainty (depending on engineers' experience), measuring uncertainty and also uncertainties that we do not know that we do not know.

To reduce some of the major uncertainties, decision makers use the possibility of gathering as much information as possible within the confines of cost-effectiveness. Nonetheless, the final outcome always depends on the quality of the information gathered. There are two distinctive types of information: perfect and imperfect information [46]. Perfect information corresponds to an ideal situation without any uncertainty. Consequently, imperfect information, as the name states, is information with some degree of uncertainty. Although the decision maker cannot usually obtain perfect information, it takes less computational effort to analyse it than that required for imperfect information. Therefore, it is a great first step in comparing the costs of obtaining information and its usefulness because the value of imperfect information cannot exceed the value of perfect information. Because of today's large number of data, especially using various sources, novel big-data techniques are often used for analysing information. Considering the condition assessment, the decision problem can be simplified to certain well-defined options, such as, e.g., 'do nothing', 'inspect', 'repair', 'strengthen', 'reduce loads', etc., as seen in Figure 1.

Given its important role, the original definition of the VoI analysis given in [7] is here briefly presented. This form of decision analysis is here presented in the form of the decision tree. Our decision problem can also be seen as a game between the decision maker and a second player called 'chance'. The game is rather simple, and it consists of four moves (Figure 3): the decision maker chooses an experiment e, chance decides the outcome z, the decision maker chooses an action a and finally, chance chooses state θ. The game is finished here and the decision maker obtains the 'payoff' through utility $u(e, a, z, \theta)$.

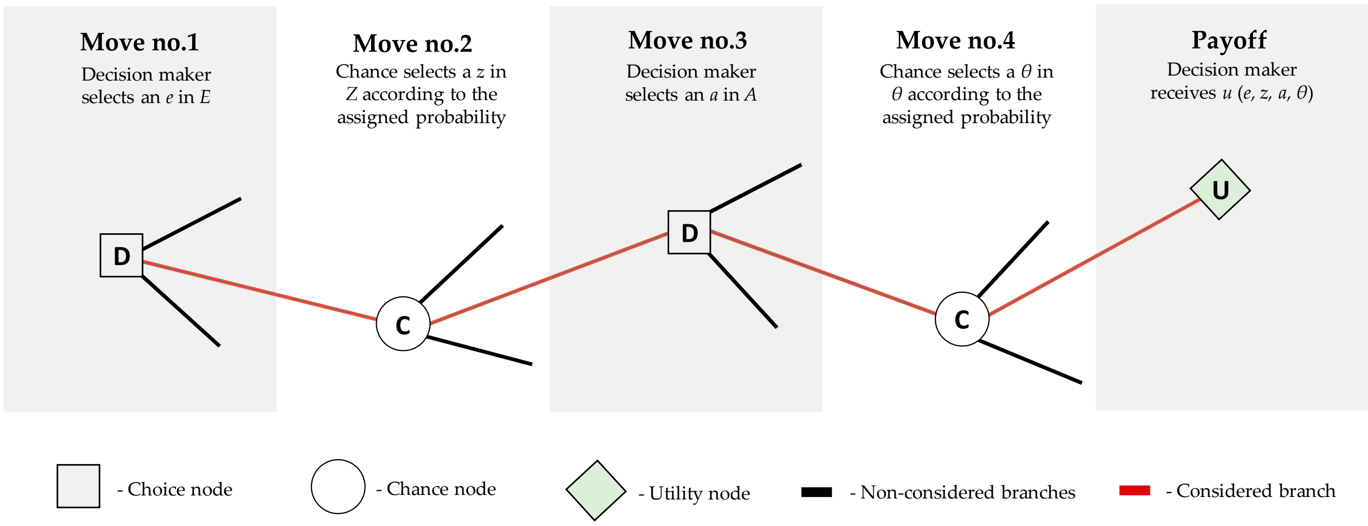

Figure 3. Decision tree.

The decision maker has complete control over choosing experiments and actions but does not have control or perfect knowledge about outcomes and states. Nevertheless, he can assign a probability measure over these choices, and the moves in the game proceed in accordance with these measures. The complexity of life cannot be measured with a decision tree and that is why one can always look ahead by adding another set of components. Also, it should be noted that by looking very far ahead, uncertainties increase, so it will not always be worth the effort. That is why knowing how and where to cut the decision tree is crucial. Along the considered branch of the tree, the decision analysis simplifies to selecting the most appropriate invasive action to maximise the expected benefit *u(a,x)*, leading to the overall expected life-cycle benefit *U*:

$$U_{prior} = \max_{a_k} E_{\theta_l}[u(a_k, \theta_l)] \tag{1}$$

where the indexes k and l represent specific actions or system states.

