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Structural Health Monitoring-Based Bridge Lifecycle Extension: Survival Analysis and Monte Carlo-Based Quantification of Value of Information

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Abstract: A key goal of structural health monitoring (SHM) systems applied to infrastructure is to improve asset management. SHM systems yield benefits by providing information that allows improved asset management decisions. Often, improvement is measured in monetary terms, whereby lower expenses are sought. The value of information (VoI) is often evaluated through the quantification of the incremental benefit, resulting from the information provided by the SHM system. The VoI can be considered as having two components: value derived from the improved operation of the infrastructure and value derived from increased useful life. This work focuses on the latter source of value in the context of concrete decks in US highway bridges. To estimate the lifecycle extension potential and the connected VoI, we need to simulate bridge deck condition degradation over time to support a discounted cash flow analysis of bridge replacement cost. We accomplish this by utilizing a neural network-based survival analysis combined with Monte Carlo simulation. We present a case study using the developed methods. We have chosen to study the southbound portion of the bridge on the US Highway 202, located in Wayne, NJ. The selected bridge is a representative concrete highway overpass, the type of which there are large numbers in the US. The case study demonstrates the applicability of the methods developed for the general evaluation of the VoI obtained via SHM. The results are encouraging for the widespread use of SHM for lifecycle extension purposes; the potential value in such applications is large.

Keywords: SHM; value of information; time value of money; Monte Carlo simulation

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1. Introduction

Structural health monitoring (SHM) is an overarching term for methods and techniques used to gain accurate, in-time information about the condition and performance of civil engineering structures. In contemporary use, the term SHM almost exclusively refers to the use of sensor measurements in combination with digital signal processing methods to monitor the condition of structures. In this work, we will demarcate between SHM and simple measurements of structural condition, where, as the name *monitoring* suggests, in SHM, the goal is to understand the development of structural condition over time, as opposed to a single measurement. SHM systems have been deployed into multiple different types of structures, from pipelines and dams to high-rise buildings and bridges.

In this paper, we show that collecting data about structures' physical condition can generate significant savings in the replacement cost of said structures. These savings are a part of SHM systems' value of information (VoI). The value is derived from postponing the replacement of structures, which will generate savings from avoiding the opportunity cost of having to commit funds for the replacement project prematurely. We combine a neural network-based deterioration model with Monte Carlo simulation to estimate what is the value potential of postponing replacement and present a case study of using this methodology to analyze the potential VoI of an existing structure.

To limit the scope of this work, we will exclusively consider SHM systems in bridges. Our work is intended to be of general nature, and bridges are chosen as an example of SHM application. They are a particularly good example due to their long lifecycles and importance to transportation systems. Bridges are a uniquely important application of SHM due to their role as significant bottlenecks in road networks. A well-functioning road network enables the efficient transportation of goods and people around a region and is of critical importance to both safety and the economy. A large number of bridges in the US highway system are considerably old [1]. This makes the maintenance of aging bridges a key aspect of road network asset management. Often, improvement in this area is interpreted as lowering operating and maintenance costs. The importance of improving asset management practices is driven by fiscal reasons. The historical gap between realized infrastructure investment and the necessary levels of investment creates fiscal challenges; see, for example, discussions over the US federal budget [2]. Optimization of the utilization of existing infrastructure is needed to make the most of the tight funding [3]. Data-based infrastructure maintenance approaches are a key enabling technology for a more effective utilization of infrastructure.

SHM allows moving from traditional maintenance and inspection approaches into a predictive approach, where data and lifecycle modeling are used to optimize operations and maintenance decisions. Even though SHM is an important technology in modern asset management, a proliferation of industrial applications is yet to be seen. SHM is still mainly a research endeavor, not an integral part of day-to-day infrastructure management practice [4,5]. Peter Cawley identifies the lack of proven and well-understood business cases as a key reason hindering SHM application [5]. This means that the lack of systematic valuation methods for SHM is withholding the field. Without methods for computing the value of SHM, it is difficult to justify SHM project costs. As SHM is primarily a tool for asset management, its value needs to be measured through the added value it provides for asset management. The increased information about structural conditions generated by the SHM system can be imagined as generating value for asset owners from various avenues, for example, the operations could be improved, or maybe the structure can be built more efficiently. This value generated by an increased understanding of the state of structures is called value of information (VoI). The VoI problem in SHM has gathered significant attention in the research community in the last decade and turned into a subfield of the broader SHM literature, with its own special editions in SHM journals and conference sessions [6–10]. We contribute to the SHM VoI literature by showing that the potential to extend remaining useful life (RUL) is a large component of bridge SHM VoI.

2. Materials and Methods

2.1. Value of SHM Information

A key goal of SHM system use infrastructure is to improve asset management [11]. SHM systems yield benefits by providing information that allows improved asset management decisions. Often, improvement is measured in monetary terms, whereby lower expenses are sought. Value of information (VoI) is a quantification of the incremental benefit, e.g., cost saving, resulting from the action taken based on information provided by the SHM system. In the case of infrastructure, the total VoI is composed of two components: the value derived from improved operation and the value derived from increased useful life. The scope of this work focuses on the latter. VoI is defined as the difference between the net present value of the expected operational expenses and replacement/refurbishment expenses when the asset is operated without utilizing SHM and the expected present value of the same expenses when SHM is utilized—assuming that the use of SHM decreases expenses. In case of lifecycle extension, the cost savings are derived from time value of money. We will discuss this mechanism in detail below.

The general idea is that infrastructure management is a series of decision problems performed under uncertainty. The quantification of VoI is based on studying the effect of SHM information on the decision analysis. We would like to note that quantifying the VoI is dependent on the characteristics of the decision-makers as shown in earlier work by one of the authors [12–14]. In the case that the existence of SHM information affects the optimal decisions, the VoI can be defined as the difference between the utility obtained based on an optimal strategy where the information is used, and the utility based on an optimal strategy where the information is not used [15]. The total VoI is composed of two components: the value derived from improved operation (here, we include risk reduction based on SHM in "improved operations"), and the value derived from increased useful life. The scope of this work is limited to the latter.

VoI can be evaluated as the difference between the net present value of the expected operational expenses and replacement/refurbishment expenses when the asset is operated without utilizing SHM and the expected present value of the same expenses when SHM is utilized—assuming the use of SHM decreases expenses. In case of lifecycle extension, the cost savings are derived from time value of money. We will discuss this mechanism in detail below.

Structural health monitoring systems can be used to extend the service life of structures, for example, through an improved estimation of capacity or an improved estimation of fatigue life [16,17]. Long et al. studied optimal monitoring strategies in the context of fatigue analysis and showed that service life could be extended based on SHM-aided decision-making [18]. Because of the time value of money, postponing the replacement is beneficial from a financial point of view. Thomson shows the effect of the time value of money by deriving the value of lifecycle extension from the borrowing costs over the funds needed to replace the bridge [16].

From an economic point of view, borrowing cost is the market price for the cost of lost opportunity (or, in short, opportunity cost) on other possible investments that are forgone when funds are used for some specific purpose. The practical embodiments of this opportunity cost are the interest rate on debt and expected return on equity, two types of capital used to fund enterprises. Due to the opportunity cost, the timing differences need to be considered when comparing evaluations of investments occurring at different times. In financial economics, the value of cash flow adjusted for the effect of timing differences is given by:

$$PV = \frac{C}{(1+r)^n} \tag{1}$$

where PV is the present value, C is the cash flow (positive or negative, depending on whether it is a cost or income), r is the discount rate, which is a measure of opportunity cost such as interest rate, and n is the number of time periods from the present until the occurrence of the cash flow.

