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Value of information: impact of monitoring on decision-making

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SUMMARY

Structural health monitoring (SHM) is a process aimed at providing accurate and in-time information concerning structural health condition and performance, which can serve as an objective basis for decision-making regarding operation, maintenance, and repair. However, at the current state of practice, SHM is less used on real structures, and one reason for this is the lack of understanding of the Value of Information obtained from SHM. Consequently, even when SHM is implemented, bridge managers often make decisions based on experience or common sense, frequently considering with reserve and sometimes disregarding the suggestions arising from SHM. Managers weigh the SHM results based on their prior perception of the state of the structure and the confidence that they have in the specific applied SHM system and then make decisions considering the perceived effects of the actions they can undertake. In order to address and overcome the aforementioned identified limitations in the use of the SHM, a rational framework for assessment of the impact of the SHM on decision-making is researched and proposed in this paper. The framework is based on the concept of Value of Information and demonstrated on the case study of the Streicker Bridge, a new pedestrian bridge on Princeton University campus.

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1. INTRODUCTION

We presume that most readers of this journal are willing to recognize that structural health monitoring (SHM) is a powerful tool supporting transportation agency decisions: it is generally claimed that it allows real-time evaluation of the need for any further inspection or repair, thus reducing the costs of routine inspection. We have also often heard, in our community, that SHM has potential to prevent adverse social, economic, ecological, and esthetic impact. Nonetheless, direct experience and interaction with real-world bridge operators show that they are frequently very reluctant to invest in SHM ('Why should I waste my money on monitoring, when I can save it for maintenance or repair?'). This skepticism is evident in another recurrent behavior pattern: even when monitoring, data are available, bridge owners make decisions based on their experience or on common sense, often disregarding the actions suggested by SHM.

This apparently compulsive behavior is in reality driven by a rationale that goes beyond the scope of the structural engineer. First, SHM is by its nature affected by uncertainties (e.g., accuracy and stability of SHM system and environmental noise and errors in models used for data analysis), so managers weigh the SHM results in combination with their prior perception of the state of the structure and their

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common sense. Second, bridge managers are very concerned with the consequences of wrong action, so they will make decisions considering all the possible effects of the actions they can undertake, and this can drive their preference to experience-based rather than to SHM-informed solution. Such a conservative approach met in practice can be justified by the lack of effective means for quantitative evaluation of the Value of Information (*VoI*) provided by SHM. However, the adverse consequences of this approach can be important as the implementation of non-efficient, expensive solutions reduces the global resources for bridge management on a wider scale [1]. In addition, this leads to depreciation of SHM, which is paradoxical: in the era of information technologies, the potential of informed decision-making is disregarded.

This paper introduces a rational framework for informed decision-making based on SHM results. The first issue, that is, the effect of prior perception, can be addressed formally by applying Bayesian logic [2,3]. The second issue, that is, quantifying the economic impact of a wrong action, is addressed in the more general framework of decision theory [4–6].

The Bayesian theory of probability originates from Bayes' well-known essay [7], and today, many modern specialized textbooks can provide the reader with a critical review and applications of this theory to data analysis; see, for instance, the work by Gregory [8] and Sivia [9]. Of all the papers dealing with application of Bayesian theory to engineering problems, we wish to underline the work of the following authors: Papadimitriou, Beck, and Katafyogiotis [10], Beck and Katafygiotis [3], and Beck and Au [11], who by disseminating these concepts have had great impact on the civil engineering community, particularly in the field of structural identification and model updating. In this paper, we present a rational method for quantifying the economic impact of the information provided by a monitoring system, using the same approach adopted by Pozzi *et al*. [12]. This is based on the concept of *VoI*, which has its background in the seminal work by Lindley [13], later formalized by Raffa and Schlaifer [14] and DeGroot [15]. By using a formal approach similar to DeGroot [15], the *VoI* of SHM is defined as the difference between the prior (i.e., expected) operational cost C of the structure when the owner is not informed by the SHM and the prior cost C^* upon receipt of the monitoring information [12]. The *VoI* represents the money saved every time the manager consults SHM (e.g., after a potentially damaging event); it can likewise be regarded as the maximum cost the owner is willing to pay for information at a given moment of time, which in turn can help assess the cost the owner may be willing to pay for the monitoring system.

To illustrate how this approach works and ground it in a real-life situation, we apply this method to the Streicker Bridge, a new pedestrian bridge built on Princeton University campus. The reason behind this choice is the fact that the bridge is equipped with monitoring systems, as explained in detail in the next section. However, in this exercise, the connection with real life ends here: the behavior and decisions of the bridge manager invented for the purposes of this paper are completely fictitious, since in this real case, the monitoring system was motivated by research and educational reasons, rather than by a real concern as to its safety. It will be clear from the formulation below how the implementation of the framework includes modeling the expected behavior of the bridge manager or more generally whoever makes related decisions. This requires definition of his/her subjective perception and psychological profile. To simplify the presentation and highlight the essential rationale of the approach (while not affecting the conclusions of the research), the problem complexity is deliberately reduced. We imagine that the Streicker Bridge is managed by a fictitious rational character, called 'Tom' (to ease narration), having a relatively simple approach to decision-making and acting predictably. Needless to say, Tom's perception and behavior are created on the basis of cases in the literature [16,17] and on the authors' own experience and do not necessarily reflect the true decision process that the real manager of the bridge, that is, Princeton Office of Design and Construction, would follow under similar conditions.

2. STREICKER BRIDGE AND ITS MONITORING SYSTEM

The pedestrian Streicker Bridge (Figure 1) was built in 2009–2010 at Princeton University campus, over the busy Washington Road. The bridge is named after its donator, alumnus John Harrison Streicker (Princeton Class 1964), while the overall design was by the Swiss bridge designer Christian Menn. Detailing was by HNTB Corporation's Theodore Zoli (Princeton Class 1988) and Ryan

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Figure 1. View of Streicker Bridge.