A decision tree can be separated into three different stages, as shown in Figure 4. Information management is where the decision makers decide on the experiment and gather information. State management is where the decision makers act based on the obtained information and enhanced knowledge. Lastly, the utility stage is where the decision makers receive a payoff considering the actions they chose.

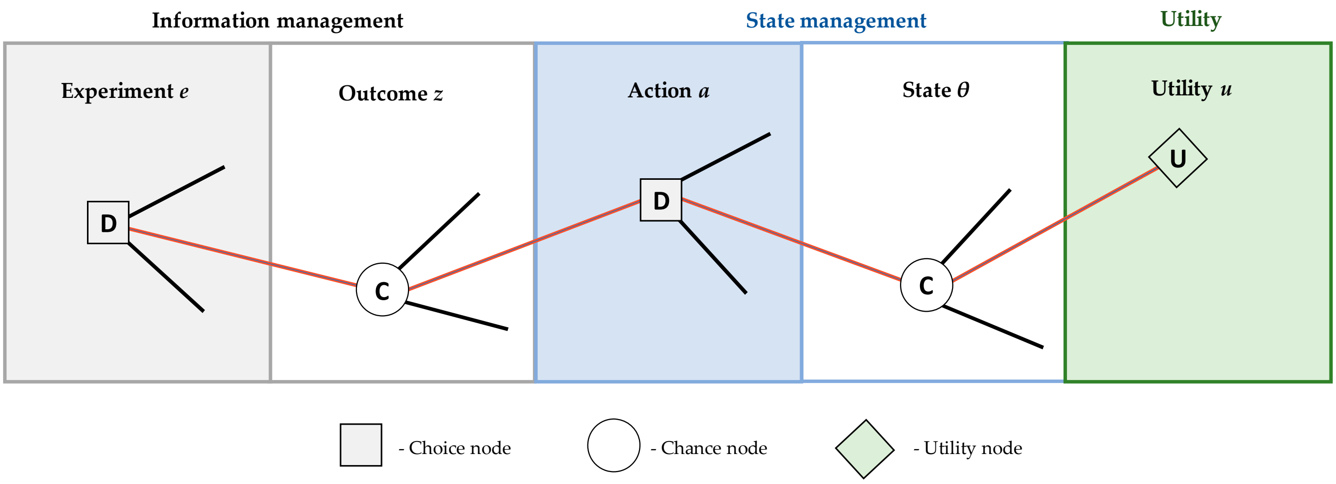

Figure 4. Different stages of the decision tree.

The Bayesian analysis developed by Raiffa and Schlaifer [7] is based on a concept in which prior belief is updated with additional information with support for likely values of that parameter drawn from sampled data. This information forms a posterior belief when using Bayes' theorem (Figure 5).

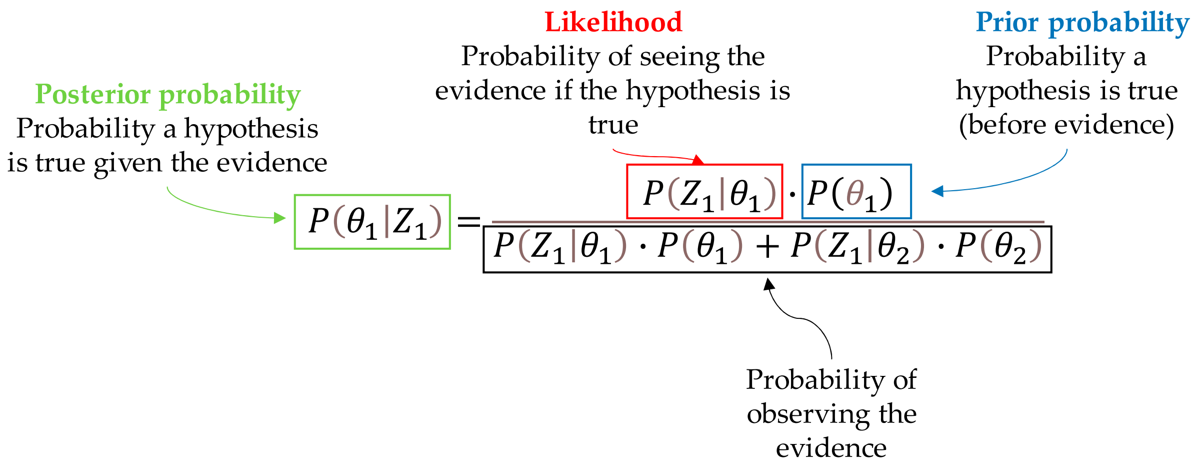

Figure 5. Bayes theorem [47].