In the context of bridge replacement, the cash flow that we are interested in is the replacement cost of the bridge. Equation (1) shows that assuming that the cost of capital and interest rate are positive, the present value of replacement cost is decreased if the cash outlay (spending for replacement of bridge) is pushed to the future. Postponing replacement is thus beneficial because it decreases the present value of the replacement cost, and if the information provided by SHM can be used to postpone bridge replacement, it creates a value for the bridge owner.

SHM can be used to postpone bridge replacement by allowing for the utilization of the reserve capacity that many bridges contain, i.e., the reserve capacity beyond the defined end of their service life [19,20]. This capability of SHM has been recognized in the literature, and good examples are found in the work by Thomson [16]. Bakht and Mufti see this potential as significant enough to justify creating a new inspection scheme for bridges [20]. The idea of using SHM to postpone replacement can be backed by considering the way bridge structures are assigned structural rating categories from the National Bridge Inventory (NBI), found in the NBI's coding guideline [21]. State Departments of Transportation (DOTs) in the United States are required to maintain records of the physical conditions of bridges [22]. According to Federal Highway Administration (FHWA) guidelines, the conditions of bridge components are recorded as Condition Ratings (CRs), which have numerical values between 0 and 9 [21]. The collection of the condition ratings for all applicable bridges in the United States is kept in the National Bridge Inventory [23]. The NBI data are available, beginning from the year 1992, and it represents a uniquely extensive record of bridge deterioration history. The verbal descriptions corresponding to the numerical values are presented in Table 1, and further description can be found in [17].

Table 1. Descriptions of NBI condition ratings (see [21]).

Rating	Condition Description
9	Excellent Condition
8	Very Good Condition
7	Good Condition
6	Satisfactory Condition
5	Fair Condition
4	Poor Condition
3	Serious Condition
2	Critical Condition
1	"Imminent" Failure Condition
0	Failed Condition—out of service—beyond corrective action

Condition rating level 4 (CR4) is taken as the condition level at the end of service life [24]. According to Kumar et al. CR4 is the level commonly used to trigger replacement and rehabilitation actions [25]. The description given in the FHWA guideline for the end-of-service life condition level is: "POOR CONDITION—advanced section loss, deterioration, spalling or scour." This does not indicate imminent failure in any way, and so clearly, even if the service life is considered depleted, the bridge might still have capacity left. It would be highly desirable to have the means to utilize this uncertain capacity as it would allow for the extension of service life.

In contrast, condition rating level 2 (CR2) is described as: "CRITICAL CONDITION—advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored it may be necessary to close the bridge until corrective action is taken". What is interesting here is the phrase "unless closely monitored, it may be necessary to close the bridge until corrective action is taken". Further use of a bridge in this condition depends on whether it is closely monitored. Many would argue that installing an SHM system would satisfy the monitoring requirement. Thus, for bridges that have reached the end of their formal service life, SHM would allow further use. Our interpretation is that with the monitoring system installed, the bridge could be used until condition rating level 1 (CR1), "IMMINENT FAILURE CONDITION", possibly allowing significant lifecycle extensions, depending on how much reserve capacity the observed bridge has left. In this work, to be conservative, we assume that a bridge with a monitoring system could be used until it is downgraded from condition rating level 3 (CR3). The time to reach this provides a convenient lower bound of the reserve capacity remaining.

Thus, within the scope of this paper, we calculate first the value of an SHM investment based on the potential of postponing the replacement as outlined above. This provides a component for the evaluation of the VoI tied to the reserve capacity. In our calculations, we assume that a non-monitored bridge reaching CR4 will trigger immediate replacement action (as per Kumar et al. [21]). We denote this strategy, that does not include SHM, by "A". In this strategy, a cash outlay would have a present value PV_A equal to the replacement cost of the bridge at CR4. Denoting this by $C_{rep,R4}$, we have:

$$PV_A = C_{rep,R4} \tag{2}$$

Now, according to the discussion given above, we assume that strategy "B" includes an instrumentation of a bridge with SHM that allows the bridge to remain in use until it has degraded to CR2. In this case, based on Equation (1), the present value PV_B of the postponed replacement cost at CR2, $C_{rep,R2}$ (the "present" being the moment the bridge reaches CR4) is given with the following expression:

$$PV_B = \frac{C_{rep,R2}}{(1+r)^N} \tag{3}$$

where N is the number of years it takes for the bridge deterioration to progress from CR4 to CR2 and r is the discount rate or interest rate used.

There is an important observation regarding Equations (2) and (3): PV_A is deterministic, while PV_B is stochastic. In the case of Strategy A, the replacement is performed immediately, the present value PV_A is fully deterministic, the replacement cost C_{rep} is known, and the time is zero because we have defined the present as the moment of reaching CR4. The number of years it takes for a bridge to reach CR2 is a result of a stochastic degradation process, and hence, the present value PV_B is a random variable.

Let us define the utility of Strategy A, U_A, as the cost of replacing the bridge at CR4, i.e., without the use of SHM, and the utility of Strategy B, U_B, as the cost incurred by postponing the replacement of the bridge, based on the information provided by SHM, to when the bridge was downgraded from R4 to CR2. The utility of Strategy B should include the discounted cost as per Equation (3), but also the cost of implementation of SHM, C_{SHM}. Note that the utilities, U_A and U_B, are both negative, since they both reflect costs, as shown in Equations (4) and (5):

$$U_A = -PV_A \tag{4}$$

$$U_B = -PV_B - C_{SHM} \tag{5}$$

Then, the monetary benefit of the SHM system, i.e., the value of information that it provides, VoI_{SHM}, can be calculated as the difference between the utilities U_B and U_A, by combining Equations (2)–(5), as follows:

$$VoI_{SHM} = U_B - U_A = (-PV_B - C_{SHM}) - (-PV_A) = C_{rep,R4} - \frac{C_{rep,R2}}{(1+r)^N} - C_{SHM} \tag{6}$$

Let us define present value of SHM, PV_{SHM}, as the difference between the present values of strategies A and B:

$$PV_{SHM} = PV_A - PV_B = VoI_{SHM} + C_{SHM} = C_{rep,R4} - \frac{C_{rep,R2}}{(1+r)^N} \tag{7}$$

PV_{SHM} presents an upper bound of how much a bridge owner should be willing to pay for the implementation of SHM for the purpose of keeping the bridge operational after the normal service life is reached. In other words, the implementation of SHM is profitable if VoI_{SHM} is positive, which occurs if and only if $PV_{SHM} > C_{SHM}$. Given that the cost of implementation of SHM, C_{SHM}, is not known a priori, we focus in this paper on evaluation of PV_{SHM} instead of VoI_{SHM}. In general, once the PV_{SHM} is evaluated, then the study of viable SHM can be performed for a specific bridge, which is considered out of the scope of this paper.