Woodward (Princeton Graduate Class 2002). Turner Construction Company was the main contractor. Supervision and coordination was by representatives from the (real) Office of Design and Construction of Princeton University.

The bridge consists of the main span and four ‘legs’ (Figure 1). Structurally, the main span is a deck-stiffened arch, and the legs are continuous curved girders supported by steel columns. The legs are curved horizontally and the shape of the main span follows this curvature. The arch and columns are weathering steel while the main deck and legs are reinforced post-tensioned concrete. The slender and elegant deck-stiffened arch represents an efficient solution to bridging the 34.75 m (114 ft) span, limiting the deck thickness to only 578 mm (22.75 in.), with a beam diameter of 324 mm (12.75 in.).

The SHM *lab* of Princeton University instrumented the bridge with two SHM systems, aiming to transform the bridge into an on-site laboratory for research and education purposes. Currently implemented monitoring approaches are (i) global structural monitoring using discrete long-gauge strain fiber optic sensors (FOS) and (ii) integrity monitoring using truly distributed FOS. The first approach is based on fiber Bragg-grating [18] technology and the second on Brillouin Optical Time Domain Analysis [19]. These two approaches are to a certain extent complementary, and they are briefly described as follows.

Standard monitoring practice is based on the choice of a reduced number of points, considered to be representative of structural behavior, and their instrumentation with discrete sensors, short-gauge or long-gauge. If short-gauge sensors are used, the monitoring will give interesting information on the local behavior of the construction materials but might not see behavior and degradation that occur at locations that are not instrumented. Using long-gauge sensors, we can cover a significant volume of a structure with sensors, enabling its global monitoring, that is, any phenomenon that has an impact on the global structural behavior is detected and characterized [20,21]. However, reliable detection and characterization of damage that occur in the locations far from the sensors remain challenging, since it depends on sophisticated algorithms whose performance may decrease because of damage masking effects, such as high temperature variations and large load changes, as also outliers and missing data in monitoring results [22].

A distributed sensor is a cable sensitive along all its length, offering solutions for improved and reliable damage detection (e.g., see literature [23,24]). The qualitative difference between monitoring with discrete and distributed sensors is that discrete sensors monitor an average strain at discrete points, while the distributed sensors are capable of one-dimensional (linear) strain field monitoring. A distributed sensor can be installed along the whole length of a structure so that all cross-sections of the structure are effectively instrumented. The sensor is sensitive at each point of its length and so allows direct damage detection, avoiding the use of sophisticated algorithms (which are characteristic for indirect damage detection). In this manner, integrity monitoring of a structure can be reliably performed (e.g., see literature [24,25]).

Discrete FOS embedded in the bridge deck have gauge length 60 cm and feature excellent measurement properties with error limits of ±4 microstrains (after temperature compensation). Thus, they are excellent for assessment of global structural behavior and for structural identification. However, their spatial disposition limits their performance in damage detection. On the other hand, distributed FOS have accuracy an order of magnitude lower than discrete sensors and so cannot be used for accurate structural identification. Nevertheless, they have improved sensitivity to damage and consequently are used for damage detection and localization. Comparison between the performances of two systems is given in the literature [26]. More details of the SHM of the Streicker Bridge can be found in the literature [24,26,27], and to avoid repetition, only the data relevant to this study is presented here.

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Because the motivation of this SHM application is research and teaching, rather than safety and maintenance, not all the bridge components were instrumented. Assuming symmetry and similarity in structural performance, it was decided to fit sensors to half of the main span (the other half being symmetrical) and to the south-east leg only (assuming that the other legs behave in a similar manner). So this is a research oriented approach, not designed for safety and maintenance purposes, as the system does not cover all bridge components. On the basis of loose structural analysis and methods presented in the literature [28,29] (but see also other literature [30]), it is estimated that approximately 90 discrete sensors would be necessary for structural monitoring of the entire bridge including the complete main span and the four legs, while approximately 400 m of distributed sensor would be necessary for full integrity monitoring. On the basis of the real values of the project, Glisic and Adriaenssens [27] estimate that the cost for hardware covering the full extension of the bridge would be of the order of \$140,000.00 (less than 2.4% of the bridge construction cost) for a discrete monitoring system and around \$190,000.00 (<3.3% of the bridge construction cost) for a distributed system. These costs were estimated for continuous, on-line monitoring but do not include maintenance costs (of SHM systems), as both systems are virtually maintenance free (except for the use of electrical power, which is estimated to \$400.00 per year and the cost of communication which is free within university). We will see in the succeeding text how the actual value of the monitoring system is not necessarily connected to its comprehensiveness in damage detection but depends more on the actual use made by the manager.

In this paper, we focus on the discrete monitoring system of the main span, so only the positions of the relevant sensors are shown in Figure 2. A number of potential damage scenarios were considered: (i) losses in post-tensioning; (ii) differential settlement of foundations; (iii) a vehicle impact against the segment of the arch between columns P9 and P10; (iv) overloading; (v) corrosion; and (vi) fatigue cracking of the steel arch structure. Two other damage scenarios are strong wind and earthquake, but they are less likely to happen.