Differing in the state of information at the time of the decision, there are three different analysis types: prior, posterior and pre-posterior analysis. Prior decision analysis is a decision analysis with known models and current knowledge, for example, historical data or previous experience. Posterior decision analysis is identical to the prior decision analysis, with the exception that the basis for the probabilistic modelling of uncertainty has been enhanced. We have gained some new information through experiments and updated it to posterior probability, which can later be used as a prior probability in a more complex decision tree. Finally, pre-posterior analysis is a decision analysis with predicted information. The current knowledge combined with these collected data allows decision makers/engineers to predict the level of knowledge after the data is collected. As a result, Bayesian analysis is often described as a pre-posterior analysis.

As said before, we are updating prior probability with additional data through Bayes' theorem (Figure 5). To do so, we use likelihoods, which are a key component of Bayesian inference because they are the bridge from the prior to the posterior probability. As stated in [46], the likelihood function of a hypothesis (H) given some data (D) is the probability of obtaining D given that H is true and it can be expressed as: $L(h) = P(D|H = h)$.

A noteworthy issue is to recognise and model the situations through which information may cause contrary consequences and to account for their possible effects [48]. The expected value of conducting an experiment e, and subsequently optimizing an invasive action a, based on the possible outcomes Z, is evaluated in order to select the experiment that will lead to the maximum expected benefit:

$$U_{prepost}(e_l) = E_{Z_{i,j}}\left[\max_{a_k} E_{\theta_l|Z_{i,j}}[u(a_k, X\theta_l)]\right] \quad (2)$$

The expected benefits are related to the preferences of the decision maker over the possible outcomes of the decisions and subsequent course of action. The benefits are typically expressed in terms of costs, such as, e.g., those of assessments, maintenance actions, and risks due to structural failure or loss of revenue. The decision maker's preferences should reflect the preferences of the organization that they represent and might include societal aspects as well.

3. Application of VoI on Real Case Studies in Post-Earthquake Assessments

3.1. Residential Building in Zagreb—Case Study 1

This building, in aggregate, in Figure 6, was built in 1896 and is located in Zagreb's historic urban core. It was originally a two-story building but was adapted and upgraded to a three-story building in 1938. It consists of a basement, ground floor, first floor and attic. It has a rectangular ground plan oriented in the north–south direction. The building's external dimensions are 14.3 × 12.0 m with massive longitudinal walls, masonry ceiling vaults in the basement, timber floors and a timber roof. The gross building area is 684 m^2.

Figure 6. Residential building in Zagreb.

3.2. Educational Building in Zagreb—Case Study 2

Today's building in Figure 7 was built in 1895 by adapting and upgrading two one-story buildings built in the early 19th century. The building was upgraded in 1906, while the building took on its current shape with complete reconstruction in 1997. The building's rectangular ground plan has its main orientation in the east–west direction. The building's external dimensions are 12 × 53 m, while the total floor area of the building is 685 m^2. The building consists of a basement, first, second and third floors and an attic. The building is built in masonry (solid brick) with load-bearing wall thicknesses that vary throughout the building, reducing with height. After the 1997 reconstruction the wooden beam floors where replaced with reinforced concrete slabs, while the basement and first-floor ceilings are masonry vaults. The building serves as an educational–scientific institution.

3.3. The Decision Problem

The main interest from the owner's perspective is to extend the service life of the structure and optimize the resources spent on retrofitting, i.e., satisfying the seismic resistance of the building. The general objective is to ensure normal and steady use of the building and to preserve its heritage value. Therefore, an appropriate decision-making process is necessary to maximize the benefits of the structure's existence. Additional investments in, e.g., SHM tools and advanced calculation procedures can be justified by fulfilling these objectives, and by that, minimizing the costs of operation and maintenance.

Figure 7. Educational building in Zagreb.