To simplify the presentation, we assume that the replacement cost is the same for both strategies, A and B, i.e., we assume that $C_{rep,R4} = C_{rep,R2} = C_{rep}$. This might be an unrealistic assumption; however, including the additional complication of the difference in the costs of replacement would offer very little added benefit in this paper, as the aim of the paper is to present the overall valuation framework. Any refinements, such as including the difference in the costs of replacement, can be considered in future work.

It is necessary to note that the quantity presented in Equation (7) is stochastic, i.e., its values are realized according to some probability distribution. Thus, we take the expected value of (7) to obtain the expected PV_{SHM}. Taking the expected value of Equations (6) and (7) provides the expected VoI and PV_{SHM}:

$$E[VoI_{SHM}] = E[U_B - U_A] = E[(-PV_B - C_{SHM})] - E[(-PV_A)] = E[C_{rep,R4}] - E\left[\frac{C_{rep,R2}}{(1+r)^N}\right] - E[C_{SHM}] \quad (8)$$

$$E[PV_{SHM}] = E[PV_A] - E[PV_B] = E[VoI_{SHM}] + E[C_{SHM}] = E[C_{rep,R4}] - E\left[\frac{C_{rep,R2}}{(1+r)^N}\right] \quad (9)$$

We have outlined the computation of the present value of the benefit which the SHM system presents to an infrastructure owner in a single realization. As the remaining lifecycle after reaching condition 4 is random, each realization will have different benefits, and the value of an SHM system will have some distribution. To uncover this distribution, we will utilize a Monte Carlo simulation method in conjunction with the degradation rate distributions discussed earlier.

The steps for computing distributions for the SHM VoI component tied to postponing replacement is given below:

1. Draw realizations of the degradation process from the distribution of RUL.
2. Compute PV_{SHM} for this realization using the formula presented above. The computed value represents a single simulated sample from the distribution of the SHM system's present value.
3. Repeat the process for N times to obtain N samples from the distribution of the VoI.

2.2. Lifecycle Extension: VoI Quantification

To estimate the lifecycle extension potential, we need to simulate bridge deck condition degradation over time. We utilize a neural network-based survival analysis and Monte Carlo simulation to quantify the expected VoI component related to lifecycle extension. We study the VoI in the context of concrete decks in US highway bridges. In this section, we present a brief overview of the dataset and the model we have used for deterioration modeling. The discussion given here is a broad overview. The focus of this paper is not on the details of deterioration modeling, so we chose to be brief.

2.2.1. Dataset Used for Deterioration Modeling

We use a bridge deck dataset created by Fleischhacker et al. [26]. The dataset is a subset of the NBI dataset, preprocessed for survival analysis purposes. The use of a specialized dataset is necessary, because without preprocessing, NBI data cannot be used for survival analysis. Survival analysis requires the dataset to possess information about the amount of time bridge decks spend in any given CR. The yearly ratings need to be transformed into TICR values and flags to show if CR decrease is observed, or if the structure had remained in the same CR until the end of the observation period, which is referred to as censoring. The dataset consists of observations of time wherein a given bridge deck stays in the same CR, and characteristics of the bridge that are used as inputs in our deterioration model. The bridge characteristics used in the deterioration model are presented below in Table 2. The reader is encouraged to see our previous work for a detailed explanation of how the dataset was used in our deterioration model. For information about the dataset, the reader should refer to the original work of Fleischhacker et al. [26].

2.2.2. Computational Approach: Survival Analysis

We utilize a neural network-based survival analysis to model bridge deck condition degradation—this results in the distribution of the time a deck spends in any given condition rating. The goal of our degradation modeling approach here is to create an estimate of the distribution of the time it takes for a given bridge deck to degrade from CR4 to CR2, the difference between the conventional end-of-service life and the service life that could be realized by utilizing SHM systems. Survival analysis is a field of statistics concerned with modeling time-to-event. Typical examples of survival analysis are analyzing time-to-failure in reliability engineering [27], important events in human life (marriage, childbirth) [28], and mortality in life sciences [29]. We utilize survival analysis to generate distributions for TICRs (Time-In-Condition-Rating). These distributions can then be used as inputs for MC.

Table 2. Description of covariates and their range of values. Modified from [26].

Description of Covariate	Abbreviation	Range of Values
Average Daily Truck Traffic	ADTT	[0.56595]
Climatic Region	ClimaticRegion	"Region 2—very hot"; "Region 3—hot"; "Region 4—average"; "Region 5—cold "; "Region 6—very cold"; "Region 7—extremely cold"; "Region 8—subarctic"; "Region 9—average marine"; "Region 10—hot marine".
Condition Rating	CR	CR3, CR4, CR5, CR6, CR7, CR8, CR9.
Deck Protection Type	DeckProt	"None"; "Epoxy-coated reinforcing"; "Galvanized reinforcing"; "Other coated reinforcing". "Cathodic protection"; "Polymer impregnated"; "Internally sealed"; "Unknown"; "Other".
Deck Type	DeckType	"Concrete cast-in-place"; "Concrete precast panels".
Distance to Sea Water	SeaDist	"Sea Less than 3 km Away"; "Sea More Than 3 km Away".
Functional Classification (NBI Item 26)	FunctClass	"Rural"; "Urban".
Maintenance Responsibility	MaintResp	"State highway agency"; "County highway agency"; "Town/township highway agency", "City/municipal highway agency", "Private (other than railroad)"; "State toll authority".
Structural Type	StructType	"Concrete-simple span"; "Concrete-continuous"; "Steel-simple span"; "Steel-continuous"; "Prestressed concrete-simple span"; "Prestressed concrete-continuous".

The goal of bridge survival analysis is to derive *survival curves* that describe an individual bridge's probability of staying (we adopt the usual practice in survival analysis and refer to staying in the same condition rating as *surviving)* in a given condition rating over time. If $f(t)$ is the probability density function (PDF) of the survival TICR, and $F(t)$ is the corresponding cumulative distribution function (CDF), the survival function is given by:

$$S(t) = 1 - F(t). \tag{10}$$

The graph of this function is known as the survival curve [30].

We generate the survival curves using a neural network model designed for this purpose in our earlier work. The model is built on top of a Python library "nnet-survival" [31]. Figure 1 shows the architecture of our neural network. The input variables used are the bridge deck characteristics presented in Table 2. The categorical variables are transformed into binary inputs. The total number of input variables after this operation is: 43 binary input variables and one numeric input variable. The basic principle of this architecture is that we treat categorical variables and the numerical variable ADTT separately, whereby these two "pipelines" have separate hidden layers, until the output layer where these two "pipelines" are combined and the outputs (hazard function values) are computed. We encourage readers to consult one of the author's dissertation for details [32].