Parallel sensors installed along the centerline of the deck are designed to capture changes in strain and curvature that can be caused by any of aforementioned scenarios. The third scenario would involve partial or complete loss of load capacity of the arch, which would in turn result in an increase of bending moments and associated strain in the deck, and could lead to a collapse of the bridge. In particular, the sensor installed at the bottom of the middle cross-section between P6 and P7 (in this text called sensor P6-7d) is the most sensitive to changes, as this cross-section would experience the largest change in bending moment, and the sensor at the bottom of the cross-section is farther from the centroid of the cross-section than the sensor at the top of the cross-section. In order to present the concept of *VoI* assessment, and to keep the paper concise and focused, we consider only the third scenario and analyze only the sensor P6-7d. While the simplification minimizes computation, it does not remove the essence of the concept of *VoI*, and consequently, it does not affect the conclusions of the research. Various static and dynamic tests performed on the bridge enabled bridge structural identification, and the finite element model of the bridge was established. This model is then used to set thresholds, that is, to determine the condition of the bridge in the case of the third damage scenario taking into account the strain measurements registered by sensor P6-7d.

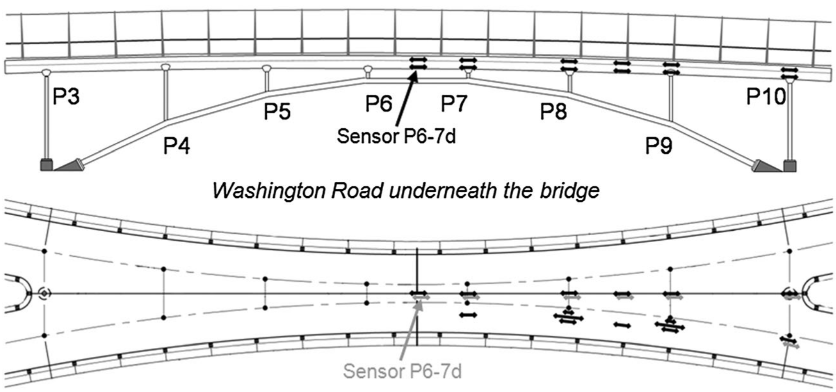

Figure 2. Location of sensors in the main span of Streicker Bridge.

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Usually at this point of a research paper, the authors are expected to state their formulation, which is then normally followed by an application to a particular case. However, to introduce less experienced readers to the concept of *VoI* and to ease narration, we decided to overturn the traditional scheme, presenting a simplified case first and generalizing the approach later.

3. INTRODUCING 'TOM'

'Tom' is a fictitious character (invented for the purposes of the paper), responsible for the bridge, a position he has held over more than a decade. He is a graduate in civil engineering and a registered professional engineer. Tom behaves rationally, and for the purpose of this exercise, we will assume he would react to minimize the total cost of operation of the infrastructure under his responsibility. Further statements describing Tom's perception of utility with regard to his job are as follows:

1. Utility has a cash value and is linear with the operational cost.
2. The indirect economic and social impact of a possible structural failure (such as downtime, casualties, or loss of life) always has a monetary value in the form of an indirect cost.
3. There is no separation between direct cost to the owner and the indirect cost to the users.

Although the authors built Tom's profile based on literature review and personal experience, we will not discuss here whether Tom's perception is correct or not: we just observe and acknowledge that he behaves as stated earlier, and our goal is to model this behavior.

We have mentioned before that the monitoring system on Streicker Bridge was not designed to detect any particular malfunction scenario but rather various types of fault such as post-tensioning loss, differential settlement of foundations, excessive bending, and cracking [27]. Yet in our simplified exercise, we will assume that Tom is concerned by a single specific scenario, namely, that a truck beneath the bridge, maneuvering or driving along Washington Road, could collide with the steel arch that supports the concrete deck. To reduce this exercise to a single-stage decision problem [6], we will further assume that in the event of a truck accident, Tom is immediately informed of the fact, so there is no missing detected event, while his only problem is to understand the extent of damage. Once informed of the collision, Tom believes (for the sake of exercise) that there can be only two possible condition states of the bridge (we recognize that in real life, the set of possible states of the bridge could be wider):

No Damage (U): the structure has either no damage or some minor damage, with negligible loss of structural capacity.

Damage (D): the bridge is still standing but has suffered major damage to the steel arch structure; although standing, Tom estimates that there is a chance of collapse of the entire bridge under a live load.

To Tom, the two states represent a set of mutually exclusive and exhaustive possibilities, which is to say that $P(D) + P(U) = 1$ (where 'P' denotes probability). On the basis of his experience and engineering sense, let us assume that he guesses that after a road accident, scenario U is more likely than scenario D, and he estimates $P(D) = 30\%$ and $P(U) = 70\%$ as prior probabilities. To further simplify the presentation, let us assume that after an accident, Tom may decide on one of the two following actions (we recognize that in real life, the set of choices could be wider):

Do nothing (DN): no special restriction is applied to the pedestrian traffic over the bridge or to road traffic under the bridge; minimal repair/maintenance work can be carried out, but this will not interfere with normal bridge use.

Close Bridge (CB): both Streicker Bridge and Washington Road (underneath the bridge) are closed to pedestrians and road traffic; access to the nearby area is restricted for the time needed for a thorough inspection, which Tom estimates to be 1 month.