The owner's decision on further actions regarding the case study building could be based on visual inspection only, assessment according to present codes, assessment based on NDT results or data gained from SHM, etc. Data obtained with advanced inspection and monitoring methods are generally useful but can be costly. The important and often rather difficult question regarding additional data is are they a worthwhile investment. Decision alternatives represent different scenarios for which the outcome probabilities and related consequences need to be quantified. A basic example of an influence diagram for choosing between condition-assessment options is shown in Figure 8.

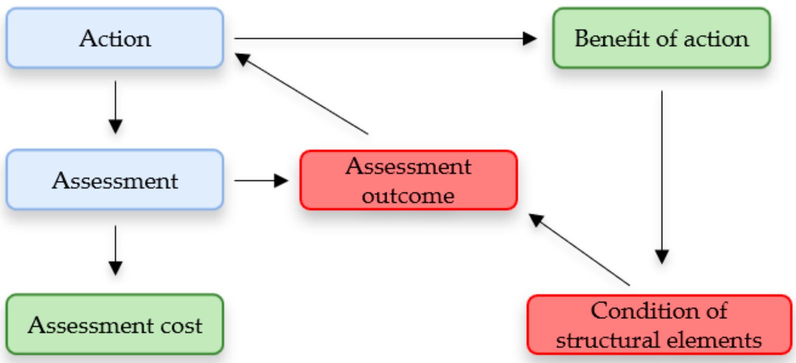

Figure 8. Basic influence diagram representing the condition-assessment problem (modified from [49]).

The following example considers the structural condition of the entire structure, which may be sufficient or insufficient. The decision maker must decide whether to opt for strengthening or proceed without intervention (do nothing). Prior to taking a final decision about physical action to alter the current condition, the owner can decide to invest in a condition assessment of the structure to see if the current state of the elements is critical or if it will show satisfying results. In the present study, three possible choices for assessment, i.e., obtaining additional data, were considered for enhanced assessment. An overview of these possibilities and the associated costs are given in Table 1.

Table 1. Levels of assessment and costs.

Assessment Level	Referent Branch	Description	Costs (€/m^2)
Level 0	e_0	No assessment	0.00
Level 1	e_1	Visual assessment, geometry check	4.00
Level 2	e_2	Detailed visual assessment, geometry and building plans, linear dynamic analysis	10.50
Level 3	e_3	Detailed visual assessment, geometry and building plans, research works (NDT, semi NDT) and nonlinear static (pushover) analysis	13.50

The decision tree for this case study has four main branches; every branch represents one of the assessment levels explained below, where e_0 is a referent branch where no assessment was conducted. Each subbranch can result in one of two system states, based on the choice in the action nodes. The outcomes are states with related probabilities when a structural failure occurs or does not. In the end, every system state is associated with benefits that appear in the case of its occurrence.

Advancing to higher levels of assessment is associated with higher additional costs, the characteristics and costs associated with the different levels from 1 to 3. The costs of the presented advanced assessment procedures in Table 1 are estimated based on the type of structure, the basic characteristics of the structure (dimensions, structural system, etc.) and the level of strengthening required. The associated costs are taken from the official government documents [50] enacted after the earthquakes in Zagreb and Petrinja. Due to the recent economic situation, prices presented in [50] and shown in Tables 1 and 2 are increased by 10%, accordingly to the Croatian bureau of statistics [51]. In order to find the optimal maintenance strategy and extend the service life of the structure, a pre-posterior analysis was performed.

Table 2. Costs of two action options.

		Residential Building	Educational Building
	Do Nothing (€/m^2)	Strengthen (€/m^2)	Strengthen (€/m^2)
Safe	0.00	447.00	375.00
Failure	1155.00	1600.00	1762.00

Different prices, summarized in Table 2, are correlated with different outcomes and structure states. The prices of strengthening defined in Table 2 are considered using the same analogy as costs of assessment from the same official national document [50]. However, costs in the case of failure are calculated from the reference price for the new building [52], the cost of demolition stated in [50] and the average cost of renting during the construction period.

After the recent earthquake in Zagreb, a public call was made for all civil engineers to help in the preliminary assessment of damaged buildings immediately after the main shock. These assessments form the HCPI (Croatian Centre of Earthquake Engineering) database [53] used in this research. The data used focused on the historic urban core of Zagreb since most of the buildings in that area are masonry structures with timber floors and roofs. In order to acquire prior probability, statistical data [53] from more than 13,300 buildings in the historic urban core of the city of Zagreb were taken into account. The number of buildings damaged in the previously mentioned earthquake in Zagreb was 2160, from which a conclusion was reached to estimate the prior probability of failure at 16% [54].