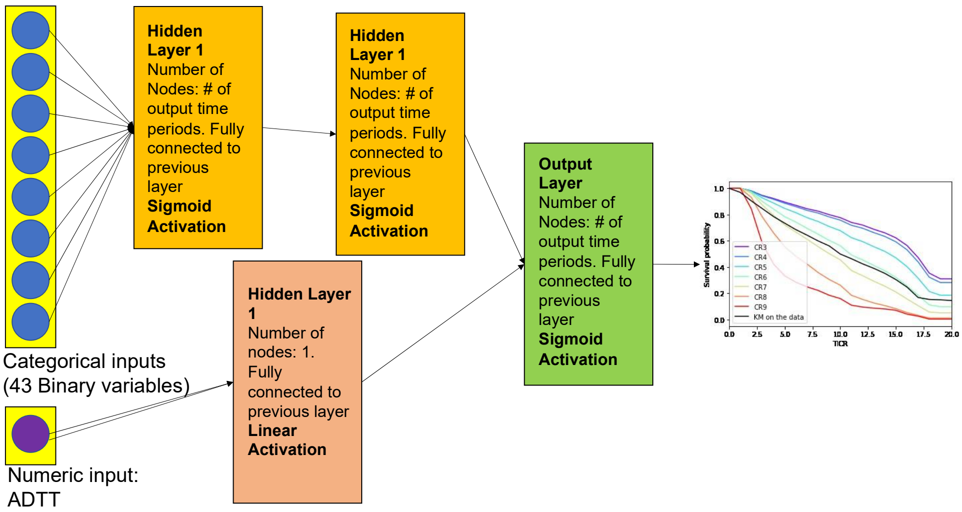

Figure 1. NN architecture to model hazard function for bridge deck survival analysis.

2.2.3. Computational Approach: Monte Carlo Simulation

The survival functions generated by the NN model provide us with the distribution of TICR. We utilize Monte Carlo simulation to sample these distributions and aggregate them to predictions of the reserve capacity. We use the inversion method to draw samples from the distributions given by the survival curves. This method is necessary because the distributions that our model generates based on the data do not fall under any general family of probability distributions for which a random number generator would be available. With the inversion method, it is possible to sample any probability distribution as long as a uniform random number generator and the means to invert the cumulative density function of the distribution of interest are available [33].

The inversion method is based on the following mathematical reasoning [34]. Let U be a uniform [0.1] continuous random variable, and we want Y to be a discrete random variable, which we want to sample that has the probability mass function $P\{Y = y_j\} = p_j$, $j = 0, 1, \ldots, \sum p_j = 1$ and a cumulative distribution function:

$$P\{Y \leq y) = F_Y(y) = \sum_{y_j \leq y} p_j \tag{11}$$

Then, if we define:

$$Y = \Phi(U) = \begin{cases} y_0 & If\ U < p_0 \\ y_1 & If\ p_0 \leq U < p_0 + p_1 \\ & \vdots \\ y_j & If\ \sum_{i=0}^{j-1} p_i \leq U < \sum_{i=0}^{j} p_i\ \# \\ & \vdots \end{cases} \tag{12}$$

Or, presented using the CDF:

$$X = \Phi(U) = \begin{cases} y_0 & If\ U < F_Y(y_0) \\ y_1 & If\ F_Y(y_0) \leq U < F_Y(y_1) \\ & \vdots \\ y_j & If\ F_Y(y_{j-1}) \leq U < F_Y(y_j) \\ & \vdots \end{cases} \tag{13}$$

Then, for $0 < a < b < 1$, $P\{a < U < b\} = p_j$, and from this, it follows that:

$$P\{X = x_j\} = P\left\{\sum_{i=0}^{j-1} p_i \leq U < \sum_{i=0}^{j} p_i\right\} = p_j \tag{14}$$

and we see that X and Y have the same distribution.

Using the inversion method, it is straightforward to draw samples from TICR distributions based on our NN model. The model provides us with survival functions, which, according to Equation (1), are defined as:

$$S(t) = 1 - F(t).$$

Using this, we can represent the cumulative distribution function as:

$$F(t) = 1 - S(t). \tag{15}$$

Then, combining this with Equation (13), we obtain the transformation needed to draw samples from the TICR distribution:

$$\text{TICR} = \Phi(U) = \begin{cases} t_0 & If\ U < 1 - S(t_0) \\ t_1 & If\ 1 - S(t_0) \leq U < 1 - S(t_1) \\ & \vdots \\ t_j & If\ 1 - S(t_{j-1}) \leq U < 1 - S(t_j) \\ & \vdots \end{cases}. \tag{16}$$

Using this, we can draw samples of TICR in a given condition rating. Since we are interested in the transition through CRs 4 and 3, we need a way to aggregate the TICRs in these states. To accomplish this, we assume that the TICR is independent of the history. In practice, this means that the distribution of TICR in CR3 is not affected by the realization of TICR in CR4. With this assumption, we can simply aggregate the TICR realizations on CR3 and CR4 by adding them. Following the procedure presented, we obtain the output of the Monte Carlo simulations, which is the excess RUL as defined earlier in Section 2.1.

3. Results

To explore the VoI achievable in SHM systems deployed to extend the RUL of concrete bridge decks and demonstrate the application of the developed methodology, we present a case study. The bridge we have chosen to study is the southbound portion of the bridge on US Highway 202, located in Wayne, NJ. We chose this bridge because it was part of a significant international SHM research project, and hence, the SHM literature contains information on this bridge; moreover, it is well-known for many members of the research community. In addition, it is a representative concrete highway overpass, the type of which there are in large numbers in the US. Because of this, we expect findings on this bridge to be somewhat applicable to a larger population.

3.1. Survival Curve Estimation

We obtain the information necessary to estimate survival curve from FHWA's NBI web portal [35]. Basic information on the bridge along with the parameter values are presented below in Tables 3 and 4.

Table 3. Basic information on the case study bridge.

NBI Structure Number	1618150
Location	Wayne Township, NJ, USA
Route	US202
Year Built	1983
Deck Area, sq. ft.	52,937.7
Latitude,	40.91485
Longitude	−74.26529

Table 4. Model parameter values for the case study bridge.

Description of Covariate	Abbreviation	Range of Values
Average Daily Truck Traffic (recording period used to calculate the average: year 2020)	ADTT	3335
Climatic Region	ClimaticRegion	"Region 5-cold ";
Deck Condition Rating (Current)	CR	CR6
Deck Protection Type	DeckProt	"Epoxy-coated reinforcing";
Deck Type	DeckType	"Concrete cast-in-place";
Distance to Sea Water	SeaDist	"Sea More Than 3 km Away"
Functional Classification (NBI Item 26)	FunctClass	"Urban"
Maintenance Responsibility	MaintResp	"State highway agency";
Structural Type	StructType	"Steel-simple span"

We input these parameters to our survival analysis model and generate survival curves for both CR3 and CR4. The resulting survival curves are visualized below in Figure 2.

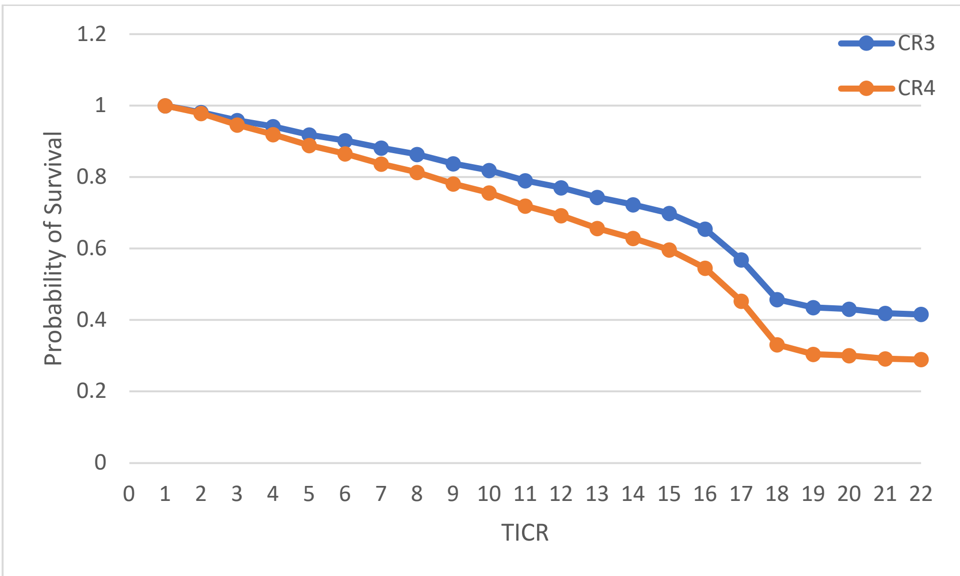

Figure 2. Survival curves for the Wayne bridge.