Tom wants to estimate the impact of any possible action, given any possible scenario, and convert it to a numerical quantity, which for this exercise, consistently with Tom's straightforward behavior, will be a mere economic loss. Tom logically understands that choosing to close the bridge (CB) will

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automatically prevent any effects due to a possible collapse of the bridge. However, this choice is not pain free. What concerns Tom is not the inspection cost (inspection is routinely carried out by the Office of Design and Construction and does not represent an extra cost). The disadvantage of this action is the Daily Road User Cost (DRUC) stemming from the 1-month downtime of road and bridge. Glisic and Adriaenssens [27], based on the calculation method used by the Kansas Department of Transportation [31,32], estimated the DRUC value for Washington Road due to work on the Streicker Bridge to be \$4660.00/day, or $C_{DT} = 4660 \times 30 = \$139{,}800.00$ for the 1-month period. To avoid this cost, Tom can decide to do nothing (DN). 'If I do nothing (DN) and the bridge is undamaged (U)'—thinks Tom—'I pay nothing. On the other hand if the bridge is really damaged (D) it may collapse and I will have to pay the consequences'. These consequences are the DRUC for a 2-month period (estimated closure time of Washington Road); the probability of a fatality (F) and of non-fatal injury (I), which he estimates, is equal to $P(F|D) = 15\%$ and $P(I|D) = 50\%$ using his experience and engineering judgment. Glisic and Adriaenssens [27] have also calculated, on the basis of the National Safety Council records [33], the average comprehensive cost of a pedestrian injury and fatality as \$52,000.00 and \$3,840,000.00, respectively, these amounts covering medical expenses, victim's loss of work, public services, and loss of quality of life. Acknowledging these values, Tom estimates for bridge collapse an overall cost of $C_F = \$881{,}600.00$, as specified in detail in Table I.

4. DECISION WITHOUT MONITORING

On the basis of Table I, Tom estimates the cost involved in any action. While the cost of action CB is identically equal to 1-month downtime cost C_{DT}, regardless of the state of the bridge, the cost of the do-nothing scenario depends on the manager's estimate of the probability of the bridge being damaged. Assume, as a first step, that Tom has no knowledge of the outcome of monitoring; then, he will quantify the cost of the do-nothing option as

$$C_{DN} = C_F \cdot P(D) \tag{1}$$

where P(D) is the a priori probability of structural damage, evaluated on the basis of his prior knowledge or experience.

We have assumed that Tom behaves rationally and that he will decide with the objective of minimizing the expected cost: so he will close the bridge when $C_{DN} > C_{CB}$, and he will do nothing when $C_{CB} > C_{DN}$. The loss C estimated by the manager in the prior situation is the minimum of the two costs $C = \min(C_{DN}, C_{CB})$. In the specific case, after an accident, Tom will think

> If I close the bridge I pay a downtime cost of $C_{DT} = \$139{,}800$. If I don't close the bridge I have 30% probability of structural failure which will cost me $C_F = \$881{,}600$—thus (assuming linear utility with cost) my overall loss will be $C_{DN} = 30\% \times \$881{,}600 = \$264{,}500$. All things considered I should really close the bridge.

Table I. Costs per action and state.

	Scenario U	Scenario D	
	No damage	Critical damage	
Action DN do nothing	Nothing happens: You pay nothing	Bridge collapses: You pay failure cost	
		2-month downtime	\$279,600.00
		Cost of fatality: \$3,840,000.00	
		Chance of fatality: $P(F\|D) = 15\%$	\$576,000.00
		Cost of injury: \$52,000.00	
		Chance of injury: $P(I\|D) = 50\%$	\$26,000.00
		Total failure cost	$C_F = 881{,}600.00$
Action CB close bridge	Bridge is closed: You pay 1-month downtime $C_{DT} = \$139{,}800.00$	Same as on the left: You pay 1-month downtime	$C_{DT} = \$139{,}800.00$

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5. DECISION WITH MONITORING

We want now to investigate to what extent the information from the monitoring system may affect Tom's decision, and his perception of doing the right thing. In order to keep the problem clear and simple, we will make some assumptions on how Tom operates the system and uses its measurements. At this point, we note that in this exercise, as well as in real life, it is less important to know what the monitoring system can theoretically do for the owner, but far more important is what information the owner can gain from the monitoring system. So first let us assume that the system is not permanently operated: Tom takes measurements every 2 years during routine bridge inspections, and no advanced data analysis is applied. As stated earlier, to simplify presentation, we assume that after an accident, Tom will pay attention only to changes in strain with respect to the last routine measurement, as recorded at the midspan sensor P6-7d.

Tom expects that if the bridge is virtually undamaged, the change in strain will be close to zero. He is also aware of the natural (normal) fluctuation of the midspan strain, mainly due to thermal effects, and to certain extent due to creep and shrinkage; On the basis of a numerical model of the structure and specifications of the monitoring system, he estimates this fluctuation to be in the order of ±300 με. Formally, we can encode this knowledge in a theoretical probability density function pdf(ε|U), with zero mean value and standard deviation $\sigma = 300\,\mu\varepsilon$, which represents Tom's expectation of the system response in the undamaged state. This distribution is usually referred to, in classical Bayesian theory, as *likelihood of no damage*. Conversely, assuming that the bridge is heavily damaged but still standing, Tom expects a significant change in strain; we can model the *likelihood of damage* pdf(ε|D) as a distribution with mean value of 1000 με and standard deviation of $\sigma = 600\,\mu\varepsilon$, which reflects Tom's uncertainty of expectation. Using his prior judgment, Tom can also predict the distribution of ε, before these data are available, by marginalizing the system states through the following formulation:

$$\mathrm{pdf}(\varepsilon) = \mathrm{pdf}(\varepsilon|\mathrm{D})\cdot \mathrm{P}(\mathrm{D}) + \mathrm{pdf}(\varepsilon|\mathrm{U})\cdot \mathrm{P}(\mathrm{U}) \quad (2)$$

pdf(ε) is usually referred to as *model evidence* in Bayesian theory. These evidence functions are plotted in the graph of Figure 3 (upper).