Each of the listed assessment procedures in Table 1, devised to optimize the maintenance strategy, is characterised by both advantages and drawbacks, which are summarized in Table 3.

Table 3. Benefits and limitations of the assessment levels evaluated in the study.

Assessment Level	Benefits	Limitations
Level 1	The cheapest method Fast method Some insight into the state of the structure	Lack of important data Many assumptions Misinterpretation of obtained data
Level 2	Better insight into the state of the structure Much additional data Identification of critical parts and elements of the structure	Time-consuming Additional instruments needed Additional learning needed Qualified personnel needed Misinterpretation of obtained data
Level 3	Identification of critical parts Updated information about materials Updated information about the state of the structure	Experienced engineers needed both for the interpretation of NDT methods and for probabilistic modelling Time-consuming Additional software might be needed

In general, the differences in the various assessment levels mainly arise from the differences in the modelling sophistication, uncertainty consideration and knowledge level [38]. The idea was to highlight how gradually decreasing the uncertainty consideration and knowledge level will affect the expected costs of the assessment. The multiple assessment levels can be presented as 'experiments' with uncertain outcomes. The results of each assessment level can either indicate acceptable or unacceptable structural performance. One could associate probabilities with each assessment level based on how well they indicate acceptable or unacceptable performance given the (unknown) real condition sufficient or insufficient. The current code approach emphasizes some of the uncertainties, while leaving aside some other important aspects involved in the seismic assessment of existing buildings.

Based on the formulation of the assessment problem from [55] and results from the study, the likelihoods in the pre-posterior analysis are taken according to Equation (4) and the CF for the acquired knowledge level. An approach is based on 'variability factors', defined in order to account for the different uncertainties while allowing CF to consider the KL of mechanical properties. Two different 'variability factors' are defined, α_{mod}, which takes into account modelling uncertainties as seen in [56] and α_{LS} for the identification of the deterministic threshold for the definition of the ultimate element drift ratios. As both variables are aleatory uncertainties, they do not depend on the acquired level of knowledge.

The definition of the CFs, as stated in the current code, is accounting for uncertainties related to knowledge levels of geometry, structural details and mechanical material properties.

As the first two sources are already connected to modelling, they are incorporated in the variability factor accounting for modelling uncertainty. Therefore, in the proposed approach, CF is taken into consideration as $\alpha_{mat} = 1/CF_{mat}$, i.e., accounting for the acquired knowledge of mechanical material properties.

Compared to the code approach, this approach presents numerous advantages for the seismic assessment of masonry buildings, as it takes into consideration all sources of uncertainty while keeping a similar formulation still based on the KLs with associated values of the CF.

Also, the methodology is easy to apply, and it does not require the practitioner to carry out fully probabilistic analyses, as suggested, for example, but only to apply predefined coefficients to the results of a deterministic analysis. Assuming all uncertainties to be independent, Equation (3) [55] can be written as a product of the different contributions to the total uncertainty, that is,

$$\alpha_{tot} = \alpha_{mod} \cdot \alpha_{LS} \cdot \alpha_{mat} \tag{3}$$

In [54], eight building prototypes of existing masonry structures were evaluated using the nonlinear static (pushover) analysis method with the equivalent frame macro-element modelling approach. To guarantee a global response, the geometry, floor plan and structural details of the analysed buildings were assumed to prevent local collapse mechanisms.

To carry out these analyses the research program TREMURI [57] was used. Following the analyses, the estimate of the 'variability factors' [43] considered earlier for the ULS are equal to the following.

$$\alpha_{tot} = \alpha_{mod} \cdot \alpha_{LS} \cdot \alpha_{mat} = 0.794 \cdot 0.925 \cdot \alpha_{mat} = 0.734 \cdot \alpha_{mat} \tag{4}$$

where αtot is, for each KL, a unique safety coefficient obtained as the product of αmod, αLS and αmat. From coefficient αtot these so-called sample likelihoods for pre-posterior analysis, depending on the acquired knowledge level (KL1–KL3) and using Equation (4) for the assessment methods used, are taken (Table 4).

Table 4. Sample likelihoods for assessment methods.