Upon inspecting the survival curves, we can see that the curves do not reach zero, and there is an inflection point at TICR = 18. We believe that this is generated by the span of the database, the maximum TICR which we have data from is 22, so there is an artificial upper limit on the observations. In addition, from our studies of the data, we know that the bridges tend to spend a longer time before downgrading on the lower condition ratings—an artifact we assume to be caused by some unknown characteristic of the rating and maintenance process. One explanation offered in the literature is that maintenance actions slow down the deterioration rate in the lower condition ratings [36]. We believe these two issues together serve to create circumstances where our model is unable to generate meaningful survival probabilities in the higher TICR values for the lower condition ratings.

This characteristic of the data, if not rectified, would cause severe distortions to the outcomes, since the survival curve does not reach zero, the inverse transform method of random number generation will present an overweight to the largest TICR value. This is caused because all random numbers from the uniform distribution that exceed the bounds are mapped to the last valid value. To rectify this, we modify the survival curve by assuming linearity after TICR = 18, which is the location of the inflection point. We calculate the slope between the TICR = 17 and 18, which are the last valid values according to our judgment. Since this approach does not necessarily lead to a curve that crosses the y-axis at an integer value, we add the rule that the first negative value will be set equal to zero. This way, we obtain meaningful survival curves that end in $S = 0$. The outcome of this modification is presented in Figure 3. To finalize this discussion, we want to point out that proceeding in the way we describe can be considered conservative. We have assumed a steep decrease in survival probabilities and removed the entire right tail of the distribution, leaving out many feasible long survival times. This means that the estimates we derive for the potential value of postponing replacement will be conservative.

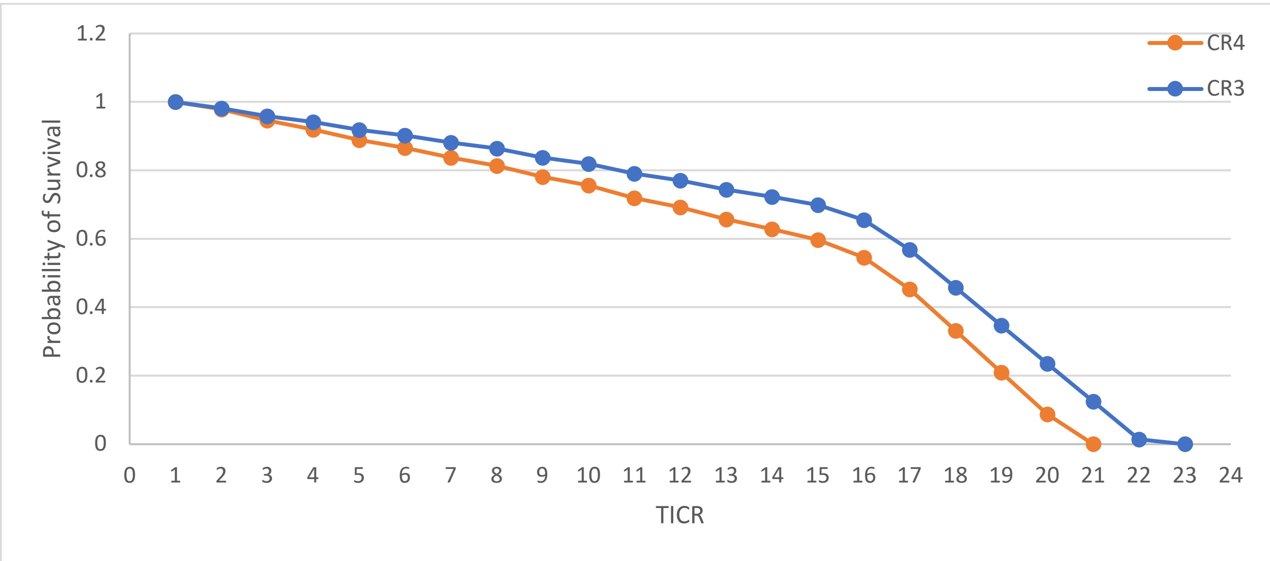

Figure 3. Corrected survival curves.

3.2. Monte Carlo Simulation of RUL Distribution

Now that we have estimated the survival curves for our bridge deck, we can utilize the inversion method discussed in Section 3.3 to draw realizations of the remaining useful life. Figure 4 shows a histogram of the simulated RUL realizations when 10,000 outcomes are drawn.

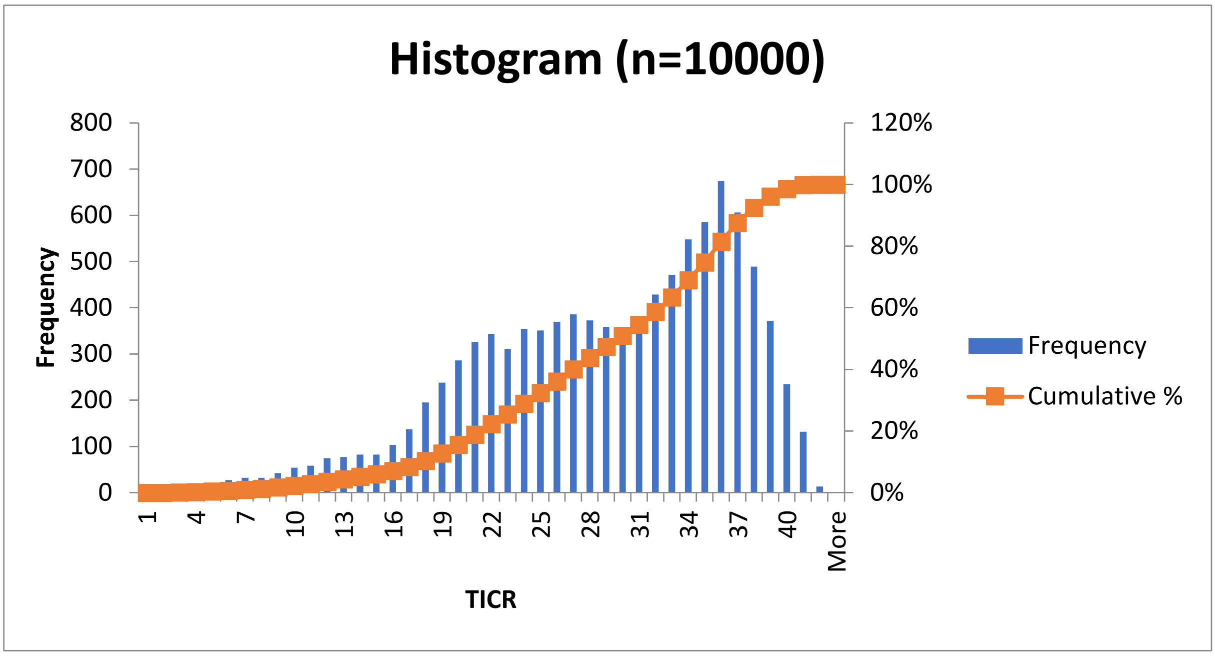

Figure 4. Histogram of RUL simulation outcomes.