When the monitoring result ε is available to the manager, he can update his estimation of the probability of damage using Bayes' formula:

$$\mathrm{P}(\mathrm{D}|\varepsilon) = \frac{\mathrm{pdf}(\varepsilon|\mathrm{D})\mathrm{P}(\mathrm{D})}{\mathrm{pdf}(\varepsilon)} \quad (3)$$

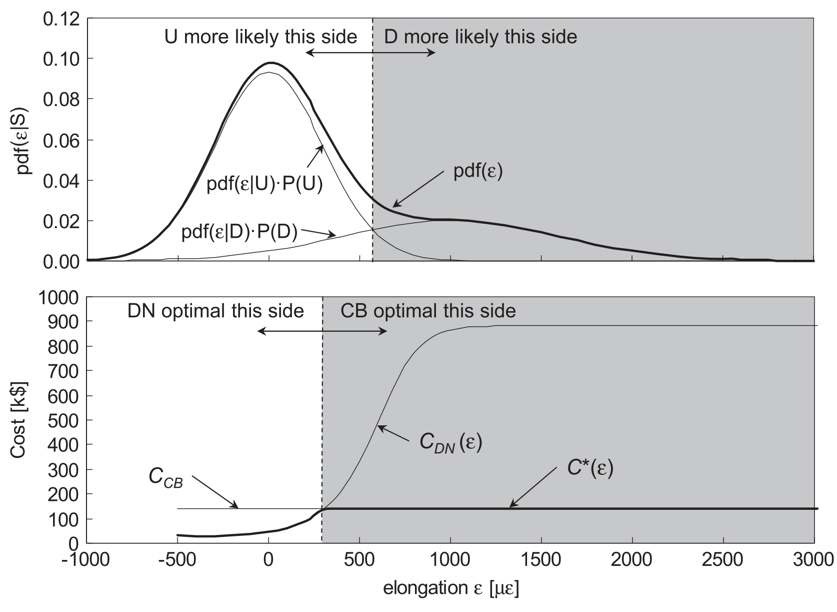

Figure 3. Evidence of scenarios (upper) and loss functions per scenario (lower).

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where prob(D|ε) is the posterior probability of damage, taking the outcome of the monitoring into account. The new (*a posteriori*) estimates of the financial losses associated with actions *DN* or *CD* are the following:

$$C_{DN|\varepsilon} = C_F \cdot \mathrm{P(D|\varepsilon)} \quad C_{CB|\varepsilon} = C_{DT} \tag{4}$$

Once again, if Tom's decision is driven by an economic principle, he will choose the least expensive option, so the loss associated with the decision, in the posterior condition, is

$$C^*(\varepsilon) = \min\left(C_{DN|\varepsilon}, C_{CB|\varepsilon}\right) = \min\left(C_F \cdot \mathrm{P(D|\varepsilon)}, C_{DT}\right) \tag{5}$$

where the star is a reminder that this cost, unlike that of Equation 1, is estimated taking account of the monitoring information. These loss functions are represented in Figure 3 (lower).

The expression formulated in Equation 5 deserves the reader's attention: the manager will likely decide on inspection not when the damage detection shows that damage is more likely than non-damage, but when the loss expected for doing-nothing, C_{DN} is greater than the cost of closing the bridge C_{CB}.

Equation 5 quantifies the loss in the case when a specific damage index (in our case strain ε) is yielded by the monitoring system. We now want to calculate the loss expected a priori, that is, before interrogating the system. To do so, we have to marginalize the loss expressed by Equation 5 using the evidence of strain ε, pdf(ε) (i.e., strain is used as a damage index):

$$C^* = \int_0^\infty C^*(\varepsilon)\mathrm{pdf}(\varepsilon)\mathrm{d}\varepsilon = \int_0^\infty \min\left(C_F\,\mathrm{pdf}(\varepsilon|\mathrm{D})\mathrm{P(D)}, C_{DT}\right)\mathrm{d}\varepsilon \tag{6}$$

This quantity encodes the total expected cost of a decision process based on the information yielded by the monitoring system and can be seen as a metric for evaluating the effectiveness of the monitoring system itself. In our specific case, calculation of the integral of Equation 6 yields a total cost of C^* = $84,600.00: this is Tom's expected loss after an accident, assuming he can take advantage of the monitoring information to drive his decision. This value should be compared with the corresponding loss C = $139,800.00 that he expects to bear when monitoring data are not available. The difference between the two is the *VoI* of the monitoring system, that is, $VoI = C - C^*$ = $55,200.00. This value can be considered as the maximum price that Tom would be willing to pay for any single interrogation of the monitoring system performed after a hazardous event.

6. DISCUSSION AND GENERALIZATION

The *VoI* is the quantity that can drive the manager's decision on whether or not to monitor a structure. For example, the exercise shown in the previous section shows that three to four interrogations of the monitoring system after a hazardous event (*VoI* = $55,200.00 for each of them) may justify the implementation of monitoring system ($140,000.00–190,000.00, see the section on Streicker Bridge) given that the input parameters needed to determine *VoI* were accurately assessed (which is a broad topic beyond the scope of this paper). *VoI* depends on operational costs C and C^* (with and without monitoring) that in turn, as evident from Equations 1 and 6, depend essentially on three quantities: (i) the expected financial consequence of a collapse C_F; (ii) the scenario likelihood of the damage index (i.e., strain ε) probability density functions; and (iii) the prior knowledge of the structure state (i.e., probability of damage) P(D). It is worth noting that these quantities are not strictly related to the mechanical behavior of the structure or to the technical features of the monitoring system. C_F is a mere economic quantity, which reflects Tom's personal loss expectation and may vary depending on the social context and the principles (ethical, judicial, or economic) that influence the individual responsible for the decision. P(ε|D) reflects the perceived capacity of the monitoring system to recognize a damaged state, which is only partially inherent in the technical features of the system. P(D) is the credibility of damage occurrence from Tom's point of view, which may or may not be based on knowledge of the actual mechanical behavior of the bridge.