	Level 1		**Level 2**		**Level 3**	
	Sufficient	**Insufficient**	**Sufficient**	**Insufficient**	**Sufficient**	**Insufficient**
Unacceptable	0.41	0.59	0.34	0.66	0.2	0.8
Acceptable	0.59	0.41	0.66	0.34	0.8	0.2

After the first choice of levels of assessment one has two action options:

1. Do nothing a_0
2. Strengthen and/or repair a_1

With the aim of carrying out the decision analysis, the decision tree was created for the case studies. Four main branches are established in the decision tree, as each one represents an alternate decision scenario. Branches consist of choice nodes (squares) and chance nodes (circles) for probabilistic models, such as decision outcomes [14]. With every choice made in the action nodes, each subbranch can result in two different system states.

The outcomes are states with related probabilities when a structural failure occurs or does not occur, with the maximum allowed probability of failure taken as $5 \cdot 10^{-5}$ [58].

Finally, to each system state, benefits that appear in case of its occurrence are added.

According to the decision tree, the decision is sought between different alternative assessment options assuming that after selecting the most appropriate assessment method, a decision on intervention will follow. In practice, however, condition assessment is carried out successively, i.e., before intervention it is possible to opt for a higher level of interventions.

4. Results and Discussion

VoI was conducted using methodology adopted from [59,60], presented with a characteristic decision tree for case studies in Figures 9 and 10, with all costs modelled with absolute values in euros. The final results for both case studies are summarized in Table 5. This paper shows utility in economic terms, i.e., the costs of strengthening the building according to the chosen assessment level. VoI in the pre-posterior analysis is easily achieved through Equation (5).