Inspecting the histogram, we see that the distribution has two major peaks, one around 23 years and the other at 36 years. The bimodality is a consequence of the way the RUL prediction is computed as the sum of the TICR in CR3 and CR4. Both distributions are skewed toward larger TICR values, so their sum will result in two peaks. Figures 5 and 6 below show the histograms of the realizations drawn for TICR for CR3 and CR4.

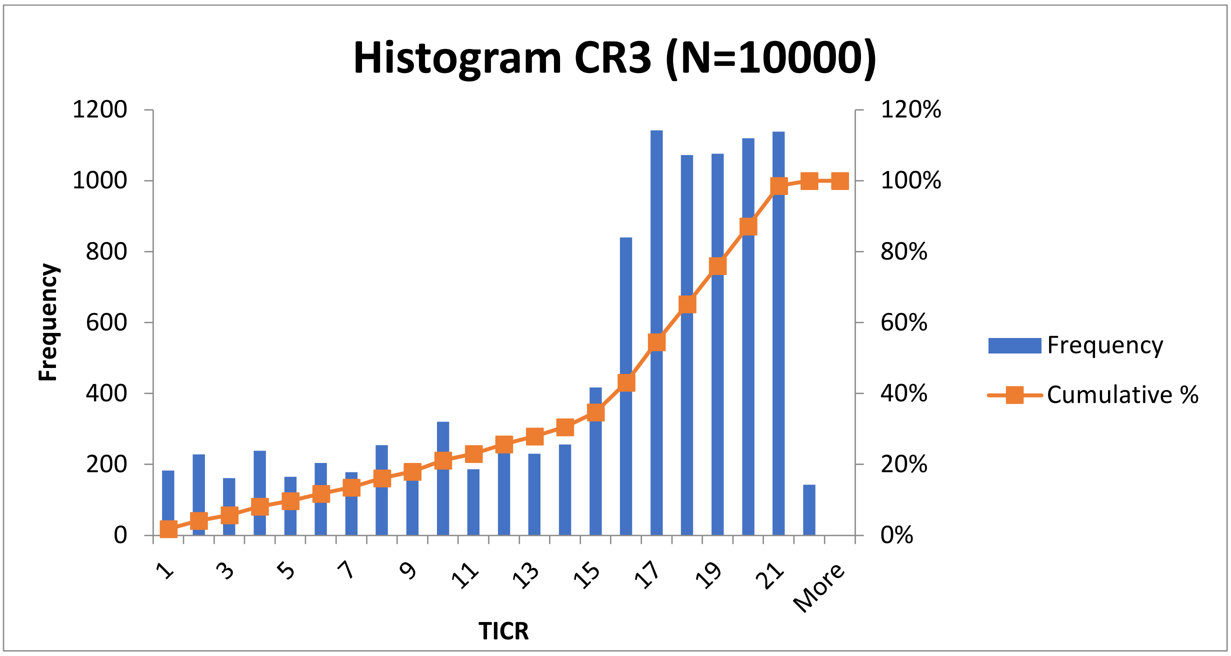

Figure 5. Histogram of realizations drawn for CR3 TICR.

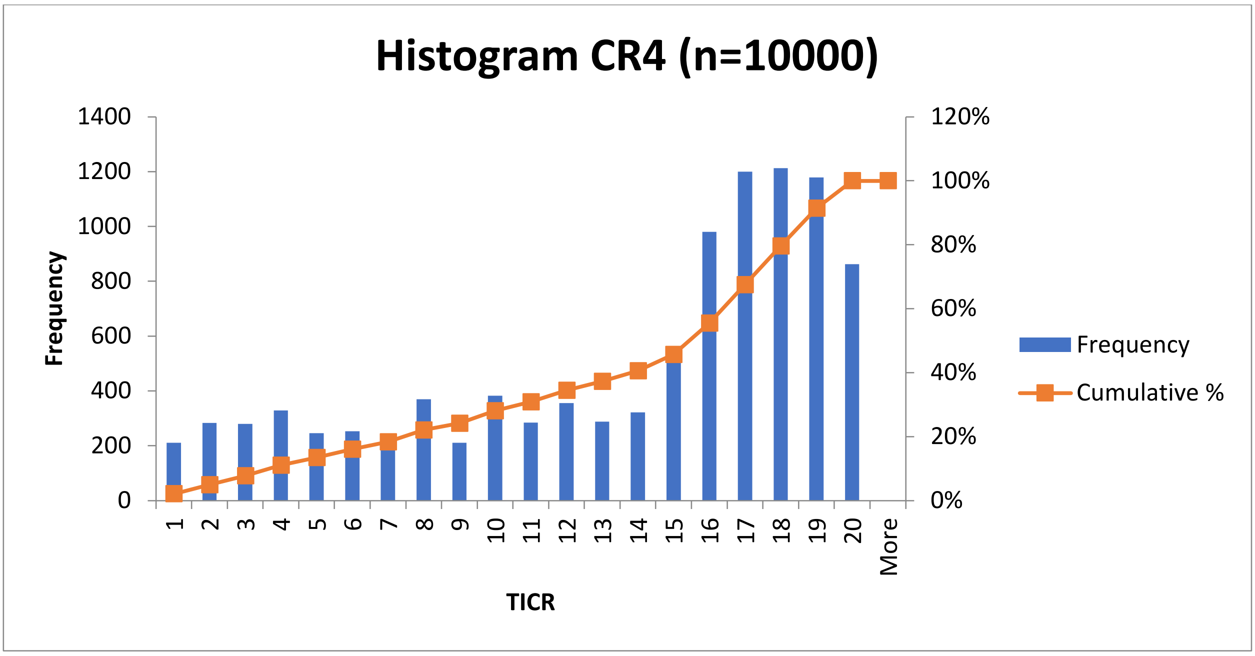

Figure 6. Histogram of realizations drawn for CR4 TICR.

3.3. Calculation of RUL Extension VoI

Now that we have simulated distributions of the remaining useful life, we can estimate the value that could be realized by being able to utilize this portion of the bridge deck's lifecycle. We will accomplish this by applying Equation (4) to the simulated RUL realizations. The calculation requires two input values in addition to the RUL distribution simulated above: the discount rate and the replacement cost. The USDOT recommends using a discount rate of 7% in the benefit–cost analysis of highway projects [37]. We use the recommended 7% but also conduct a sensitivity analysis. We use values from New Jersey DOT's cost estimating guide for the deck replacement cost [38]. The data in Table 5 below are taken from the guide and shows values for replacement costs in year 2016. According to the guide, the cost estimates are to be adjusted for inflation using a 3% simple interest factor. We adjust the prices to the level of 2023, meaning the values in the table need to be increased by a factor of: $(2023 - 2016) \times 3\% = 21\%$. To obtain an estimate of the total replacement cost, we multiply the per square values with the deck area of 52,937.7 sqf. The deck area is sourced from NBI (see Table 1). Table 6 shows the inflation-adjusted values for the bridge deck replacement item.