To better understand the practical meaning of the formulation derived, we analyze some extreme cases. First, we assume that the monitoring system provides perfect information, which means that Tom can always determine univocally the state of the bridge based on the sensor measurements. This happens when the two likelihood distributions pdf(ε|U) and pdf(ε|D) do not overlap; thus, only one

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possible state is associated with any one value of strain. In this case, it can be seen that Equation 6 becomes

$$C^* = C_{DT}\mathrm{P}(\mathrm{D}) \tag{7}$$

which means that Tom will close the bridge only if the sensor tells him there is a damage, and this is expected to happen with a probability P(D). Thus, in this case, the *VoI* will be

$$VoI = C - C^* = C_{DT} - C_{DT}\mathrm{P}(\mathrm{D}) = C_{DT}\mathrm{P}(\mathrm{U}) \tag{8}$$

which is basically the cost Tom will incur for taking the wrong decision because of his lack in knowledge of the bridge state. Equation 8 also represents to Tom the upper bound value of *VoI*, using any possible monitoring system installed on Streiker Bridge independently of its comprehensiveness in damage detection or level of accuracy.

Two other cases are those of extreme prior perceptions of the state of the structure. Let us assume, for example, that Tom is firmly convinced that the bridge is invulnerable. This perception can be encoded in the prior probabilities P(U) = 1 and P(D) = 0. It can be concluded that under these conditions, Tom's perception is that $C = 0$ ('Trust me, no need to close the bridge, nothing will happen') and so will be the perception of *VoI*, regardless of accuracy and comprehensiveness of the monitoring system. Similarly, for an over-concerned Tom, who believes that the bridge is highly vulnerable to truck collision, the prior probability will be P(D) = 1, that is, the action will be to close the bridge regardless the information obtained from the monitoring system. In this case, evidently, Tom's perception would be $C = C_{CB}$; Equation 6 yields $C^* = C_{CB}$ ('Too dangerous, I'd better close the bridge anyway'), and therefore, again, Tom's perception will be that $VoI = 0$. These two examples confirm numerically the real-life observation that if the bridge owner or manager is too strongly convinced of the prior state of the bridge, no information coming from monitoring system can ever change his/her mind.

Lastly, we have another extreme case when an action has no direct consequence for the manager. Say, for example, that to Tom, the indirect cost to users is irrelevant, that is, $C_{CB} = 0$ (in contrast with the assumption earlier). In this case, closing the bridge will always be the natural choice ('I'll close it—it costs me nothing'), and because $C = 0$, here again, a monitoring system will be perceived as useless, that is, $VoI = 0$.

Now, following a similar approach, we can reformulate Tom's decision problem in more general terms. Earlier, we assumed that Tom conceived only two possible states of the bridge, damaged and undamaged: now, let us assume that to Tom, the number of possible states might be more than two (e.g., no damage, moderate damage, severe damage, and collapse): we label the n possible states as $S_1, S_2, \ldots, S_n$, and we assume these possibilities to be mutually exclusive and exhaustive.

To further generalize, say that after he received knowledge of a hazardous event (e.g., a truck collision, earthquake, vandalism, or other event), Tom can choose among a wider set of actions (instead of the sole two assumed earlier), which we generally indicate with $a_1, a_2, \ldots, a_m$, m being the number of possible options.

Any action undertaken by Tom will result in a cost, which in general depends on the real state of the bridge. Label c_{ij} is the expected cost for action a_i, knowing that the bridge is in state S_j. We will accept that the decision occurs in a single step and that to Tom utility is linear with cost, so in this generalization, we can still exchange the concepts of cost and negative utility. Because initially Tom has no information on the state of the structure, he will estimate the expected cost C_i of action i based on his prior knowledge of the state:

$$C_i = \sum_{j=1}^{m} c_{ij} P(S_j) \tag{9}$$

where $\mathrm{P}(S_j)$ is the prior probability of state S_j. As a rational agent, Tom will choose the most economic option, which causes the minimum loss c_i; thus, the total cost a priori is calculated by

$$C = \min_i C_i = \min_i \sum_{j=1}^{m} c_{ij} P(S_j) \tag{10}$$

Equation 10 encodes the cost of operation of the bridge without the monitoring system. Now, assume the monitoring system provides a set of observations **y** (e.g., strain, tilt, and acceleration); the

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knowledge of the monitoring information modifies Tom's prior knowledge of state Sj from $\mathrm{P}(S_j)$ to posterior $\mathrm{P}(S_j|\mathbf{y})$, so in general, Equation 7 rewrites to

$$C_i^*(\mathbf{y}) = \sum_{j=1}^{m} c_{ij} P\left(S_j|\mathbf{y}\right) \tag{11}$$

where the star * is a reminder that this is an expected cost *posterior* to the knowledge of information **y**. The posterior probability is formally given by Bayes' rule:

$$\mathrm{P}\left(S_j|\mathbf{y}\right) = \frac{\mathrm{pdf}\left(\mathbf{y}|S_j\right)\mathrm{P}\left(S_j\right)}{\mathrm{pdf}(\mathbf{y})} \tag{12}$$

where the term at the denominator, the *evidence*, reads:

$$\mathrm{pdf}(\mathbf{y}) = \sum_{j=1}^{n} \mathrm{pdf}\left(\mathbf{y}|S_j\right)\mathrm{P}\left(S_j\right) \tag{13}$$

Here again, once known the observation set **y**, the optimal action i is that which causes the minimum loss C; therefore, similarly to Equation 5, we can write

$$c^*(\mathbf{y}) = \min_i C_i^*(\mathbf{y}) = \min_i \sum_{j=1}^{m} c_{ij} P\left(S_j|\mathbf{y}\right) \tag{14}$$