$$V = U_{preposterior} - U_{prior} \tag{5}$$

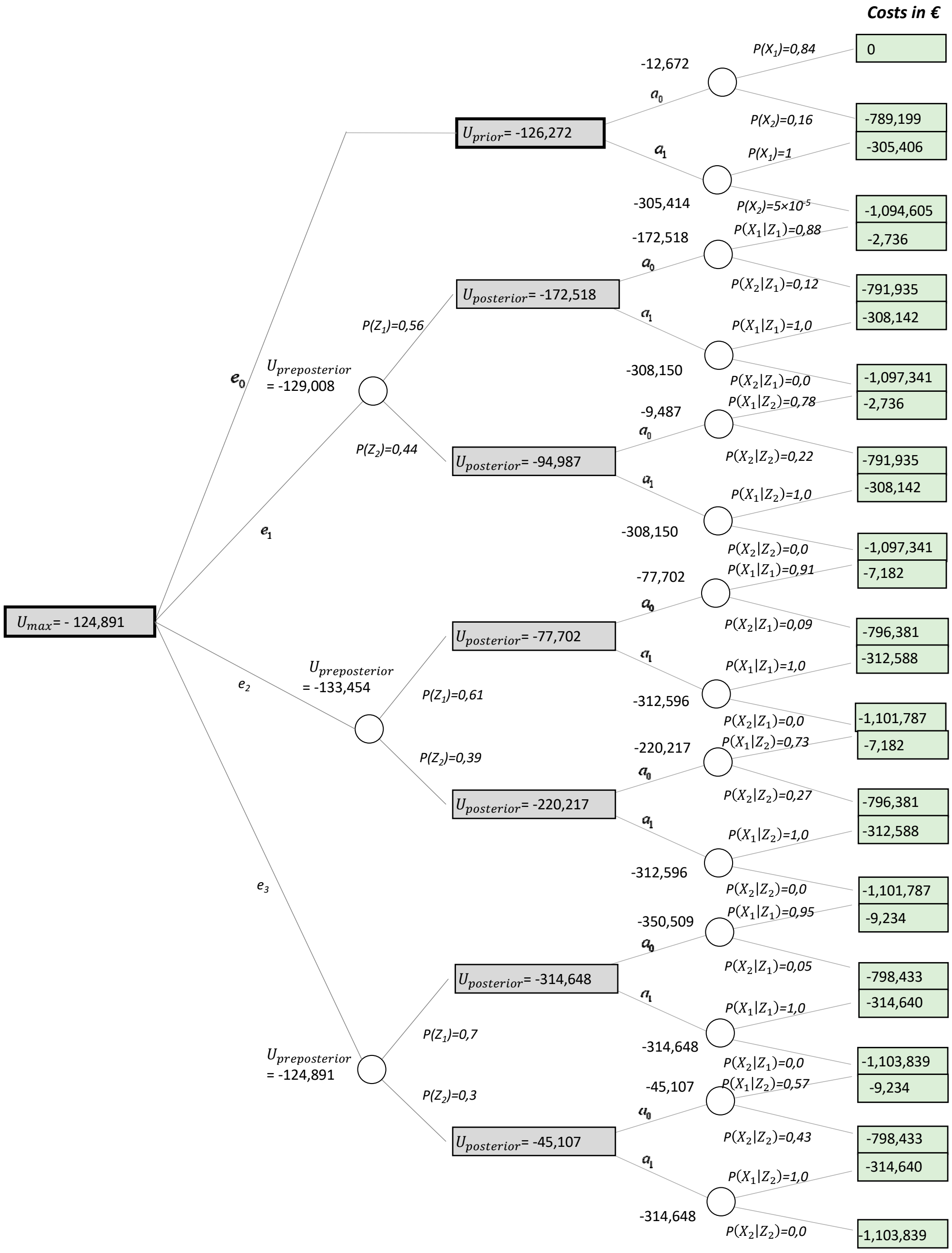

Figure 9. VoI analysis for case study 1.

Table 5. Results of VoI analysis for both case studies.

	Utility Pre-Posterior [€]	Utility Prior [€]	VoI–Absolute Value [€]
Case study 1-Residential building	124,891	126,272	1381
Case study 2-Educational building	445,652	523,032	77,380