Table 5. Construction cost estimates for bridge elements.

Project Category	Units Used for Calculations	Median Cost per Unit	Low Cost	Average Cost	High Cost
Bridge Deck Replacement	Square Foot	USD 320	USD 150	USD 380	USD 730
Bridge Superstructure Replacement	Square Foot	USD 400	USD 230	USD 530	USD 1300
Bridge Replacement	Square Foot	USD 1800	USD 750	USD 1900	USD 3500
Culver Replacement	Square Foot	USD 2700	USD 1300	USD 2300	USD 3300

Table 6. Deck replacement cost adjusted for inflation.

	Low Cost	Median Cost	Average Cost	High Cost
Bridge Deck Replacement Cost (Dollars per Square Foot)	181.5	387.2	459.8	883.3
Total Replacement Cost (Millions of Dollars)	9.6	20.5	24.3	46.8

With this information, we can analyze the value linked to the potential for lifecycle extension. We substitute the information above to Equation (5), using the recommended discount rate r = 7%, and compute the result for each of the 10,000 realizations of the RUL. Table 7 below shows a summary of the results. Figure 7 shows the quartiles and outliers of the data. These results show that the VoI for an SHM system that would allow utilizing the entire RUL of a bridge deck could be potentially very large, with an average VoI of USD 17.9 million, representing 74% of the replacement cost, if replaced immediately. However, as can be seen from Figure 7, there is considerable variance in the potential VoI, with the cost assumption dramatically affecting the realizable VoI. In addition, the VoI of the replacement cost is sensitive to the discount rate assumption. The USDOT guidance instructs to use the 7% discount rate, but to gain understanding on the effect of these assumptions on the VoI, we conducted a sensitivity analysis. Figure 8 shows the result of the sensitivity analysis. Figure 8 clearly shows how the discount rate has a large effect on the potential VoI in each of the replacement cost scenarios. It is noteworthy that in case of negative discount rates, the VoI can even be negative, and postponing would be detrimental. Theoretically, negative discount rates are possible. However, how realistic a negative discount rate would be in the case of infrastructure projects is not obvious. This issue is outside the scope of this work, and the entire question of determining discount rates remains a topic of further research.

Table 7. Summary of the VoI calculation results.

	Low Cost	Median Cost	Average Cost	High Cost
Max VoI (Millions of Dollars)	9.0	19.3	22.9	44.0
Min VoI (Millions of Dollars)	1.2	2.6	3.1	5.9
Average VoI (Millions of Dollars)	8.0	17.1	20.3	39.0

In conclusion, in the right conditions, for an SHM system installed for with the purpose of extending the RUL of a bridge, the potential payoff is large. Because the bridge used in our case study is an "ordinary" bridge, meaning that there are large number of similar bridges in the US highway system, we believe that the potential benefits for the programmatic deployment of SHM to the entire highway system are large.

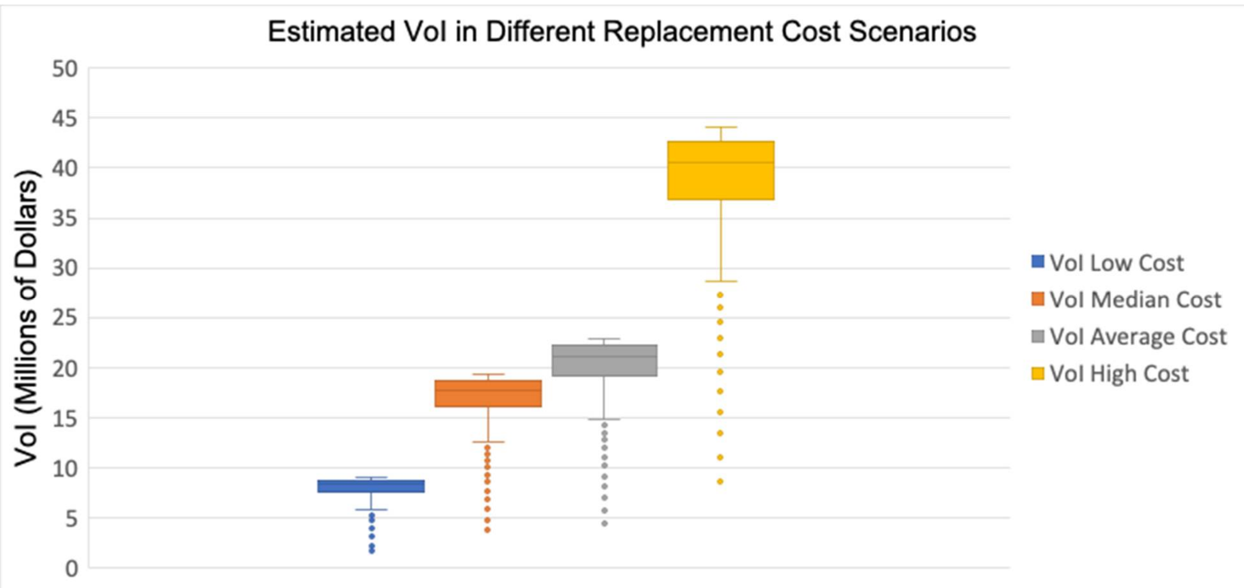

Figure 7. Quartiles and outliers of the simulated data.

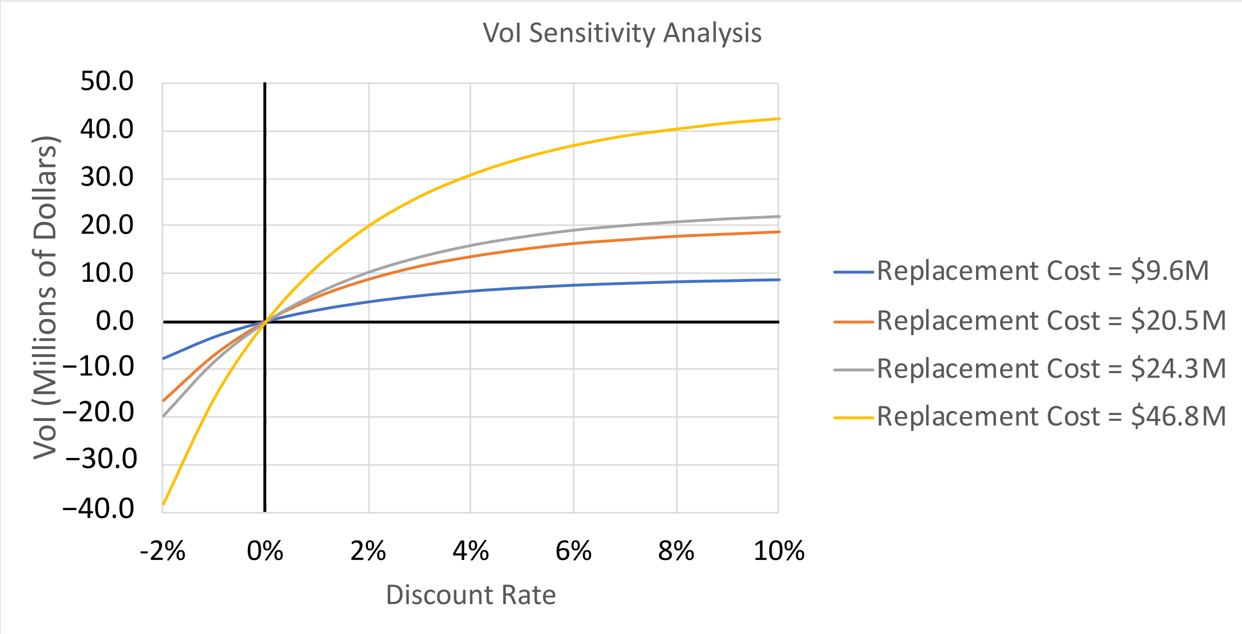

Figure 8. Sensitivity of average VoI on replacement cost and discount rate assumptions.