Equation 12 states the expected loss with an individual realization of **y**. To evaluate the *VoI*, however, we want to estimate the cost when the observation has still to happen. Following the same approach as in the previous simplified example, we know Tom's expected distribution of occurrence of **y** is actually the evidence stated in Equation 11. Similarly to Equation 6, we can estimate the operational cost expected a priori with monitoring; and in a similar way as earlier, we want now to estimate the prior operational cost:

$$C^* = \int_{D\mathbf{y}} c^*(\mathbf{y})\,\mathrm{pdf}(\mathbf{y})\,\mathrm{d}\mathbf{y} = \int_{D\mathbf{y}} \min_i \left\{ \sum_{j=1}^{m} c_{ij} \ \ \mathrm{P}\left(S_j|\mathbf{y}\right) \right\} \mathrm{pdf}(\mathbf{y})\,\mathrm{d}\mathbf{y} \tag{15}$$

where the integral is extended to the domain Dy of all possible observations. Using Bayes' rule, as stated in Equation 12, we obtain

$$C^* = \int_{D\mathbf{y}} \min_i \left\{ \sum_{j=1}^{m} c_{ij} \ \ \mathrm{pdf}\left(\mathbf{y}|S_j\right)\mathrm{P}\left(S_j\right) \right\} \mathrm{d}\mathbf{y} \tag{16}$$

So in conclusion, the *VoI* of an independent monitoring interrogation reads

$$VoI = C - C^* = \min_i \sum_{j=1}^{m} c_{ij} \ \ \mathrm{P}\left(S_j\right) - \int_{D\mathbf{y}} \min_i \left\{ \sum_{j=1}^{m} c_{ij} \ \ \mathrm{pdf}\left(\mathbf{y}|S_j\right)\mathrm{P}\left(S_j\right) \right\} \mathrm{d}\mathbf{y} \tag{17}$$

Here again, we can conclude that the value of a monitoring system depends on the three types of parameters mentioned earlier: (i) the expected losses c_{ij}; (ii) the perceived capability of the monitoring system to recognize various damage states $\mathrm{pdf}(\mathbf{y}|S_j)$; and (iii) the prior knowledge of the structure state $\mathrm{P}(S_j)$. It is worth noting that all these parameters vary in general with the subjective principles and perception of the individual who makes the decision, although his/her perception is supposedly educated by his/her knowledge of the physics of the problem.

7. 'WHY SHOULD I WASTE MY MONEY ON MONITORING?'

At this point, we can go back to the original dilemma ('Why should I waste my money on monitoring?') and answer it by further generalizing Equation 8 in the framework of life-cycle analysis [34,35]. In the most general form, we can define the life-cycle value $\mathcal{V}$ of monitoring as

$$\mathcal{V} = \mathcal{C}_{\mathcal{LC}} - \mathcal{C}_{\mathcal{LC}}^* \tag{18}$$

where $\mathcal{C}_{\mathcal{LC}}$ denotes the life-cycle cost of the monitoring-free bridge and, as per established notation, the additional star * indicates the corresponding cost when a monitoring system is installed and operating.

In Equation 18 and hereinafter, we use script fonts (e.g., $\mathcal{C}$) to denote life-cycle quantities, in contrast with the Roman fonts (e.g., C) of Equation 8, which refer to single monitoring interrogations. By using a similar formulation as in [36], the life-cycle cost $\mathcal{C}_{\mathcal{LC}}$ can be broken down into

$$\mathcal{C}_{\mathcal{LC}} = \mathcal{C}_0 + \mathcal{C}_{\mathcal{M}} + \mathcal{C}_{\mathcal{R}} \tag{19}$$

where $\mathcal{C}_0$ is the initial investment (which include the bridge construction cost), $\mathcal{C}_{\mathcal{M}}$ ('M' for maintenance) is the present cost of routine maintenance, and $\mathcal{C}_{\mathcal{R}}$ ('R' for repair) is the present value of the expected cost for unscheduled maintenance and repair, including any indirect cost to the users. In general terms, the present value of the maintenance cost is estimated cumulating over the lifespan t_L of the bridge the future maintenance cost $c_{M,i}$ planned for year i:

$$\mathcal{C}_{\mathcal{M}} = \sum_{i=1}^{t_L} \frac{c_{M,i}}{(r+1)^i} \tag{20}$$

where r is the discount rate. Assuming the annual maintenance cost constant and equal to the annuity c_M, Equation 17 reduces to [34]:

$$\mathcal{C}_{\mathcal{M}} = \frac{c_M}{r}\left\{1 - \frac{1}{(1+r)^{t_L}}\right\} \tag{21}$$

Cost $\mathcal{C}_{\mathcal{R}}$ incorporates all cost for unscheduled maintenance and repair during the bridge lifespan, and in a broader sense, for any cost not routinely planned. In general, we can say that any such unplanned cost is the ultimate result of the occurrence of an event. For example, in Tom's case earlier, a cost C (of Equation 10) is expected in reaction to event 'truck collision'. Assume our Tom may conceive N different types of event and label ${}^{(j)}k_i$ the number of occurrences of event j at year i: similarly, label ${}^{(j)}C$ the resulting expected cost calculated as per Equation 10; then, $\mathcal{C}_{\mathcal{R}}$ simply writes

$$\mathcal{C}_{\mathcal{R}} = E\left[\sum_{i=1}^{t_L}\sum_{j=1}^{N} \frac{{}^{(j)}ki^{(j)}C}{(r+1)^i}\right] \tag{22}$$

where notation $E[.]$ means expected value. To simplify the formulation, assume that random variable $k_i^{(j)}$ has Poisson distribution with mean occurrence rate of λ_j, independently of bridge age i. In this case, Equation 22 reduces to

$$\mathcal{C}_{\mathcal{R}} = \frac{\sum_{j=1}^{N} \lambda_j{}^{(j)}C}{r}\left\{1 - \frac{1}{(1+r)^{t_L}}\right\} \tag{23}$$