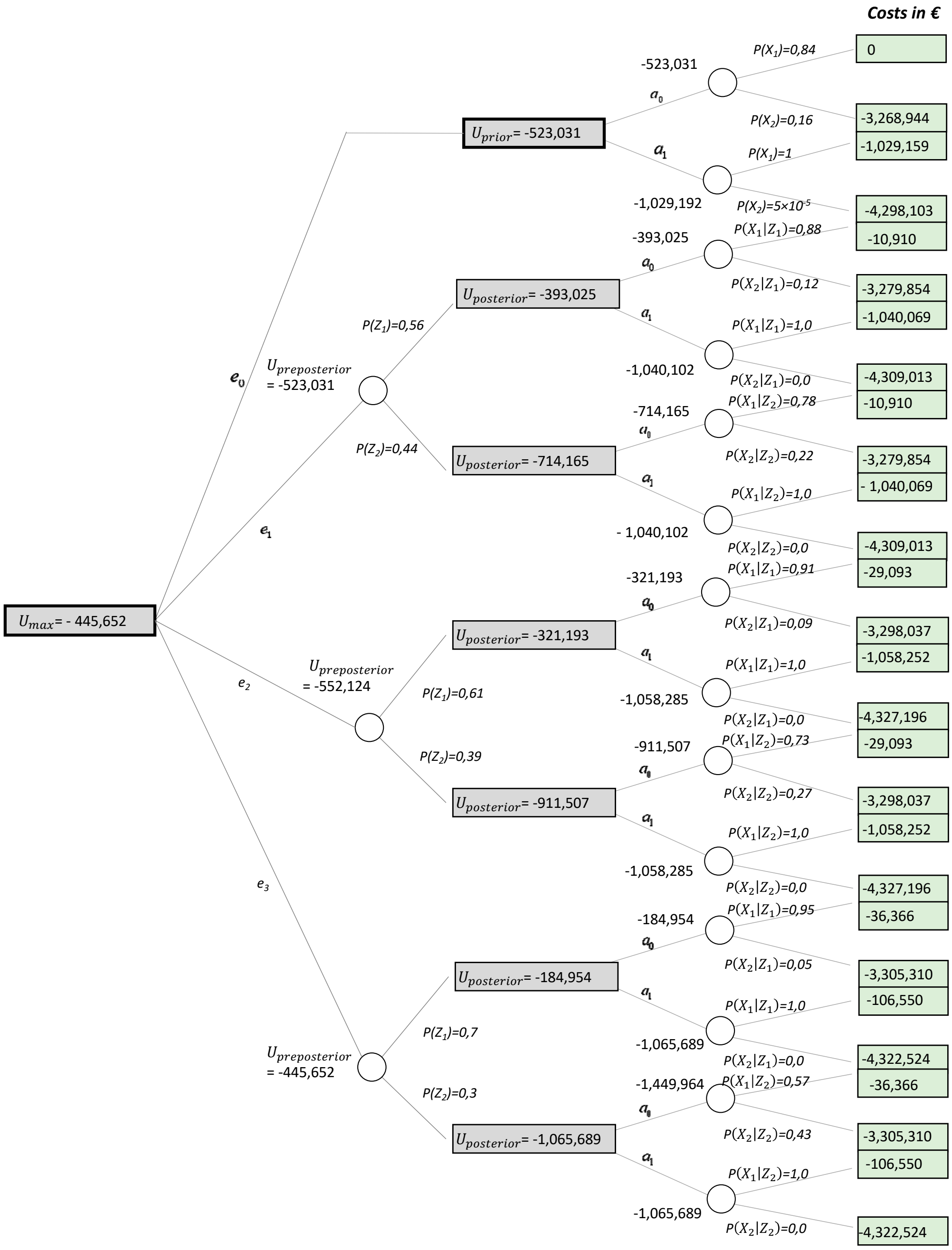

Figure 10. VoI analysis for case study 2.

In order to obtain quantitative value from reducing uncertainty through obtaining additional information, as seen in Equation (5), the value of maximum utility must be subtracted from the value of prior utility when no additional data are provided.

Results of the analysis in Table 5 show that assessment level 3 is the optimal strategy for the assessment of the residential and educational masonry building in economic terms of utility for owners and users. VoI analysis shows utility through economic terms, in this case, for post-earthquake assessment of two case studies. The value of additional knowledge is shown through costs with or without additional 'experiments', i.e., by subtracting prior and pre-posterior utility. It is visible that if the most complex assessment level is chosen, with the greatest reduction in uncertainty and thus a safer building, in the end, the utility is maximized. This also increases the seismic resistance of the building, increases the comfort of living and reduces maintenance costs. Even though the utility for both case studies is visible, it is obvious that the utility in the case of an educational building is substantially higher. It is to be expected that utility should rise with higher damage, but that is a topic to be more closely investigated in further research. The difference between the utility of the two case studies, 1% of the investment for the residential and 17% for the educational building, can also be explained by classifying the buildings into importance classes. Classifying includes several important aspects for public safety and civil protection in the urgent post-earthquake period, as well as social, economic and consequences for human life in case of collapse [36].

5. Conclusions

In this paper, the focus was to show the VoI analysis for updating knowledge in post-earthquake assessment and strengthening. In order to evaluate the complex problem of reconstruction of buildings in the historic urban complex, optimizing the reconstruction process was explored. The general aim of the presented paper was to compare the expected utility following one of the three levels of post-earthquake assessment after the earthquakes in Croatia in 2020. The expected utility for either the 'strengthen and/or repair' or 'do nothing' strategy was calculated for various prior probability levels. The prior probabilities represent the probabilities based on the historical data from earthquakes in Zagreb in 2020 concerning the sufficiency of the structural condition. Despite the uncertainties, epistemic and aleatory, and the lack of information, a decision by owners and decision makers has to be made on how to strengthen the structure. The strengthening and assessment options considered by the structural engineer are discussed and associated together with their costs. It should be mentioned that such decisions should not be based purely on the expected costs and it needs to be checked that the probability of failure is acceptably low. Thus, they should be based on maximum utility. Furthermore, if an extensive assessment is made, more insights about the system's behaviour and the nature of the initial damage can be obtained. Consequently, the subjective probability assignments of the decision maker can be altered not only numerically but also informatively. This paper presents VoI analysis for post-earthquake assessment of two case study buildings, a residential and an educational building, both located in Zagreb. As can be seen from the results, the most cost-effective way to strengthen the building is an approach that involves gathering information about every aspect of the building. Also, it shows that optimizing the process is the best long-term solution. Pre-posterior analysis, which was conducted for both case studies, has shown that updating knowledge has economic benefits as well as benefits in terms of safety and user comfort. The results also show a correlation between the benefits and importance classes, as it is more beneficial in the case of the educational rather than the residential building. The results shown should also encourage owners of buildings with expired design working life to inspect seriously and, if necessary, strengthen their buildings.

Future development of the study should be in the direction of collecting more data on the likelihoods, variability factors, historical data and how the updated knowledge and knowledge levels affect the modelling and design of masonry structures. In this paper, VoI analysis does not consider the gradation of damage to buildings, which could significantly impact utility results. Furthermore, a defined framework for VoI can be used, with certain modifications, for pre-posterior analysis, as a tool to define optimal building maintenance strategy.

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