4. Discussion

The large effect of the discount rate is an important observation for two reasons. First, there is no obvious objective way to decide the discount rate that should be used in analyzing the benefit of postponing the replacement of the deck. As discussed earlier, the discount rate presents an opportunity cost related to the benefits of the projects that could have been performed instead of the bridge deck replacement. How this value should be decided is a complicated question and is connected to diverse topics such as the other investment opportunities available, priorities, and funding situation. Since most infrastructure projects require lending to finance, the cost of this financing, or the interest rate, is one potential discount rate. Using the financing cost to calculate the SHM system's VoI derived from service life extension has been previously analyzed in the literature [16].

Second, when the financing cost is used as the discount rate, it gives rise to significant timing issues because interest rates change over time. For reference, Figure 9 shows the historic 30-year borrowing cost for the US government. We see that in the period spanning from the early 1980s to the present day, the interest rate has varied between ~15% and ~1%. It is thus clear that the interest rate effect on SHM VoI is large and potentially varies in time.

An interesting characteristic of SHM VoI can be deduced from the two observations discussed above: the VoI is not dependent only on the technical aspects, such as the bridge replacement costs and the SHM system characteristics, but also on external socioeconomic factors in the form of the discount rate. It is worth emphasizing that the effect of the discount rate is large. The conclusion of this is that, when evaluating whether SHM should be deployed, and the extent of deployment, a holistic socio-technoeconomic analysis is necessary. Further, as the borrowing costs that influence discount rates change over time, the analysis needs to take the timing and current situation broadly into account, including the interest rate environment.

The analysis we have presented shows impressive results but some discussion of the drawbacks of the method is necessary. The first concerns the question of the reliability of the data. The estimation of the RUL distributions that was necessary for the Monte Carlo simulation is dependent on data from the NBI bridge inspection data. The inspection process is based on bridge inspectors' evaluations of the bridge condition and thus creates a subjective element to the data. This factor adds to the uncertainty of the results and is difficult to evaluate its impact on the results. Second, we have made the simplifying assumption that the time spent in CR4 and CR3 are independent. This assumption could be a source of inaccuracy for the analysis and should be tested in further research. The third drawback of our analysis is that we do not have an estimate the degree of the method's scalability. As inspection methods and practices improve, more data can be collected and potentially used in forecasting the RUL. Estimates of the scalability of the methods presented here are needed to evaluate how well the methods could be utilized if more data are available.

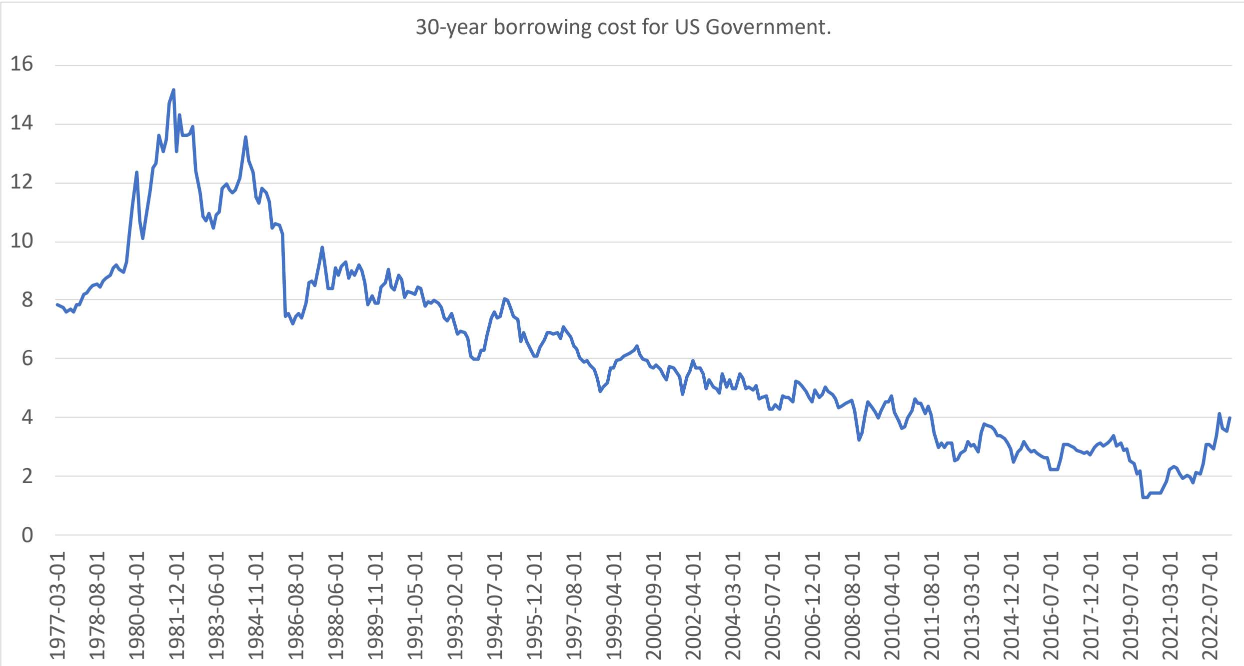

Figure 9. Historical 30-year borrowing cost for the US government. Data used to generate the graph from [39].

5. Conclusions

We have utilized a neural network-based survival analysis in conjunction with Monte Carlo analysis to show that significant VoI exists in SHM for bridge decks if deployed with the purpose of extending the RUL. We have shown this to be true using a case study. Our case study focused on a type of bridge that is very common in the US. Because of the promising results of our case study, we believe a substantially large value could be realized if SHM would be programmatically deployed to the entire highway system with the goal of extending service life. Future research is needed to generalize our results to different types of bridges and bridge components. We studied the topic in the context of concrete bridge decks; to understand the potential of RUL extension on the entire bridge population, a similar analysis is needed for other bridge components, such as the substructures or superstructures, and different bridge deck types. In addition to extending the analysis to different bridge types and components, a portfolio analysis over the entire bridge population would be necessary to estimate the potential of a large-scale SHM deployment. Because it is not feasible to deploy SHM on every bridge, the portfolio analysis would allow for maximizing the return on investment of such a program. Finally, we have focused on the potential benefits gained from SHM implementation. To complete the analysis, the cost of SHM systems that would allow RUL extensions need to be evaluated, both the initial project costs and the ongoing operational cost of such systems.

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