In a similar way, when a monitoring system is installed and operating, we can estimate the life-cycle cost $\mathcal{C}^*_{\mathcal{LC}}$ and its components $\mathcal{C}^*_0$, $\mathcal{C}^*_{\mathcal{M}}$, and $\mathcal{C}^*_{\mathcal{R}}$. In this case, the initial investment $\mathcal{C}^*_0$ will also include the additional cost $\Delta\mathcal{C}^*_0$ of design, supply, and installation of the monitoring system:

$$\mathcal{C}^*_0 = \mathcal{C}_0 + \Delta\mathcal{C}^*_0 \tag{24}$$

It is worth noting that $\Delta\mathcal{C}^*_0$ comprises in the broader sense any cost related to the initial monitoring investment, including, for example, costs for consultants and/or structural modeling, which are instrumental to the design and operation of the monitoring system. The cumulative-time bridge maintenance cost will also include an annual monitoring operation cost Δc^*_M , which typically includes hardware maintenance, system management, and personnel cost for routine data analysis. Thus, Equation 21 changes to

$$\mathcal{C}^*_{\mathcal{M}} = \frac{c_M + \Delta c^*_M}{r}\left\{1 - \frac{1}{(1+r)^{t_L}}\right\} \tag{25}$$

The expression for unscheduled maintenance and repair cost $\mathcal{C}^*_{\mathcal{R}}$ is formally similar to that of Equation 23, with the only difference that the expected cost ${}^{(j)}C^*$ is now estimated with Equation 16:

$$\mathcal{C}^*_{\mathcal{R}} = \frac{\sum_{j=1}^{N} \lambda_j{}^{(j)}C^*}{r}\left\{1 - \frac{1}{(1+r)^{t_L}}\right\} \tag{26}$$

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Finally, keeping in mind Equations 19, 20, 21, 23, 24, 25, and 26, the life-cycle value $\mathcal{V}$ of monitoring can be expressed as

$$\mathcal{V} = \left\{ \sum_{j=1}^{N} \lambda_j {}^{(j)}VoI - \Delta c_M^* \right\} \frac{1}{r} \left\{ 1 - \frac{1}{(1+r)^{t_L}} \right\} - \Delta \mathcal{C}_0^* \tag{27}$$

where ${}^{(j)}VoI = {}^{(j)}C - {}^{(j)}C^*$ indicates, similarly to Equation 17, the *VoI* of an independent monitoring interrogation, on occurrence of any event of type *j*. On the basis of Equation 27, monitoring can be seen as an investment with initial cost $\Delta \mathcal{C}_0^*$ and an expected annual net benefit B^* equal to

$$B^* = \sum_{j=1}^{N} \lambda_j {}^{(j)}VoI - \Delta c_M^* \tag{28}$$

which depends on the *VoI* of individual interrogations, the expected occurrence rate of the events demanding interrogation and monitoring operation cost. Evidently, installing a monitoring system is economical when its return in terms of benefit overcomes its initial investment. The break-even point t_{BEP}, that is, the time when monitoring benefit has repaid the initial investment [34], is calculated putting

$$\mathcal{V}(t_{\mathcal{BEP}}) = \frac{B^*}{r} \left\{ 1 - \frac{1}{(1+r)^{t_{BEP}}} \right\} - \Delta \mathcal{C}_0^* = 0 \tag{29}$$

which eventually yields

$$t_{BEP} = \frac{\log\ B^* - \log\left(B^* - r\Delta \mathcal{C}_0^*\right)}{\log(1+r)} \tag{30}$$

In conclusion, monitoring is worthwhile for Tom when the system life-cycle value $\mathcal{V}$, estimated by Equation 27, is greater than zero. Which is to say that Tom will not 'waste his money' when the system lifespan t_L exceeds the break-even point t_{BEP} calculated with Equation 30.

8. CONCLUSIONS

In this paper, we present a methodology for economic evaluation of the impact of monitoring on bridge management using the *VoI*. The general approach is based on the observation that the information yielded by an assessment procedure (monitoring) allows the manager to recognize the most cost-effective action strategy. The methodology developed uses Bayesian logic and decision theory and is based on the hypothesis that the bridge manager will decide to act (i.e., perform repair, conservation, or maintenance work) not when the monitoring system shows that structure is more likely to be in a damaged state than in a non-damage state but rather when the loss expected for non action is greater than the cost of action.

The methodology was applied to the simplified case of the Streicker Bridge, managed by a fictitious manager, Tom, and it shows that three to four measurements provided by the monitoring system following a hazardous event can justify the implementation of monitoring; this demonstrates the applicability of the proposed methodology. The case study exemplifies how we can estimate the economic benefit of a monitoring system for any detectable event, which requires damage assessment. Four extreme cases related to possible manager perceptions of system performance, to prior structure state and to indirect costs, are analyzed and discussed, resulting in outcomes that are recognizable in real-life situations.

Generalized models were developed including various multiple damage scenarios and remedial actions, and a general formulation for evaluating the life-cycle value of monitoring has been provided. Within this general framework monitoring is, in an abstract sense, 'anything which produces information useful to take decisions'; therefore, visual inspection, consultants, archive research, and any other investment producing information are equivalent to monitoring for the scope of this formulation. The applicability of the methodology depends on input parameters that may be difficult to estimate (e.g., manager's prior perception of bridge condition after the damage), and accurate determination of these parameters represents the challenge to be addressed in future work. Statistical analysis of large amounts of relevant data collected over years by bridge management authorities worldwide (e.g., the Federal

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Highway Administration and state Departments of Transportation in the USA) may be a good starting point for this future study.

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